CARMA $\lambda =$ 1 cm Spectral Line Survey of Orion-KL

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Abstract

Orion-KL is a well-known high-mass star-forming region that has long been the target of spectral line surveys and searches for complex molecules. One spectral window where the region had never been surveyed is around wavelengths of $\lambda = 1$ cm. This is an important window to observe, due to the fundamental and low energy transitions of numerous complex molecules that indicate the maximum spatial extent of the molecular species; knowing the spatial distribution of a molecule aids in determining the formation mechanism(s) of that molecule. Additionally, there are fewer transitions in this window, reducing confusion caused by blended lines that can be very problematic at shorter wavelengths ($\lambda < 3$ mm). In this work, we present the first spectral line survey at $\lambda = 1$ cm of the Orion-KL region. A total of 89 transitions were detected from 14 molecular species and isotopologues, and two atomic species. The observations were conducted with the Combined Array for Research in Millimeter-wave Astronomy in both interferometric and single dish modes.

Key words: astrochemistry – ISM: individual objects (Orion-KL) – ISM: molecules – radio lines: ISM

1. Introduction

The Orion-KL region, the closest high-mass star-forming region, is very complex, both chemically and spatially. The region was originally brought to the attention of astronomers by the discovery of an extremely bright infrared object (BN) by Becklin & Neugebauer (1967). Future studies have determined that BN is an embedded B type star moving away from the Trapezium region (e.g., Goddi et al. 2011; Plambeck et al. 2013). Additional infrared studies of the region have found a plethora of compact source within 20″ of BN (e.g., Beuther et al. 2004). Radio studies of Orion-KL have found both a compact rotating disk and bipolar massive outflow, traced by SiO maser emission and centered on Source I (e.g., Wright et al. 1983, 1995; Plambeck et al. 2009); water and methanol masers (e.g., Plambeck & Wright 1988; Horiuchi & Kameya 2000); emission from CS, DCN, and many complex molecules (e.g., Mundy et al. 1986; Blake et al. 1987; Mangum et al. 1991); and many compact continuum sources (e.g., Eisner & Carpenter 2006; Friedel & Widicus Weaver 2011). Studies of BN and Source I over time have indicated that they likely interacted ~560 years ago (Goddi et al. 2011). Whether this interaction triggered the outflow and subsequent molecular release is not known at this point (Friedel & Widicus Weaver 2012; Widicus Weaver & Friedel 2012).

Orion-KL has been extensively studied due to its rich chemical inventory. There have been dozens of molecular searches and spectral line surveys of the region spanning wavelengths of $\lambda =$ 1.3 cm to 188 $\mu$m (e.g., Sutton et al. 1985; Turner 1989, 1991; Friedel & Widicus Weaver 2012; Gong et al. 2015). Several studies have indicated that the complex chemistry of the Orion-KL region displays so-called nitrogen-oxygen “chemical differentiation,” where the emission from complex nitrogen-bearing molecules such as ethyl cyanide [CH$_2$CN] trace the Orion Hot Core, and emission from complex oxygen-bearing molecules such as methyl formate [CH$_3$OCHO] trace the Orion Compact Ridge, thus being near totally spatially distinct. This concept comes from the original millimeter line survey of this source (Blake et al. 1987), where the spectral lines from these two classes of molecules were found to have different rest velocities and were therefore assumed to occupy different parcels of gas. Follow-up studies over the last three decades confirmed this differentiation through imaging of molecular emission at >1 arcsecond spatial resolution. However, the concept of these spatially distinct regions in Orion-KL was called into question by Friedel and Snyder (2008), who showed that acetone [(CH$_3$)$_2$CO] traces the gas at the intersection of the regions shown to contain spatially distinct N-bearing and O-bearing molecules. Additionally, Friedel & Widicus Weaver (2011) showed that the $\lambda = 3$ mm continuum of Orion-KL is composed of numerous, compact, bright continuum sources; and Friedel & Widicus Weaver (2012) and Widicus Weaver & Friedel (2012) suggested that much of the molecular emission may actually trace these compact regions, rather than the more extended structures traditionally associated with the Hot Core and Compact Ridge.

Spectral line surveys are a particularly powerful method in investigating the coupled dynamical and chemical evolution of molecular clouds. They provide a uniformly calibrated set of data that diminishes the errors associated with derived quantities. This survey studies a frequency range (26.938–34.938 GHz) that has not been surveyed before in Orion-KL. In this range there are many low energy transitions of complex molecules that indicate the true spatial distribution of the individual species. This in turn can give insight into the formation mechanisms of the different species. Additionally, this frequency range is less cluttered than those at 90 GHz and above, where many transitions are present, and at $\sim$30 GHz the lines are less likely to be blended with others, leading to lower uncertainties in derived quantities.

Figure 2 of Friedel & Widicus Weaver (2011) and the associated text give an overview of the major sources in this region. Due to the limited spatial resolution (>5″) of our observations, we do not focus on many of the individual sources, but instead focus on the larger scale structures (CS1, IRc6, Compact Ridge) and those compact structures that have strong molecular emission (Hot Core/I). Table 1 gives an
Table 1
Description of Sources in Orion-KL

| Name       | α(J2000)          | δ(J2000)       | $v_{LSR}$ (km s$^{-1}$) | FWHM (km s$^{-1}$) | Description                                                                 | References |
|------------|-------------------|---------------|-------------------------|-------------------|-----------------------------------------------------------------------------|------------|
| BN         | 05°35′14″106      | −05°22′22″528 | ...                     | ...               | Embedded B type star                                                        | 1          |
| CS1        | 05°35′15″179      | −05°22′03″76  | 10.5                    | 1.5               | Extended structure containing two compact sources MMS & MM6                 | 2, 3       |
| I/Hot Core | 05°35′14″511      | −05°22′32″101 | 2.5 − 7.5              | 5.5               | Compact source and a significant region of complex molecular emission       | 4, 5       |
| IRc6       | 05°35′14″155      | −05°22′27″19  | 7                       | 1.5–6             | Compact source with a mix of O and N-bearing molecules                      | 4, 6       |
| Compact Ridge | 05°35′14″15      | −05°22′37″40 | 7 − 8                   | 1–3               | Extended structure, source of complex molecular emission                    | 6, 7       |
| HC-NE      | 05°35′14″78       | −05°22′20″86  | 9 − 21                  | 4–8               | An extension of the Hot Core to the northeast                              | 8          |
| CR-SW      | 05°35′13″55       | −05°22′53″80  | 9                       | 1.1               | An extension of the Compact Ridge to the southwest                         | 8          |
| Orion Bar  | a                 |               |                         |                   | Highly irradiated region dominated by atomic lines                         | 9, 10      |

Notes.

a The Orion Bar is a very extended structure; no single coordinate set can describe its position.
b The structure is very large and has a wide variety of velocities, FWHM, and structure sizes.

References. (1) Plambeck et al. (2013), (2) Mundy et al. (1986), (3) Eisner & Carpenter (2006), (4) Widicus Weaver & Friedel (2012), (5) Wright et al. (1996), (6) Friedel & Snyder (2008), (7) Friedel & Widicus Weaver (2012), (8) this work, (9) Goicoechea et al. (2016), (10) O’Dell et al. (2017).

and molecular structure of the Orion-KL region as we currently understand it.

2. Observations

The data were taken with the $\lambda = 1$ cm receivers on the Combined Array for Research in Millimeter-wave Astronomy (CARMA) 10 and 6 m telescopes, which operated between 26.938 and 34.938 GHz in single sideband mode. CARMA was used in its C (24.3–300.0 m baselines) and D (10.2–119.0 m baselines) configurations to conduct observations in 2014 March–April and 2014 December–2015 April, respectively. The phase center for all observations was $\alpha$ (J2000) = 05°35′14″35 and $\delta$ (J2000) = −05°22′35″0. The synthesized beam sizes are $\sim 7'' \times 5''$ for the C configuration and $\sim 15'' \times 12''$ for the D configuration. One arcsecond is $\sim 414$ au at the distance of Orion-KL (Menten et al. 2007).

There are notable differences in the beam sizes for observations in the same array configuration; due to issues with the receivers, no observations had the entire 15 element array, and on average had 13 dishes.

The correlator setup for the observations was to put eight 31 MHz wide windows end to end, overlapping a few channels and integrating for 2.5 hr. The IF frequency of the windows was then shifted by 240 MHz and the process was repeated. Each of the windows had 393 spectral channels, giving a velocity resolution of 0.842–1.07 km s$^{-1}$, depending on frequency. Numerous strong spectral birdies, due to emission from hardware components, were found in the lowest end of the spectrum (below 27.13 GHz), and the corresponding data were discarded. The rest of the data were closely inspected for additional birdies; none were found. Due to hardware limitations, there was a small unobservable gap in our frequency coverage (30.885–30.945 GHz). The flux density was calibrated using observations of Mars, and the antenna-based gains were calibrated with observations of 0423-013 and 0607-085. The flux density calibration is good to 10%; all stated uncertainties in this paper are statistical in nature. A continuum map was constructed from line-free channels. This map was subsequently used to self-calibrate the data to reduce overall noise. All calibration, continuum subtraction, and imaging were performed using the MIRIAD software package.
Unless otherwise stated, all presented maps were produced using natural weighting.

Once the data were fully reduced, some of the spectral lines appeared to have larger spatial scale components. We initiated further observations with CARMA in auto-correlation mode, effectively acting as an array of single dishes. Fourteen transitions from 11 species were selected for this study (see notes in Table 3). The observations were done by position switching between the on positions and an off position 1° east and 0°5 south of the phase center position. The initial
observations used a 19 point hexagonal mosaic centered on the phase center and had a primary beam FWHM of 165° at each pointing. In subsequent observations, this was expanded to a 32 point mosaic to cover some potentially extended regions. Figure 1 shows the mosaic pattern and sensitivity coverage of the single dish observations. Only data from the 10.1 m dishes were used, due to their higher sensitivity. For the single dish observations, the correlator was set up with eight 31 MHz channels with line emission from the spectrum and fourier transforming the remainder together, and they contain no zero spacing data from the single dish observations. Figure 3 shows the resulting maps. Figure 3(a) is the C configuration data, while (b) is the D configuration data. In this, and all other

maps, the * icons denote the position of Trapezium stars and the + icons denote the positions of CS1, BN, Source I, and the Compact Ridge, for reference. The two continuum maps show the same general shape to the continuum structure and peak at nearly the same place. The bulk of the continuum emission comes from the compact sources detected in the C configuration, but there is notable emission from extended structure. Figure 4 shows a comparison map of the 1 cm continuum (black contours, dominated by free–free emission) and 3 mm continuum (red contours, dominated by dust emission) from Friedel & Widicus Weaver (2011). The map shows that different emission mechanisms are dominant in the different regions. There is some overlap near Source I, but all other 3 mm emission has no corresponding 1 cm emission. Several of the point-like sources to the southeast of the 3 mm map are coincident with the known optical/IR sources and local 1 cm peaks. Sources of note are labelled.

3. Results and Discussion

The full spectra from the survey are shown in Figure 2, where panel (a) displays the spectrum toward the Hot Core region (α(J2000) = 05h35m14.53, δ(J2000) = −05°22′30″) and panel (b) shows the spectrum toward the Compact Ridge region (α(J2000) = 05h35m14.2, δ(J2000) = −05°22′40″). Spectral line of select species are noted: methanol [CH₃OH] (red), SO₂ (blue), ammonia [NH₃] (green), H₂N (dark red), ethyl cyanide [CH₃CH₂CN] (orange), methyl formate [CH₃OCH] (magenta), and Hα (light blue).

3.1. Continuum

The λ = 1 cm continuum was mapped in both the C and D configurations, giving synthesized beams of 6′8 × 5′6 and 14′7 × 12′7, respectively. The maps were created by removing all channels with line emission from the spectrum and Fourier transforming the remainder together, and they contain no zero spacing data from the single dish observations. Figure 3 shows the resulting maps. Figure 3(a) is the C configuration data, while (b) is the D configuration data. In this, and all other

Table 2

| Name Detected Transitions |
|---------------------------|
| CH₃OH                     | 21 |
| ³⁵CH₃OH                   | 8  |
| H Recom.                  | 9  |
| He Recom.                 | 2  |
| H₂CO                      | 2  |
| H₂CS                      | 1  |
| SO                        | 1  |
| ³¹SO                      | 2  |
| SO₂                       | 6  |
| ³¹SO₂                     | 1  |
| CH₃OCHO                   | 8  |
| CH₃OCH₃                   | 17 |
| CH₃CH₂CN                  | 3  |
| HC₃N                      | 1  |

Table 2 lists a count of all lines detected, by molecule. The columns give the quantum numbers, rest frequency in MHz, upper state energy in K, line strength times the appropriate dipole moment in Debye², synthesized beam in arcseconds, fitted intensity in Jy/beam, fitted ν₁SR in km s⁻¹, fitted FWHM in km s⁻¹, position the spectrum was taken from, rms noise in mJy/beam, and array configuration the data were taken in, respectively. There were no unidentified lines in the entire survey. The following sections detail the results for each molecular species. For those where rotation temperatures and column densities were calculated, the following equations were used. Assuming local thermodynamic equilibrium, the upper state column density (Nᵤ) for a single transition can be

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5 All rest frequencies and transition information were obtained from the Pickett et al. (1998) and Müller et al. (2001) databases presented through the Splatologue Database for Astronomical Spectroscopy (http://www.cv.nrao.edu/php/splat/).
### Table 3
Molecular Parameters of Observed Lines

| Quantum Numbers | Frequency (MHz) | $E_v$ (K) | $S_{21}^2$ (pcm)$^2$ | $\theta_2 \times \theta_2$ ($'' \times ''$) | $I_0$ (Jy/bm) | $v_{LSR}$ (km s$^{-1}$) | FWHM (km s$^{-1}$) | Pos.$^a$ (mly/bm) | Array Config. |
|-----------------|----------------|-----------|----------------------|----------------------------------|---------------|-------------------------|-----------------|-----------------|----------------|
| CH$_3$OH        |                |           |                      |                                  |               |                         |                 |                 |                |
| 14--15$^{13}$    | 27,783.14 (0.05) | 367.6     | 3.6                  | $10.4 \times 9.6$                | 0.02 (0)      | 4.5 (0)                 | 5.2 (0)         | 18.6 C          |                |
| $^{13}$CH$_3$OH  | 27,842.53 (0.05) | 233.6     | 14.2                 | $7.6 \times 6.5$                 | 0.13 (0)      | 4.5 (0)                 | 7.2 (0)         | 12.7 C          |                |
| 12$^{13}$H$_{11}A + \nu = 1$ | 27,700.18 (0.05) | 479.2     | 7.1                  | $12.7 \times 5.3$                | 0.02 (0)      | 4.5 (0)                 | 5.2 (0)         | 6.8 C           |                |
| CH$_3$OH         | 27,820.84 (0.05) | 576.7     | 4.8                  | $12.7 \times 5.3$                | 0.06 (0)      | 8.0 (0)                 | 5.3 (0)         | 9.3 C           |                |
| 11.5--12$^{13}$  | 28,169.47 (0.05) | 266.1     | 15.2                 | $9.3 \times 5.5$                 | 0.01 (0)      | 7.6 (0)                 | 1.9 (0)         | 11.8 C          |                |
| 3$^4$S, 3$^2$E   | 28,316.07 (0.05) | 35.0      | 1.4                  | $9.3 \times 5.5$                 | 0.03 (0)      | 4.5 (0)                 | 5.2 (0)         | 10.7 C          |                |
| 2$^4$D, 2$^2$E   | 28,874.13 (0.17) | 718.4     | 12.8                 | $7.7 \times 5.3$                 | 0.06 (0)      | 4.4 (1)                 | 5.2 (3)         | 11.5 C          |                |
| 15$^{13}$H$_{15}A$ | 28,905.81 (0.05) | 301.0     | 16.1                 | $7.7 \times 5.3$                 | 0.07 (0)      | 4.5 (0)                 | 5.2 (0)         | 13.2 C          |                |
| CH$_3$OH         | 28,969.96 (0.05) | 121.3     | 3.0                  | $7.7 \times 5.3$                 | 0.04 (0)      | 4.5 (0)                 | 5.2 (0)         | 14.9 C          |                |
| 16$^{13}$H$_{15}A$ | 29,636.94 (0.05) | 338.1     | 16.8                 | $6.6 \times 5.4$                 | 0.10 (0)      | 4.5 (0)                 | 5.2 (0)         | 13.8 C          |                |
| 2$^3$D, 2$^1$E   | 29,972.84 (0.14) | 662.8     | 14.0                 | $6.8 \times 5.5$                 | 0.06 (0)      | 3.9 (4)                 | 4.8 (10)        | 10.4 C          |                |
| CH$_3$OH         | 30,010.55 (0.02) | 98.8      | 0.2                  | $6.8 \times 5.5$                 | 0.11 (0)      | 7.6 (0)                 | 1.9 (0)         | 11.8 C          |                |
| 17$^{13}$H$_{16}A$ | 30,308.03 (0.05) | 377.6     | 17.2                 | $7.0 \times 5.2$                 | 0.08 (0)      | 8.0 (0)                 | 5.3 (0)         | 12.0 C          |                |
| CH$_3$OH         | 30,752.08 (0.11) | 609.6     | 15.1                 | $6.2 \times 5.3$                 | 0.04 (0)      | 4.5 (0)                 | 5.2 (0)         | 6.1 C           |                |
| 18$^{13}$H$_{17}A$ | 30,858.30 (0.05) | 419.4     | 17.3                 | $6.2 \times 5.3$                 | 0.10 (0)      | 4.5 (0)                 | 5.2 (0)         | 10.3 C          |                |
| 2$^1$D, 2$^3$D   | 31,209.68 (0.09) | 558.6     | 16.0                 | $6.9 \times 5.0$                 | 0.07 (0)      | 4.5 (0)                 | 5.2 (0)         | 8.0 C           |                |
| 19$^{13}$H$_{18}A$ | 31,226.75 (0.05) | 463.5     | 17.2                 | $6.9 \times 5.0$                 | 0.02 (0)      | 4.5 (0)                 | 5.2 (0)         | 8.4 C           |                |
| 20$^{13}$H$_{19}A$ | 31,358.42 (0.05) | 509.9     | 16.7                 | $7.7 \times 4.9$                 | 0.26 (0)      | 7.6 (0)                 | 1.9 (0)         | 8.4 C           |                |
| 19$^{13}$H$_{20}A$ | 31,977.79 (0.05) | 536.7     | 6.3                  | $11.0 \times 8.3$                | 0.08 (0)      | 8.0 (0)                 | 5.3 (0)         | 19.8 C/D        |                |
| 23$^{13}$H$_{21}$ | 34,003.14 (0.13) | 777.9     | 7.4                  | $14.1 \times 12.2$               | 0.06 (2)      | 4.5 (9)                 | 5.2 (18)        | 9.0 C/D         |                |
| 14$^{13}$H$_{22}A$ | 34,236.95 (0.05) | 306.4     | 4.7                  | $16.4 \times 11.2$               | 0.23 (0)      | 4.5 (0)                 | 5.2 (0)         | 21.2 D          |                |
| 1$^1$CH$_3$OH    | 32,398.48 (0.05) | 28.3      | 2.5                  | $5.7 \times 5.3$                 | 0.09 (2)      | 7.2 (2)                 | 2.0 (5)         | 12.7 C          |                |

$^a$CH$_3$OH

$^{13}$CH$_3$OH

$^b$Hydrogen Recombination Lines
### Table 3 (Continued)

| Quantum Numbers | Frequency (MHz) | $E_J$ (K) | $S_{12}^2$ (D²) | $\theta_s \times \theta_b$ (\arcsec × \arcsec) | $\lambda_{LSR}$ (km s⁻¹) | FWHM (km s⁻¹) | Pos. \( \Delta \) | rms Noise (mJy/beam) | Array Config.
|-----------------|----------------|----------|-----------------|-------------------------------|----------------|----------------|-------------|----------------|------------------|
| H(27)\( \beta \) | 27,724.10 (0.00) | … … | 9.3 × 5.5 | 0.02 (0) | -0.3 (10) | 35.7 (24) | 1 | 6.4 | C |
| H(61)\( \alpha \) | 28,274.87 (0.00) | … … | 9.3 × 5.5 | 0.04 (0) | -6.2 (6) | 14.3 (20) | 2 | 6.4 | C |
| H(60)\( \alpha \) | 29,700.36 (0.00) | … … | 6.6 × 5.4 | 0.03 (0) | 3.3 (10) | 20.2 (29) | 5 | 10.5 | C |
| H(59)\( \alpha \) | 31,223.31 (0.00) | … … | 6.9 × 5.0 | 0.05 (0) | 1.1 (5) | 22.5 (16) | 5 | 7.3 | C |
| H(83)\( \gamma \) | 32,718.50 (0.00) | … … | 15.9 × 11.2 | 0.06 (1) | -17.9 (6) | 4.6 (17) | 11 | 11.6 | D |
| H(91)\( \beta \) | 32,732.67 (0.00) | … … | 15.9 × 11.2 | -0.02 (1) | -20.6 (13) | 4.5 (28) | 4 | 10.6 | C/D |
| H(58)\( \alpha \) | 32,852.20 (0.00) | … … | 15.9 × 11.2 | 0.16 (0) | -2.5 (1) | 20.6 (3) | 4 | 23.5 | C/D |
| H(72)\( \beta \) | 33,821.51 (0.00) | … … | 8.1 × 7.4 | 0.04 (1) | -6.3 (16) | 14.4 (40) | 2 | 14.4 | C/D |
| H(57)\( \alpha \) | 34,596.38 (0.00) | … … | 17.2 × 11.2 | 0.07 (0) | 1.8 (8) | 9.7 (22) | 4 | 15.8 | D |

#### Helium Recombination Lines

| … | … | 15.9 × 11.2 | \( \Delta \) | 1.2 | 9.5 | C/D |

| … | … | 17.2 × 11.1 | 0.07 (1) | 7.4 (5) | 4.8 (10) | 3 | 15.8 | D |

#### H\(_2\)CO

| $3_22-3_13$ \( b \) | 28,974.80 (0.01) | 33.4 | 0.6 | 7.7 × 5.3 | 0.12 (0) | 4.1 (7) | 11.1 (9) | 1 | 11.2 | C |
| 10\( 0_10 -10_20 \) | 34,100.05 (0.01) | 240.7 | 4.0 | 14.1 × 12.2 | 0.07 (3) | 7.8 (14) | 6.8 (38) | 12.0 | C/D |

#### H\(_2\)CS

| … | … | 16.4 × 11.2 | 0.08 (1) | 8.4 (2) | 2.3 (6) | CR | 17.8 | D |
| … | … | 1.0 | 1.0 | 1.0 | 0.09 (5) | 10.6 (4) | 1.4 (10) | CS1 |

#### SO

| … | … | 6.8 × 5.5 | 0.85 (0) | 5.3 (0) | 12.4 (1) | HC/CR | 8.6 | C |
| … | … | 2.0 | 0.0 | 2.0 | 0.16 (0) | 20.9 (3) | 11.5 (8) | HC/CR | 8.6 | C |
| … | … | 9.2 | 0.0 | 9.2 | 0.18 (1) | 9.2 (81) | 7.2 (42) | HC-NE | 8.6 | C |
| … | … | 10.7 | 0.0 | 10.7 | 0.40 (1) | 10.7 (0) | 4.0 (2) | HC-NE | 8.6 | C |
| … | … | 21.6 | 0.0 | 21.6 | 0.10 (1) | 21.6 (5) | 8.1 (12) | HC-NE | 8.6 | C |
| … | … | 1.6 | 0.0 | 1.6 | 0.24 (0) | 1.6 (5) | 25.0 (9) | IRc6 | 8.6 | C |
| … | … | 11.7 | 0.0 | 11.7 | 0.33 (4) | 11.7 (2) | 6.8 (4) | IRc6 | 8.6 | C |
| … | … | 18.5 | 0.0 | 18.5 | 0.22 (2) | 18.5 (87) | 4.3 (51) | IRc6 | 8.6 | C |

#### $^{34}$SO

| … | … | 6.6 × 5.4 | 0.02 (0) | 8.0 (9) | 22.8 (27) | 11.7 | C |
| … | … | 15.1 | 0.0 | 15.1 | 0.12 (1) | 2.4 | 15.5 | 15.9 | D |
| … | … | 17.6 | 0.0 | 17.6 | 0.05 | 17.6 | 10.5 | D |
| Quantum Numbers | Frequency (MHz) | $E_u$ (K) | $S_u^2$ $(D^2)$ | $\theta_u \times \theta_u$ (° x °) | $l_u$ (Jy/beam) | $V_{10.08}$ (km s$^{-1}$) | FWHM (km s$^{-1}$) | Pos. | rms Noise (mJy/beam) | Array Config. |
|-----------------|----------------|----------|----------------|-----------------------------|-----------------|-----------------------------|----------------|------|---------------------|----------------|
| $^{35}$SO$_2$   |                |          |                |                             |                 |                             |                 |      |                     |                |
| $4_{0,4-3_{1,3}}$ | 29,321.33 (0.02) | 9.2 | 1.7 | 7.4 x 5.6 | 0.08 (0)$^b$ | 2.9 (9) | 40.4 (33) | I | 28.0 | C |
| $^{13}$CH$_3$CCH |                |          |                |                             |                 |                             |                 |      |                     |                |
| $2_{10}^b$      | 34,183.42 (0.04) | 2.5 | 2.0 | 16.4 x 11.2 | 0.29 (3) | 10.6 (0) | 1.6 (1) | CS1 | 14.3 | D |
| $^{15}$NH$_3$   |                |          |                |                             |                 |                             |                 |      |                     |                |
| $9_{0,9-8_{1,0}}$ | 27,477.94 (0.01) | 852.8 | 145.8 | 7.6 x 6.5 | 0.21 (0) | 1.0 (0) | 6.3 (0) | C | 8.9 | C |
| $^{12}$CH$_3$OCHO |                |          |                |                             |                 |                             |                 |      |                     |                |
| $h_0=\lambda_{1,2}AE$ | 30,670.58 (0.05) | 30.2 | 1.8 | 6.5 x 5.1 | 0.06$^c$ | 7.4 (0.5) | 0.5 | 8.4 | C |
| $h_0=\lambda_{1,3}AE$ | 30,695.15 (0.05) | 30.2 | 1.8 | 6.5 x 5.1 | 0.02 (0) | 8.9 (11) | 5.5 (31) | 10.2 | C |
| $h_0=\lambda_{1,5}AE$ | 34,156.88 (0.05) | 4.0 | 7.2 | 16.4 x 11.2 | 0.36 (0) | 7.9 (0.6) | 2.4 (0) | 17.1 | D |
| $h_0=\lambda_{1,6}AE$ | 34,158.12 (0.05) | 3.9 | 7.2 | 16.4 x 11.2 | 0.30 (0) | 7.9 (0.6) | 2.4 (0) | 24.8 | D |
| $h_0=\lambda_{1,7}AE$ | 34,671.76 (0.05) | 15.4 | 2.4 | 15.1 x 11.5 | 0.11 (1) | 7.6 (1) | 2.0 (2) | 10.4 | D |
| $h_0=\lambda_{1,5}AE$ | 34,682.81 (0.05) | 15.3 | 2.4 | 15.1 x 11.5 | 0.11 (1) | 8.0 (0) | 2.6 (1) | 8.0 | D |
| $h_0=\lambda_{1,6}AE$ | 34,766.00 (0.05) | 11.7 | 1.9 | 15.1 x 11.5 | 0.13 (2) | 7.8 (1) | 1.2 (2) | 10.9 | D |
| $h_0=\lambda_{1,7}AE$ | 34,775.65 (0.05) | 11.7 | 1.9 | 15.1 x 11.5 | 0.08 (6) | 7.6 (5) | 1.6 (9) | 7.1 | D |
| $h_0=\lambda_{1,1}AE$ | 31,105.26 (0.10) | 4.2 | 6.6 | 6.9 x 5.0 | 0.03 (1) | 8.1 (0.1) | 1.4 (0) | 8.0 | C |

Table 3 (Continued)
| Quantum Numbers | Frequency (MHz) | $E_u$ (K) | $S_{12}^2$ ($D^2$) | $\theta_x \times \theta_y$ (" x ") | $I_v$ (Jy/bm) | vlsr (km s$^{-1}$) | FWHM (km s$^{-1}$) | Pos. ($\alpha$) | rms Noise (mJy/bm) | Array Config. |
|-----------------|----------------|-----------|-----------------|-----------------|--------------|----------------|-------------------|----------------|------------------|--------------|
| $^2_1g-^2_0dEA$ | 31,105.26 (0.10) | 4.2 | 13.2 | 6.9 x 5.0 | 0.03 (0) | 8.1 (0) | 1.4 (0) | 8.0 C |  |
| $^2_1g-^2_0dEE$ | 31,106.20 (0.05) | 4.2 | 52.6 | 6.9 x 5.0 | 0.12 (1) | 8.1 (0) | 1.4 (0) | 8.0 C |  |
| $^2_1g-^2_0dAA$ | 31,107.12 (0.10) | 4.2 | 19.7 | 6.9 x 5.0 | 0.05 (0) | 8.1 (0) | 1.4 (0) | 8.0 C |  |
| $^9_3d-^8_1dAA$ | 31,996.10 (0.03) | 47.0 | 15.8 | 8.2 x 4.2 | 0.01 (0) | 8.0 (2) | 1.7 (6) | 7.9 C |  |
| $^9_3d-^8_1dEE$ | 31,999.33 (0.03) | 47.0 | 25.2 | 8.2 x 4.2 | 0.03(1) | 8.0 (2) | 1.7 (6) | 7.9 C |  |
| $^3_2f-^3_1dAE$ | 32,977.34 (0.14) | 7.0 | 26.8 | 6.7 x 4.3 | 0.03 (1) | 8.2 (2) | 1.6 (5) | 14.6 C |  |
| $^3_2f-^3_1dEA$ | 32,977.34 (0.14) | 7.0 | 17.8 | 6.7 x 4.3 | 0.03 (1) | 8.2 (2) | 1.6 (5) | 14.6 C |  |
| $^3_2f-^3_1dEE$ | 32,978.29 (0.05) | 7.0 | 71.4 | 6.7 x 4.3 | 0.09 (5) | 8.2 (2) | 1.6 (5) | 14.6 C |  |
| $^3_2f-^3_1dAA$ | 32,979.24 (0.10) | 7.0 | 44.6 | 6.7 x 4.3 | 0.07 (6) | 8.2 (2) | 1.6 (5) | 14.6 C |  |
| $^8_{4d}-^9_{3d}E$ | 33,943.17 (0.01) | 55.3 | 13.1 | 14.1 x 12.2 | 0.09 (0)$^{a}$ | 7.9 (0) | 1.6 | 17.8 C/D |  |
| $^8_{4d}-^9_{3d}AA$ | 33,943.96 (0.01) | 55.3 | 6.8 | 14.1 x 12.2 | 0.05 (0)$^{a}$ | 7.9 (0) | 1.6 | 17.8 C/D |  |
| $^8_{4d}-^9_{3d}EA$ | 33,944.05 (0.02) | 55.3 | 2.8 | 14.1 x 12.2 | 0.02 (0)$^{a}$ | 7.9 (0) | 1.6 | 17.8 C/D |  |

CH$_3$CH$_2$CN

| 3-2, $F = 3-3^b$ | 27,292.90 (0.01) | 2.6 | 1.5 | 10.4 x 9.6 | 0.02 (0) | 10.0 (0) | 1.8 (0) | CSI | 17.6 C |
|-----------------|----------------|-----------|----------------|----------------|--------------|----------------|-------------------|----------------|------------------|--------------|
| 3-2, $F = 2-1^b$ | 27,294.06 (0.03) | 2.6 | 8.3 | 10.4 x 9.6 | 0.11 (0) | 10.0 (0) | 1.8 (0) | CSI | 17.6 C |
| 3-2, $F = 3-2^b$ | 27,294.31 (0.03) | 2.6 | 12.3 | 10.4 x 9.6 | 0.16 (1) | 10.0 (0) | 1.8 (0) | CSI | 17.6 C |
| 3-2, $F = 4-3^b$ | 27,294.31 (0.03) | 2.6 | 17.8 | 10.4 x 9.6 | 0.24 (1) | 10.0 (0) | 1.8 (0) | CSI | 17.6 C |
| 3-2, $F = 2-2^b$ | 27,296.23 (0.01) | 2.6 | 1.5 | 10.4 x 9.6 | 0.02 (0) | 10.0 (0) | 1.8 (0) | CSI | 17.6 C |

Notes:
- $^a$ Position where the spectra were taken. See the text in each section for specific meanings. If it is blank, then spectra are taken from the emission peak.
- $^b$ This transition was part of the mosaics and single dish observations.
- $^c$ These transitions of $^{13}$CH$_3$OH and CH$_3$CH$_2$CN are blended.
- $^d$ Spectral profile is too complex for a reliable fit.
- $^e$ Uncertainties could not be calculated.
- $^f$ There could be more components, and likely are, but due to high noise, no reliable fits could be made.
- $^g$ In order to obtain line fits, the ratio of the lines was fixed—as was the FWHM.
- $^h$ Intensity ratios were fixed for low opacity.

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Table 3

(Continued)
calculated from Friedel (2005):
\[
N_u = \frac{2.04W}{g_u B_\theta a S \mu^2 \nu^3} \times 10^{20} \text{ cm}^{-2},
\]
where \( g_u \) is the upper state degeneracy, \( W \) is the integrated intensity of the line in Jy beam\(^{-1}\) km s\(^{-1}\), \( B \) is the beam filling factor, \( a \) and \( b \) are the major and minor axes of the synthesized beam, \( S \mu^2 \) is the product of the line strength and the square of the relevant dipole moment in Debye\(^2\), and \( \nu \) is the transition frequency in GHz. The beam filling factor is defined as
\[
B = \frac{\Theta_S^2}{\Theta_S^2 + \Theta_B^2},
\]
where \( \Theta_S \) is the source size in square arcseconds and \( \Theta_B \) is the area of the synthesized beam. The source size can be determined by fitting the data in the \( u-v \) plane, by fitting a Gaussian in the image plane with the MIRIAD task *imfit*, or by iterating over source sizes with the rotation temperature diagram method (discussed later) to minimize the \( \chi^2 \) of the

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**Figure 5.** Maps of CH\(_3\)OH at two different resolutions, overlaid on the appropriate grayscale continuum. (a) shows the \( J = 4_0,4 - 3_1,2 \) transition and has a resolution of 9\(''\)3 \( \times \) 5\(''\)5, (b) shows the \( 14_{-3,2} - 15_{-2,14} \) transition and has a resolution of 16\(''\)4 \( \times \) 11\(''\)2. Contours are \( \pm 3\sigma, \pm 7\sigma, \pm 11\sigma \ldots \), where \( \sigma = 3.0 \) and 5.6 mJy/beam, respectively.

**Table 4.** Partition Functions and Vibrationally Excited Energies\(^a\)

| Species    | Rotational Partition Function \((Q_r)\) | Vibrational Energies (K) | \(Q_r\) (150 K) | \(Q_v\) (150 K) | % Diff. | References |
|------------|--------------------------------------|--------------------------|-----------------|-----------------|---------|------------|
| CH\(_3\)OH | 1.20\(T^{1/2}\)                      | 300.5, 423.6\(^b\)       | 2263.5          | 2776.0          | 23      | 1          |
| H\(_2\)CO  | 0.55\(T^{3/2}\)                      | d                        | ...             | ...             | ...     | 2, 3       |
| H\(_2\)CS  | 1.15\(T^{1/2}\)                      | d                        | ...             | ...             | ...     | 2, 3       |
| SO         | 0.98\(T\)                           | d                        | ...             | ...             | ...     | 1          |
| SO\(_2\)\(^c\) | 2.30\(T^{3/2}\)                   | 744.8                    | 4164.7          | 4193.8          | 1       | 1          |
| CH\(_3\)CCH | 1.04 \(T^{1/2}\)                    | 471.8, 910.6             | 1910.6          | 2000.8          | 5       | 1, 3       |
| NH\(_3\)  | 0.70\(T^{3/2}\)                     | d                        | ...             | ...             | ...     | 2, 3       |
| CH\(_3\)OCHO | 12.45\(T^{1/2}\)                   | 187, 457, 478            | 2.3 \(\times\) 10\(^4\) | 3.5 \(\times\) 10\(^4\) | 52      | 2, 4       |
| CH\(_3\)OCH\(_3\) | 2.86\(T^{1/2}\)               | 292, 348, 601            | 1.7 \(\times\) 10\(^3\) | 2.2 \(\times\) 10\(^3\) | 29      | 2, 5       |
| CH\(_3\)CH\(_3\)CN | 7.17\(T^{1/2}\)               | 297, 306, 544, 784      | 1.3 \(\times\) 10\(^4\) | 1.8 \(\times\) 10\(^4\) | 38      | 2, 6       |
| H\(_2\)CS\(_N\) | 4.57\(T\)                        | 320.8, 717.8, 954.0     | 685.5           | 783.8           | 14      | 1          |

Notes.

\(^a\) Only vibrationally excited states below 1000 K are listed, because even at hot core temperatures the population of vibrationally excited states above 1000 K will be less than 10% of the total.

\(^b\) Isotopomers are assumed to have the same energies for their vibrationally excited states, unless otherwise noted.

\(^c\) The energies refer to the first vibrational state of the A and E torsional states.

\(^d\) Lowest vibrationally excited state lies above 1000 K.

\(^e\) In order to calculate the column density, one needs to multiply by 64/2 and weight the integrated intensity by the spin weight of the transition (see Friedel 2005 [Appendix II]).

References. (1) Müller et al. (2001), (2) Jacox (2005), (3) Pickett et al. (1998), (4) Oesterling et al. (1999), (5) Groner et al. (2002), (6) Mehringer et al. (2004).
fit. In the case of multiple velocity components that are unresolved, the only reliable option is with the rotation temperature diagram method.

From a single transition, the total beam averaged column density can be calculated as

$$\langle N_T \rangle = \frac{N_u}{g_u} Q_{rv} e^{E_u/T} \text{ cm}^{-2},$$

(3)

where $Q_{rv}$ is the rotational–vibrational partition function, $E_u$ is the upper state energy of the transition, and $T_r$ is the rotation temperature. The rotation temperature diagram is an extension of the calculations for a single transition, in that it is a plot of the natural log of Equation (1) versus $E_u$. A weighted fit to the plot gives the rotation temperature (the negative inverse of the slope) and $N_u/g_u$ at $E_u = 0$ (the y-axis intercept). The total column density can be calculated from Equation (3).

Traditionally, when calculating column densities and relative abundances, only the rotational part of the partition function has been used (e.g., Remijan et al. 2003, 2004). The vibrational part of the partition function is usually only employed when vibrationally excited transitions of a species have been detected (see, e.g., Nummelin & Bergman 1999; Mehringer et al. 2004; Remijan et al. 2005). The rotational transitions of vibrationally excited states have been catalogued for only a few states of a few species. Thus it is likely high that transitions of vibrationally excited states are in spectra, but their identity may not be known. In general the vibrational part of the partition function should be included in the analysis, even if vibrationally excited transitions have not been detected. While the lowest lying vibrationally excited state of many simple species are more than 1000 K above ground, for many larger species, the lowest lying vibrationally excited states can be very low. For example, l-C$_3$H has its lowest vibrationally excited state only 39 K above ground, HC$_3$N has three vibrationally excited states below 720 K, and the asymmetric top acetone [(CH$_3$)$_2$CO] has two vibrationally excited states below 200 K (Müller et al. 2001; Groner et al. 2005). Thus, at temperatures commonly seen in Hot Cores, these low-lying states will contain a significant population, which needs to be included in the column density.

The addition of the vibrational part of the partition function is rather straightforward. From Widicus Weaver et al. (2005) we have

$$Q_{rv} \approx \sum_{i=0}^{n} e^{-E_i/T} Q_i,$$

(4)

where $Q_{rv}$ is the rotational–vibrational partition function, $n$ is the number of vibrationally excited states in the calculation, and $E_i$ is the energy above ground of the vibrationally excited state. Note that for $n = 0$, this reduces to just $Q_{rv} = Q_i$. Table 4 gives the known vibrational energies (below 1000 K) for each molecular species detected in this survey. The columns give the name of the species, rotational partition function, vibrational energies in K, the value of the rotational partition function at a temperature of 150 K, the value of the ro-vibrational partition function at 150 K, the percent difference between the two partition function values, and the references for the molecular parameters, respectively. All of the species listed have vibrational states above 1000 K; however, at Hot Core temperatures, these states will contribute a negligible amount to the column density. In addition to the energies listed in column (3), there are combination bands (whose energies are the sum of any two or more of the energies listed in column (3)) and overtones (integer multiples of the energies listed in column (3)), which need to be taken into account. Both of these types have been detected in several species, such as C$_2$H$_3$CN (overtones; Nummelin & Bergman 1999; Friedel 2005) and HC$_3$N (overtones and combinations; Remijan et al. 2005; Friedel 2005). To include overtones and combination bands, additional terms need to be added to Equation (4) with the energy of the overtone or combination.

One must be careful when calculating partition functions for molecules with one or more internal rotors where the ground state energy between the torsional states is noticeable (e.g., CH$_3$OH has a 14 K difference between the ground state energies of the A and E torsional states). Under typical hot core conditions, the energy difference is insignificant and the partition function is just two times that for the A torsional state (Turner 1991). However, in the extremes (i.e., cold dark clouds and very hot cores), the partition function must be calculated for each torsional state separately. For cold dark clouds, the effect is obvious: the higher energy torsional state may not be populated. But for hot cores, the effect is not as obvious, until you look at the energies of the vibrational states. The 14 K energy difference between the A and E ground torsional states grows to a ~120 K difference between the A and E torsional states of the first vibrationally excited state. With such a difference in energy, the partition function and column density for each torsional state must be calculated separately and then combined.

### 3.2.1. Methanol [CH$_3$OH and $^{13}$CH$_3$OH]

Methanol had the largest number of detected transitions (21 for the main isotopologue and 8 for $^{13}$CH$_3$OH) of all detected species. The analysis presented here focuses on the main
Figure 7. Spectra of each detected CH$_3$OH transition taken at the peak of emission. The abscissa is velocity in km s$^{-1}$, and the ordinate is intensity in Jy/beam. Some of the spectra are scaled in intensity, denoted by “$\times 5$” or “$\times 10$” in the plot. The frequency of each transition is given at the top of the sub-plot, and the “$I$” bar denotes the 1$\sigma$ rms noise for each spectra.
isotopologue, but applies to $^{13}$CH$_3$OH as well. The average intensity maps (over the width of the line) of the 4$_{0,4}$–3$_{1,2}$ and 14$_{3,1}$–15$_{2,4}$ transitions in Figure 5 show that the emission is compact around the Hot Core/Compact Ridge region, with the exception of a weakly emitting region extending to the southeast. The CH$_3$OH emission at 28.3 and 96.7 GHz are compared in Figure 6. Both transitions have very similar upper state energy (35 K and 28 K, respectively). The 96.7 GHz data are at a considerably higher resolution, but the vast majority of the emission appears to come from the region designated by the 96.7 GHz contours.

In order to create a rotation temperature diagram to estimate the temperature of the CH$_3$OH gas, we must resolve the individual gas components along the line of sight. Figure 7 shows the spectra from the 20 lowest energy CH$_3$OH lines taken at the emission peak of each map (all peaks are within Figure 8. Example fits to a lower energy (three component) line and a high energy (single component) line. The abscissa is velocity in km s$^{-1}$, and the ordinate is intensity in Jy/beam. (a) shows the three component fit, with the 4.5 km s$^{-1}$ component shown in red, the 7.6 km s$^{-1}$ component in cyan, the 8.0 km s$^{-1}$ component in blue, and the sum total fit in green. (b) shows a single component fit, shown in red, to a high energy line, centered at 4.4 km s$^{-1}$.

Figure 9. Rotation temperature diagrams of the three CH$_3$OH velocity components, plotting the natural log of the upper state column density ($N_{\rm u}/a_0$) vs. the upper state energy ($E_u$). (a) is from the 4.5 km s$^{-1}$ velocity component, (b) is from the 7.6 km s$^{-1}$ velocity component, and (c) is from the 8.0 km s$^{-1}$ component. The error bars are 3σ and are dominated by the rms noise of each spectrum. The upper limits (middle and lower plots, three highest energy components) are based on our 3σ detection limit.
fits to each profile are described in Table 3. The three highest energy transitions (662, 718, and 778 K) are best fit with a single Gaussian with a $v_{\text{LSR}}$ of 4.4 (0) km s$^{-1}$ and FWHM of 5.1 (1) km s$^{-1}$. The remaining 18 transitions were best fit with three Gaussians with $v_{\text{LSR}}$'s of 4.5 (0), 7.6 (0), and 8.0 (0) km s$^{-1}$ and FWHMs of 5.2 (0), 1.9 (0), and 5.3 (0) km s$^{-1}$, respectively. The fitting was done simultaneously on all 18 transitions by constraining the $v_{\text{LSR}}$ and FWHM of the 4.5 km s$^{-1}$ component to be close to the values found for the three highest energy transitions and constraining all intensities to be positive valued. For a few of the transitions, the intensity of the 4.5 km s$^{-1}$ component is so small as to be undetectable in our observations, and is not reported. Figure 8 shows an example of the three component fit in the panel (a). The fit for each Gaussian is shown individually (red for the 4.5 km s$^{-1}$ component, green for the 7.6 km s$^{-1}$ component, and blue for the 8.0 km s$^{-1}$ component), and the

Figure 10. Spectra of each detected $^{13}$CH$_3$OH transition taken at the peak of emission. The abscissa is velocity in km s$^{-1}$, and the ordinate is intensity in Jy/beam. The frequency of each transition is given at the top of the sub-plot, and the “I” bar denotes the 1σ rms noise for each spectra.

Figure 11. Spectra from single dish observations (black) and array observations (red) of the 132:11–131:12 transition of CH$_3$OH. The abscissa is velocity in km s$^{-1}$, and the ordinate is intensity in Jy/beam. The “I” bars denote the 1σ rms noise for the respective spectrum.

Figure 12. Array average intensity map of the 132:11–131:12 transition of CH$_3$OH (contours) overlaid on the color scale map of the same transition from single dish observations. Contours are $\pm 3\sigma, \pm 6\sigma, \pm 9\sigma, \ldots$, where $\sigma = 7.2$ mJy/beam.
sum of the Gaussians is shown by the green fit. The right-hand plot shows the fit (in red) for a single component in the high energy lines.

With the velocity components fit, we constructed a rotation temperature diagram for each of the three components (Figure 9). Panel (a) shows the fit for the 4.5 km s\(^{-1}\) component, giving a beam average total column density of \(3.7(5) \times 10^{18}\) cm\(^{-2}\) and a rotation temperature of 248(102) K. These data were also best fit by a source size of \(\sim 2\sigma^2\). Panel (b) shows the fit for the 7.6 km s\(^{-1}\) component, giving a beam average total column density of \(2.8(9) \times 10^{18}\) cm\(^{-2}\) and a rotation temperature of 138(26) K. These data were best fit by a source size of \(\sim 7\sigma^2\). Panel (c) shows the best fit for the 8.0 km s\(^{-1}\) component, giving a beam averaged total column density of \(4.0(1) \times 10^{18}\) cm\(^{-2}\) and a rotation temperature of 117(1) K. These data were best fit with a source size of \(\sim 10\sigma^2\). The uncertainties for each point are 3\(\sigma\), and the upper limits for the three highest energy transitions are based on a 3\(\sigma\) detection threshold. The transition at 30.01055 GHz was excluded from these calculations because it had an abnormally high intensity; it also has the lowest line strength of all transitions by nearly an order of magnitude, and is the only parity changing transition. Based on the calculated total column densities and rotation temperatures, there are no missing transitions from CH\(_3\)OH in this survey. A missing transition is one that should have been detected above our 3\(\sigma\) cutoff, but was not.

The same procedures were followed for the \(^{13}\)CH\(_3\)OH transition (Figure 10). Fits to each profile are described in Table 3. Unlike the main isotopomer, \(^{13}\)CH\(_3\)OH was best fit with only a single component with a \(v_{\text{LSR}}\) of 7.6 (0) km s\(^{-1}\) and a FWHM of 2.7 (3) km s\(^{-1}\). The \(v_{\text{LSR}}\) is consistent with the strongest component from the main isotopomer, but the FWHM is 50% larger, indicating that it too may be blended by other unresolved velocity components. Given that the \(^{13}\)CH\(_3\)OH line intensities are much weaker than those of CH\(_3\)OH, the presence of other velocity components similar to those of CH\(_3\)OH would be undetectable in our observations. Based on the rotation temperature of the 7.6 km s\(^{-1}\) CH\(_3\)OH component, the total beam averaged column density of \(^{13}\)CH\(_3\)OH is \(2.8(2) \times 10^{17}\) cm\(^{-2}\). Based on this total column density and rotation temperature, there are no missing \(^{13}\)CH\(_3\)OH lines in this survey.

From Figure 5(a) there is an extension to the southeast that indicates that there may be some extended structure to the CH\(_3\)OH emission. To investigate the extent of the large scale structure, the \(13\gamma\), \(13\alpha\), and \(13\beta\) transitions were detected in this survey. The detection of the \(13\gamma\) transition was observed in single dish mode.\(^4\) Figure 11 shows the single dish (black) and interferometric (red) spectra of the \(13\alpha\), \(13\beta\), and \(13\gamma\) transitions of CH\(_3\)OH. The interferometric spectra were generated by convolving the array map with a 165\(\alpha\) 2D Gaussian. By comparing the spectra, it can be seen that the interferometric observations detect nearly all of the flux seen by the single dish, indicating that there is little extended emission from this transition. The average intensity maps of this transition also show that the emission is from a compact source (Figure 12). The interferometric average intensity map is the contours overlaid on the single dish average intensity map. Note that the single dish data are clipped at 2\(\sigma\) before calculating the average intensity maps.

### 3.2.2. Hydrogen Recombination

A total of nine H recombination lines (5\(\alpha\), 2\(\beta\), 1\(\gamma\), and 1\(\delta\)) were detected in this survey. The detection of the emission was highly dependent on the size of the synthesized beam. The emission appears to emanate from a large region, as the C configuration only picked up the tightest knots of emission, while the D configuration data show significantly more structure. Figure 13 shows maps from the H(59)\(\alpha\), H(58)\(\alpha\), and H(83)\(\gamma\) transitions, from the C, D, and D configurations, respectively. The compact H recombination emission (panel (a)) is concentrated along the bar, with a few knots associated with the more prominent continuum peaks. Contrasting this, the more extended emission is concentrated to the southwest of the trapezium, tracing the bulk of the continuum. The emission peaks toward the edge of the map and the large bowl are due to sidelobes and the array’s response to more extended structure. Emission from the bar is notably absent from the panel (b). This is likely due to emission that is both weaker than our

\(^4\) The lowest energy CH\(_3\)OH transitions could not be observed, due to a limitation on the number of spectral windows available.
Figure 14. Spectra from the H recombination transitions. The rest frequency of each is given at the top of the panel, the abscissa is $v_{\text{LSR}}$ in km s$^{-1}$, and the ordinate is intensity in Jy/beam. The rest frequency for each transition is given in each panel, and the “I” bars denote the 1σ rms noise.
detection threshold (due to higher noise in this region of the spectrum) and the sidelobes. The emission from the H(83)γ transition (panel (c)) also traces the main continuum peak, although it is offset to the northwest from the Hα peak. The red numbers denote the positions of the spectra.

Figure 14 shows the spectra of the detected H recombination lines from different regions. The position at which the spectra were taken is denoted by the red number in the lower right corner of each panel. These numbers correspond to those in Figure 13(c). There are numerous missing H recombination lines, but this is to be expected, since the detection is highly correlated with the size of the synthesized beam.

In order to determine how much flux was being resolved out by the array, the H(58)α transition was also observed in single dish mode, with a 32 point mosaic pattern. Figure 15 shows an average intensity map of the line in color, overlaid by the array map of the same transition. The single dish map indicates that the vast majority of the recombination emission comes from the region of Orion-KL, with an extension toward the bar in the southeast, and an additional extension to the east, which is outside of the field of view of the interferometer. Figure 16 shows the spectra from the single dish (black) and interferometric (red) observations. The black spectrum was taken at the peak of the single dish emission, and the red spectrum is from the peak of the interferometric emission. The interferometric data are scaled by a factor of 6.0 to show them on the same scale, and were best fit by three Gaussians with \( v_{\text{LSR}} \) s of \(-3.5\) (32), \(10.5(49)\), and \(39.8(456)\) \( \text{km s}^{-1}\), and FWHM of \( 20.4(22)\), \(20.3(67)\), and \(17.0(1580)\) \( \text{km s}^{-1}\), respectively. Conversely, the single dish data are best fit by a single large Gaussian with a \( v_{\text{LSR}} \) of \(-2.8(0)\) \( \text{km s}^{-1}\) and an FWHM of \( 26.1(0)\) \( \text{km s}^{-1}\), indicating that there is a significant extended component that is resolved out by the interferometer.

### 3.2.3. He Recombination

A total of three He recombination lines were detected in our survey. Due to its extended nature and weaker emission than H, it was only detected with the larger D configuration beam. Figure 17 shows the emission map of the He(58)α transition overlaid on the D configuration continuum, and Figure 18 shows the spectra. The He emission is very similar to the Hγ emission, as expected.

Figure 19 shows the single dish average intensity map of the He(58)α transition overlaid by the interferometric average intensity map. The single dish map is very similar to the H(58)α map in structure. Figure 20 shows the single dish spectrum (black) and interferometric spectrum (red) of the same line.
transition. The interferometric data are scaled by a factor of 3.0 and were best fit by a single Gaussian with a \( v_{\text{LSR}} \) of \(-2.3(8) \) km s\(^{-1}\) and FWHM of 16.4(20) km s\(^{-1}\). The single dish spectra were best fit with a pair of Gaussians with \( v_{\text{LSR}} \)'s of \(-17.9(0) \) and \(-2.7(0) \) km s\(^{-1}\), with FWHM of 4.8(2) and 6.5(2) km s\(^{-1}\), respectively. While the \(-17.9 \) km s\(^{-1}\) velocity component is not detected in the convolved interferometric map, it is detected in the unconvolved spectra of this transition in the first two panels of Figure 18. It disappears from the convolved spectra due to its overall weak emission and strong sidelobes produced by the interferometer's response to the large scale structure. While the He(58) \( \alpha \) single dish transition shows this \(-17.9 \) km s\(^{-1}\) feature, the corresponding H transition does not. H was detected in some of the interferometric observations. Its absence in the H spectra may be due to much stronger components at other velocities overpowering it.

### 3.2.4. Methyl Acetylene \([\text{CH}_3\text{CCH}]\)

All methyl acetylene \([\text{CH}_3\text{CCH}]\) transitions in our frequency range were detected. Figure 21 shows the average intensity map of the lower energy \( \text{CH}_3\text{CCH} \) transition as contours overlaid on the D configuration continuum. The emission is primarily in two regions, one to the southwest of the Compact...
Figure 21. Average intensity map of the lowest energy methyl acetylene transition as contours overlayed on the D configuration continuum. The emission is primarily confined to two regions: one northeast of the Hot Core and one to the southwest of the Hot Core. The contours are ±2σ, ±4σ, ±6σ, ..., where σ = 0.316 Jy/beam and the synthesized beam is in the lower left corner.

Ridge (CS-SW) and the other centered on CS1 and extending to the northeast. The spectrum from each peak is shown in Figure 22. Panel (a) is from the peak to the southwest, panel (b) is from the peak near CS1, and panel (c) is from the \( J = 5_{\text{a}} - 4_{\text{a}} \) transitions at 85.4556 GHz. All detected CH3CCH transitions are shown in each spectra, and the velocity axis is referenced to the 20–1 line. Each set of transitions was fit together, and each is best fit by a single, narrow Gaussian component. The southwest peak has a \( v_{\text{LSR}} \) of 8.8(0) km s\(^{-1}\) and FWHM of 1.1(3) km s\(^{-1}\), and the CS1 peak has a \( v_{\text{LSR}} \) of 10.6(0) km s\(^{-1}\) and FWHM of 1.6(1) km s\(^{-1}\).

In order to understand the physics of the CH3CCH emission regions, we compare the CH3CCH emission to the emission of tracers of different physical regions: SiO and H recombination transitions. The SiO emission (a shock and outflow tracer) from Plambeck et al. (2009) is shown overlaid on a color scale of CH3CCH emission in Figure 23. The peak to the southwest appears to be in line with the SiO outflow, but it is notably separated from the SiO emission. The peak near CS1 appears to be a direct extension of the SiO outflow and may be forming/contracting from grains where the outflow is impacting a denser region. Since H recombination is a tracer of ionized regions, we compared the H recombination line emission with the CH3CCH emission in Figure 24. The southeast component boarders along the H emission, and a faint ridge of CH3CCH emission roughly follows the H emission ridge to the southwest, indicating that the ionizing radiation may be destroying it.

Although CH3CCH is easily dissociated by UV radiation, it is thought to form in the gas phase and is a dense gas tracer (Kuiper et al. 1984; Charnley et al. 1992; Bisschop et al. 2007). However, the transitions detected in this work have critical densities \( \lesssim \times 10^4 \), which is too low to consider these transitions dense gas tracers.

To further understand the physical conditions of the CH3CCH emission regions, we obtained data of the \( J = 5_{\text{a}} - 4_{\text{a}} \) (85.4556 GHz) transitions of CH3CCH toward Orion-KL from the CARMA data archive.\(^5\) The data were taken in 2012 March, in C configuration, giving a beam of 3\('\)6 × 2\('\)5 and channel spacing of 1.7 km s\(^{-1}\). The \( J = 5_{\text{a}} - 4_{\text{a}} \) (\( K = 0–2 \)) transitions were detected with upper state energies of 12.3, 19.5, and 41.1 K. The resulting spectrum from the northwestern peak is shown in Figure 22(c), and that from the southern peak is shown in Figure 22(d).

Using these fits, we constructed rotational-temperature diagrams for the CS1 and CR-SW peaks. These fits are shown in Figure 25. Panel (a) is from the northeastern core and yields a total column density of \( \sim 2.8 \times 10^{15} \) cm\(^{-2}\) and a rotation temperature of \( \sim 22 \) K. Panel (b) is from the CR-SW peak and yields a total column density of \( \sim 1.1 \times 10^{15} \) cm\(^{-2}\) and a rotation temperature of \( \sim 36 \) K. Bolstering the results of these calculations are the lack of any high (>50 K) temperature line, from any molecular species, in either region. Additionally, since no complex molecules, not even CH3OH, in this survey were detected toward these sources, this indicates that not only are these regions cold, but the gas is also dominated by gas phase reaction products, as any grain surface reaction products are still locked on the grains.

Since it forms so easily in the cool gas phase and the interferometric maps show potential extended structure, we observed CH3CCH in single dish mode too. Figure 26 shows the average intensity maps of the 20–1 line of CH3CCH for both array and single dish. From these maps we see that there are at least three distinct large scale regions of emission of CH3CCH. The \( v_{\text{LSR}} \) of both the northern interferometric and single dish peaks share a common velocity, as do the southern peaks. The large scale peaks may be extension of the outflows. The spectra from both are in Figure 27. Panel (a), from the northern peak of the single dish map, was best fit with a single Gaussian with a \( v_{\text{LSR}} \) of 9.6(0) km s\(^{-1}\) and FWHM of 2.1(0) km s\(^{-1}\). The array data were also best fit with a single Gaussian with a \( v_{\text{LSR}} \) of 10.1(1) km s\(^{-1}\) and FWHM of 1.5(2) km s\(^{-1}\). Panel (b), from the southern peak, was best fit with a pair of Gaussians with \( v_{\text{LSR}} \)'s of 7.6(1) and 10.4(2) km s\(^{-1}\) and FWHM of 2.9(3) and 1.7(5) km s\(^{-1}\). The interferometric data have been scaled by a factor of 3.0, indicating that there is significant emission that is resolved out by the array, which is also supported by the maps. The emission from the northern peak has a rather narrow line profile, while the emission from the southern peak has a notably wider line profile.

3.2.5. Formaldehyde [H2CO]

A total of two H2CO transitions were detected in this survey (Figure 28). The lower energy transition (panel (a)) peaks near the Hot Core and IRC6 with an extension to the southeast, just as CH3OH does. Panel (b) shows the emission from the same transition, but over a very narrow velocity range (9.4–11.4 km s\(^{-1}\)), which highlights the weak emission coming from HC-NE. The higher energy transition (panel (c)) has a single peak near the Hot Core. Figure 29 shows that spectra from the transitions. Panel (a) is from the peak of the lower energy transition. The spectrum was best fit by a pair of Gaussians, with \( v_{\text{LSR}} \) of 4.1(7) and 8.5(1) km s\(^{-1}\) and FWHM of 11.1(9) and 4.2(6) km s\(^{-1}\), respectively. There may be more components, but without more lines to use for the analysis, the uncertainties grow well beyond the values of the fit. Panel (b) is a spectrum taken through the southeast wing of the low energy transition. It was best fit by a single narrow Gaussian with a \( v_{\text{LSR}} \) of 7.5(0) km s\(^{-1}\) and a FWHM of 1.7(0) km s\(^{-1}\). Panel (c) shows the narrow line from the HC-NE region. It is best fit by a
single Gaussian with a $v_{\text{LSR}}$ of 10.7 km s$^{-1}$ and FWHM of 1.6 (3) km s$^{-1}$. Panel (d) shows the spectrum from the intensity peak of the higher energy transition and was best fit by a single Gaussian with a $v_{\text{LSR}}$ of 7.8 (14) km s$^{-1}$ and FWHM of 6.8 (38) km s$^{-1}$; however, the spectral profile does indicate the presence of other components (similar to panel (a)), but below our detection threshold. Both the low and high energy intensity peaks are within 3$''$ (a fraction of the beam) of each other. There were not enough transitions to form a rotation temperature diagram for this molecule, so we assume a rotation temperature of 138 K from the similarly distributed CH$_3$OH. This yields beam averaged column densities of $4.8(9) \times 10^{17}$ and $1.1(0) \times 10^{18}$ cm$^{-2}$ for the two component low energy spectrum, $6.4(4) \times 10^{17}$ cm$^{-2}$ for the southeast wing, and $1.3(10) \times 10^{17}$ cm$^{-2}$ for the high energy transition. Using a rotation temperature of 30 K, we find a beam averaged total column density of $3.2(0) \times 10^{16}$ cm$^{-2}$ toward HC-NE. The sources were assumed to fill the beam (giving a beam filling factor of 0.5). Based on these values, there are no missing H$_2$CO transitions.

Like CH$_3$OH, H$_2$CO shows an extension to the southeast and was observed in single dish mode. Figure 30 shows the single dish and interferometric spectra from the $J_{\text{1,2}}-J_{\text{1,1}}$ transition of H$_2$CO. The spectra indicate that there is a significant extended component, possibly from the HC-NE/CS1 interface region, which has a $v_{\text{LSR}}$ of $\sim$10.6 km s$^{-1}$ that is resolved out by the interferometer. There is a slight velocity offset between the peaks ($\sim$1 km s$^{-1}$), indicating that the extended structure is at a slightly higher velocity. Figure 31 shows the interferometric average intensity map overlaid on the single dish average intensity map of this transition. The map indicates that any extended emission comes from the same region as the compact emission and has little extension, as it is confined to a single beam.

### 3.2.6. Thioformaldehyde [H$_2$CS]

The fundamental transition was the only H$_2$CS transition detected in our survey. Figure 32 shows the average intensity
map of the transition. It has two notable components, the strongest near CS1 and a slightly weaker one near the HC/CR. This is in contrast to its cousin, H₂CO, which has the vast bulk of its emission coming from the Hot Core and Compact Ridge regions and only a trace from CS1, but with similarly narrow lines and $v_{\text{LSR}}$. Figure 33 shows a comparison of the two tracers.

While they are not equivalent transitions (e.g., the H₂CO transition is not its fundamental transition) they are both low upper state energy transitions. The weak H₂CO emission from the overlapping regions and lack of H₂CS emission from the HC could be explained by a stark difference between the temperatures of the Hot Core and the overlap regions. The differences in emission could also stem from distinctly different formation mechanisms for these structurally similar molecules. Formaldehyde is thought to form in high abundance in icy grain mantles (e.g., Tielens & Allamandora 1987; Cuppen et al. 2009; Madzunkov et al. 2009), but may also have a notable gas formation pathway (Leurini et al. 2010). It is likely released from the grain surfaces by the shock and higher temperatures$^6$ of the SiO outflow as it interacts with the dust. Its emission is well-correlated with the 3 mm continuum of the region (see Figure 4). Conversely, thioformaldehyde is thought to have a strong gas phase formation path (Ghosh & Ghosh 1979). This is supported by the map, as the emission is from the more extended, cooler gas. Additionally, the H₂CS may be destroyed in the denser, hotter region around the Hot Core. Thus if the regions of H₂CS emission are cold (as the CH₃CCH data indicate), the H₂CO emission would be suppressed, as most would still be in the solid state on grains. Then as the outflow interacts with these regions, the H₂CO will be liberated from the grain surfaces into the gas phase while the H₂CS is destroyed.

Figure 25. Rotation temperature diagrams for the two detected CH₃CCH peaks. (a) is from the northwest peak and (b) is from the southeast peak.

Table 5

| Quantum Numbers | Frequency (MHz) | $E_u$ (K) | $S(\mu)^2$ (D$_\mu^2$) | $\theta_u \times \theta_v$ ($'' \times ''$) | $I_0^a$ (Jy/bm) | $v_{\text{LSR}}$ (km s$^{-1}$) | FWHM (km s$^{-1}$) | Position$^a$ | rms Noise (mJy/bm) | Array Config. |
|----------------|----------------|-----------|--------------------------|-------------------------------|-----------------|-----------------|----------------|--------------|-----------------|---------------|
| $5_2 \rightarrow 4_2$ | 85.45073 (6) | 41.1 | 2.4 | 3.6 $\times$ 2.5 | 0.69 (4) | 10.4 (0) | 2.1 (1) | N | 4.5 | C |
| $5_1 \rightarrow 4_1$ | 85.45562 (6) | 19.5 | 2.7 | 3.6 $\times$ 2.5 | 0.55 (2) | 10.4 (0) | 2.1 (1) | N | 4.5 | C |
| $5_0 \rightarrow 4_0$ | 85.45727 (6) | 12.3 | 2.8 | 3.6 $\times$ 2.5 | 0.32 (7) | 10.4 (0) | 2.1 (1) | N | 4.5 | C |

Note. $^a$ The uncertainties to the fits are dominated by the fact that the lines are just over a single channel wide.

$^6$ H₂CO evaporates at $\sim$40 K from grain surfaces (Garrod et al. 2008).
Figure 34 shows the spectra from the northern (panel (a)) and southern (panel (b)) peaks, respectively. Each was best fit by a single Gaussian with $v_{\text{LSR}}$'s of 8.4(2) and 10.6(4) km s$^{-1}$ and FWHM of 2.3(6) and 1.4(10) km s$^{-1}$, respectively. Using a temperature of 30 K, we find a beam averaged column density of $2.1 \times 10^{15}$ cm$^{-2}$ for the CR-SW peak and $1.5 \times 10^{15}$ cm$^{-2}$ for the CS1 peak. Given the column densities, there are no missing H$_2$CS transitions.

3.2.7. Sulphur Monoxide [SO and $^{34}$SO]

All sulphur monoxide, SO and $^{34}$SO transitions in our frequency range were detected. Figure 35 shows the average intensity maps of the only SO transition (panel (a), C configuration) and the higher energy $^{34}$SO transition (panel (b), D configuration). From the average intensity maps, it appears that SO has a rather extended distribution centered near...
the Hot Core. However, the channels maps in Figure 36 indicate a much more complex structure. The channel maps are shown from −17.5 to 40.3 km s\(^{-1}\), with the \(v_{\text{LSR}}\) in the upper right corner of each panel. While the emission is constrained to a rather compact region, there are three distinct peaks, visible between 9.0 and 14.8 km s\(^{-1}\), which surround the primary peak. Previous work by Plambeck et al. (1982), Wright et al. (1996), and Esplugues et al. (2013), of higher energy transitions near 86 and 219 GHz, indicated a clumpy SO structure. Our observations do indicate this clumpiness, but also with an encasing shell-like structure.

Figure 37 shows the \(\sim 10\) km s\(^{-1}\) SO emission, from the center of the shell, as a color scale overlaid by SiO emission from Plambeck et al. (2009). The SiO emission indicates the extent of the outflow and shocked regions. The SO emission is well-correlated with the SiO emission edges and known structures. This indicates that the SO is being formed, or liberated from the grains, in the energetic regions as a shock moves and interacts with the gas and dust. The northern most peak is coincident with the lower edge of \(\text{CH}_3\text{CCH}\) emission in the HC-NW. The western peak is coincident with IRc6, a region associated with emission of complex organic molecules (e.g., Friedel & Snyder 2008; Friedel & Widicus Weaver 2012; Widicus Weaver & Friedel 2012), and the third peak is near the Hot Core. Panel (b) is the same data as in panel (a), but restored with a \(2'' \times 2''\) beam and shows a nearly complete ring like structure, which is obscured in the lower resolution map, that is expected from the center slice of a shell. The only notable gap is to the northwest, near BN. It is possible that after the interaction, BN created the hole as it left the region. The hole can be seen more clearly in Figure 38 (d). Figure 38 shows the pseudo-3D structure of SO, which uses \(v_{\text{LSR}}\) as a proxy for distance. The three SO clumps can be seen in all panels. Panel (a) looks down the R.A. axis, (b) looks down the DEC axis, (c) looks down the \(v_{\text{LSR}}\) axis, and (d) shows the hole in the SO structure.

Figure 39 shows the spectra from the three main SO emission peaks. The blue line is a reference set at a \(v_{\text{LSR}}\) of

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**Figure 28.** Average intensity maps of the two detected formaldehyde transitions. (a) is the lower energy transition and shows an extension of emission to the southeast from the Hot Core region; (b) is the same transition as (a), but with only the 9.4–11.4 km s\(^{-1}\) velocity components showing the emission from near CS1; and (c) is from the higher energy transition that is confined to the Hot Core region. The contours are \(\pm 3\sigma, 6\sigma, 9\sigma \ldots\), where \(\sigma = 2.2\) and 3.3 mJy/beam, respectively.

**Figure 29.** Spectra from the H\(_2\)CO data. (a) is from the intensity peak of the lowest energy transition, (b) is from the southeast wing of the lowest energy transition, (c) is from the CS1 region of the lowest energy transition, and (d) is from the intensity peak of the highest energy transition. The abscissa is \(v_{\text{LSR}}\) in km s\(^{-1}\), and the ordinate is intensity in Jy/beam. The rest frequency for each transition is given in each panel, and the “I” bars denote the 1\(\sigma\) rms noise.
7.0 km s\(^{-1}\). Panel (a), from the southern peak, was best fit by a pair of Gaussians, with \(v_{\text{LSR}}\)’s of 5.3(0) and 20.9(3) km s\(^{-1}\) and FWHM of 12.4(1) and 11.5(8) km s\(^{-1}\). Panel (b), from the northern peak, was best fit by three Gaussians, with \(v_{\text{LSR}}\)’s of 9.2(81), 10.7(0), and 21.6(5) km s\(^{-1}\) and FWHM of 7.2(42), 4.0(2), and 8.1(12) km s\(^{-1}\). Panel (c), from the western peak near IRc6, was best fit by at least three Gaussians, with \(v_{\text{LSR}}\)’s of 1.6(5), 11.7(2), and 18.5(87) km s\(^{-1}\) and FWHM of 25.0(9), 4.0(2), and 8.1(12) km s\(^{-1}\).

**Figure 30.** Spectra from single dish observations (black) and array observations (red) of the \(3_1^2-3_1^1\) transition of H\(_2\)CO. The array data have been scaled by a factor of 3.0. The abscissa is \(v_{\text{LSR}}\) in km s\(^{-1}\), the ordinate is intensity in Jy/beam, and the “I” bars denote the 1\(\sigma\) rms noise of the associated spectrum. The blue line indicates a \(v_{\text{LSR}}\) of 7 km s\(^{-1}\).

**Figure 31.** Array average intensity map of the \(3_1^2-3_1^1\) transition of H\(_2\)CO (contours) overlaid on the color scale map from single dish observations of the same transition. Contours are \(\pm 3\sigma, \pm 6\sigma, \pm 9\sigma, \ldots\), where \(\sigma = 11.2\) mJy/beam.

**Figure 32.** Contour map of the H\(_2\)CS transition overlaid on the grayscale continuum. Contours are \(3, 6, 9, \ldots\ssss\), where \(\sigma = 3.7\) mJy/beam. The synthesized beam is given in the lower left corner of the map.

**Figure 33.** Comparison map of H\(_2\)CO (black contours) and H\(_2\)CS (red contours). Contours are \(3, 6, 9, \ldots\ssss\), where \(\sigma = 2.2\) and 3.7 mJy/beam, respectively.

**Figure 34.** Spectra of the two H\(_2\)CS peaks. (a) is from the northern peak and (b) is from the southern peak. The abscissa is \(v_{\text{LSR}}\) in km s\(^{-1}\), the ordinate is intensity in Jy/beam, and the “I” bars denote the 1\(\sigma\) rms noise.
6.8(4), and 4.3(51) km s\(^{-1}\). Since none of the peaks are coincident, we calculated the column densities for each based on a range of temperatures (30–200 K). For the IRc6 peak, we find column densities of \(0.3–1.9 \times 10^{17} \text{ cm}^{-2}\), \(1.2–8 \times 10^{16} \text{ cm}^{-2}\), and \(0.8–5.1 \times 10^{17} \text{ cm}^{-2}\), for the three Gaussians. For the northern peak, we find column densities of \(1.1–6.8 \times 10^{16} \text{ cm}^{-2}\), \(0.2–1.1 \times 10^{17} \text{ cm}^{-2}\), and \(0.2–1.4 \times 10^{17} \text{ cm}^{-2}\), for the three Gaussians. For the southern source, we find column densities of \(0.2–1.6 \times 10^{17} \text{ cm}^{-2}\) and \(1.4–8.9 \times 10^{17} \text{ cm}^{-2}\) for the two Gaussians.

Figure 40 shows the spectra from the two detected \(^{34}\text{SO}\) transitions. Panel (a), from the lowest energy transition, was best fit by a single wide Gaussian, with a \(v_{\text{LSR}}\) of 8.0 km s\(^{-1}\) and FWHM of 22.8 km s\(^{-1}\), although more components may be blended in. Panel (b), from the higher energy transition, was best fit by a pair of Gaussians, with \(v_{\text{LSR}}\)’s of 2.4 and 17.6 km s\(^{-1}\) and FWHM of 15.5 and 10.5 km s\(^{-1}\). For the lowest energy transition, we find column densities of \((0.7–4.2) \times 10^{16} \text{ cm}^{-2}\). For the higher energy transition, we find column densities of \((0.9–3.4) \times 10^{16} \text{ cm}^{-2}\) and \((2.6–9.6) \times 10^{15} \text{ cm}^{-2}\), for the two Gaussians.

In order to understand the full extent of the SO emission, the transition was observed in CARMA’s single dish mode with a 32 point mosaic. Figure 41 shows the resulting average intensity map in color overlaid with the interferometric observations as contours. As can be seen, the bulk of the flux is constrained to the Hot Core region. Figure 42 shows a comparison of the spectra from the single dish (black) and interferometric (red) observations. The interferometric data were generated by convolving a 165\(^\circ\) Gaussian with the output maps. Both spectra have similar structures, as the interferometric emission well traces the wide emission wings of the single dish data. However, there is a notable strong peak that is not detected by the interferometer. The interferometric data were best fit by three Gaussians with peaks of 0.7(3), 1.46(2), and 2.1(2) Jy/beam; FWHM of 4.6(23), 2.6(53), and 24.3(10) km s\(^{-1}\); and \(v_{\text{LSR}}\) of 10.7(9), 3.7(53), and 8.1(0) km s\(^{-1}\). Given the complexity of the SO emission, there could be many more components that are lost in the blend.

A total of seven sulphur dioxide transitions (six SO\(_2\) and one \(^{34}\text{SO}_2\)) were detected with this survey. Like SO, SO\(_2\) displays a shell-like structure with three (or more) distinct peaks: HC-NE, IRc6, and HC/CR. Figure 43 shows average intensity maps, overlaid on the appropriate continuum, from two of the transitions. Panel (a) is from the lowest energy transition, which was observed in C configuration, and panel (b) is from a middle energy transition, which was observed with the combined C/D configurations.

Not all transitions were detected from each peak, and there were not enough transitions to construct a reliable rotation temperature diagram; therefore all column densities are calculated based on rotation temperatures of 30–200 K. Figure 44 shows the spectra from the three detected transitions from the northern peak. The lowest two energy transitions (panels (a) and (b)) were best fit with pairs of Gaussians, with \(v_{\text{LSR}}\)’s of 7.5(9) and 10.5(5) km s\(^{-1}\) (panel (a)) and 4.4(4) and 8.4(8) km s\(^{-1}\) (panel (b)), and FWHM of 17.8(21) and 19.8(22) km s\(^{-1}\) (panel (a)) and 3.7(10) and 19.8(22) km s\(^{-1}\) (panel (b)). Given the overall low S/N of the spectra, it is possible that more components may be hidden in the profile. The highest energy transition (panel (c)) was best fit by a single Gaussian with a \(v_{\text{LSR}}\) of 4.9(3) km s\(^{-1}\) and FWHM of 5.4(8) km s\(^{-1}\). These transitions yield a total column density of \(3.6 \times 10^{16}–8.6 \times 10^{20} \text{ cm}^{-2}\).

Figure 45 shows the three detected SO\(_2\) transitions from the IRc6 peak. The lowest energy transition (panel (b)) was best fit by three Gaussians, with \(v_{\text{LSR}}\)’s of 6.2(15), 12.0(8), and...
Figure 36. Individual channels maps of SO. Contour levels are ±3σ, ±11σ, ±19σ,..., where σ = 8.6 mJy/beam. The velocity of each channel is given in the top right corner of each panel.
18.6(16) km s\(^{-1}\) and FWHM of 26.8(22), 5.6(17), and 6.1(30) km s\(^{-1}\). The other transitions were best fit by a pair of Gaussians, with \(v_{\text{LSR}}\)'s of \(-6.4(19), 5.0(2),\) and 5.6(7) km s\(^{-1}\); 2.9(9), 4.5 (1), and \(-4.9(1)\) km s\(^{-1}\); and \(-1.5(15), 4.9(2),\) and 11.4(15) km s\(^{-1}\), respectively, and FWHM of 2.8(47), 5.4(5), and 15.7(17) km s\(^{-1}\); 40.4(33), 9.7(6), and 2.7(3) km s\(^{-1}\); and 7.5(27), 5.9(5), and 32.9(22) km s\(^{-1}\), respectively. The fourth of these lower energy transitions (30.2 GHz) was best fit by only a single Gaussian, with a \(v_{\text{LSR}}\) of 3.8(4) km s\(^{-1}\) and FWHM of 4.0(8) km s\(^{-1}\). The other Gaussian components are likely lost in the noise, as this transition has a line strength that is a factor of four (or more) lower than the other transitions. The two higher energy transitions (27.9 and 34.1 GHz) were best fit by a single Gaussian, with \(v_{\text{LSR}}\)'s of 4.5(9) and 5.5(2) km s\(^{-1}\), respectively, and FWHM of 18.3(23) and 6.2(7) km s\(^{-1}\), respectively. These give a total column density of 9.8 \(\times\) 10\(^{16}\)–1.8 \(\times\) 10\(^{17}\) cm\(^{-2}\). While SO\(_2\) appears to have a similar spatial distribution to SO, the spectra show that they likely occupy different gas in the northern core, due to the notability different \(v_{\text{LSR}}\)’s and FWHM; toward IRc6 and the southern core, the picture is less clear, as there are similar velocity components for both molecules, but also ones that are distinctly different. This indicates that SO and SO\(_2\) do not form under the same physical conditions; however, there is some overlap.

Figure 47 shows the only detected \(^{34}\)SO\(_2\) transition from this survey. This transition was detected toward the HC/CR region. It was best fit by a pair of narrow Gaussians, with \(v_{\text{LSR}}\)'s of 8.5 (9) and 15.9(3) km s\(^{-1}\) and FWHM of 1.2(22) and 2.0(8) km s\(^{-1}\), giving a total column density of 5.1 \(\times\) 10\(^{15}\)–1.5 \(\times\) 10\(^{17}\) cm\(^{-2}\). Based on the absence of any other detected \(^{34}\)SO\(_2\) transitions, we calculate that the rotation temperature must be no more than 150 K, yielding an upper limit of 2.5 \(\times\) 10\(^{16}\) cm\(^{-2}\) for the total column density. Temperatures higher than this would have yielded a detection of the \(^{17}\)\(\text{O}\)\(^{16}\)\(\text{N}\) transition at 33.21281 GHz. Since SO\(_2\) and \(^{34}\)SO\(_2\) should share a common rotation temperature, this yields an upper limit of 6.0 \(\times\) 10\(^{17}\) cm\(^{-2}\) for SO\(_2\).

3.2.9. Ammonia [\(\text{NH}_3\)]

A total of five ammonia lines were detected in this survey, mostly concentrated near the Hot Core (Figure 48). Figure 49 shows the spectrum from the emission peak of each detected line. All transitions were simultaneously fit with Gaussians by assuming a consistent FWHM and \(v_{\text{LSR}}\). The transitions at 27.4779 and 28.6047 GHz were best fit with a pair of Gaussians with \(v_{\text{LSR}}\)'s of 1.0(0) and 6.0(0) km s\(^{-1}\) and FWHM of 6.3(0) and 5.7(0) km s\(^{-1}\), respectively. The remaining three were best fit by a single Gaussian at 6.0(0) km s\(^{-1}\) and FWHM of 5.2(0) km s\(^{-1}\). From these fits we constructed rotation temperature diagrams for each component (Figure 50). The narrow component (panel (a)) only has two points, but does give reasonable results of 6.4 \(\times\) 10\(^{14}\) cm\(^{-2}\) and 165 K. The other three points are shown as upper limits based on the same
Figure 38. The pseudo-3D SO structure of Orion-KL, using $v_{\text{LSR}}$ as a proxy for distance. (a) shows a view down the R.A. axis, (b) down the decl. axis, and (c) down the velocity axis. (d) shows the hole in SO emission, which may have been created by BN escaping the region.

Figure 39. Spectra from each of the SO peaks at $\nu = 30.0015$ GHz. (a) is from the southern peak, (b) is from the northern peak, and (c) is from the western peak. The blue line is a reference set at a $v_{\text{LSR}}$ of 7 km s$^{-1}$. The abscissa is $v_{\text{LSR}}$ in km s$^{-1}$, and the ordinate is intensity in Jy/beam. The rest frequency for each transition is given in each panel, and the “I” bars denote the 1$\sigma$ rms noise.
line width and an intensity of 1σ. The main component (panel (b)) is best fit with $2.2 \times 10^{14} \text{ cm}^{-2}$ and 297 K. The temperature is consistent with previous observations of NH$_3$ by Goddi et al. (2011), who found a temperature range of 160–490 K, at higher resolution. The total column density reported by Goddi et al. (2011) is three orders of magnitude larger than what we find in this work. This could be due to us sampling different gas that was resolved out by their smaller beam and/or a very small source size. Given our column densities and rotation temperatures, there are no missing transitions.

The $9_0\sigma$–$9_0\sigma$ transition of NH$_3$ was observed in single dish mode. Figure 51 shows the single dish average intensity map as a color scale overlaid by the array average intensity map as contours. Figure 52 shows the single dish spectrum (black) and the array spectrum (red). The peaks of the average intensity maps do not perfectly correspond, nor does the NH$_3$ array spectrum match that of the single dish as it has to be scaled by a factor of 3.0 in order to match. For a transition of such high energy (850 K), to have so much flux resolved out is unusual, but not unprecedented. Wilson et al. (1993) found there are two temperature components to the NH$_3$ emission toward Orion-KL. According to Figure 3 of Wilson et al. (1993), a transition at 850 K would have significant flux from both components. Wilson et al. (2000) noted a significant amount of flux was resolved out of array observations of a lower energy NH$_3$ transition, when compared with single dish observations. Thus the missing flux could be due to our observations resolving out the lower temperature component. The offset between the single dish and array peaks is likely due to the two temperature components being offset. Figure 3 of Murata et al. (1990) shows an elongation of the NH$_3$ emission to the southeast from Source I, and CO emission has a small peak in this direction as well.

3.2.10. Methyl Formate [CH$_3$OCHO]

A total of eight CH$_3$OCHO transitions were detected in this survey. Two of these transitions were detected with the C configuration, but were poorly fit by Gaussians, and were left out of the calculations. Figure 53 shows the maps of two transitions, one from C configuration (panel (a)) and one from D configuration peaking between the Compact Ridge and the BN (panel (b)). The contours are $\pm 3\sigma, \pm 5\sigma, \pm 7\sigma, \ldots$ for panel (a) and $\pm 3\sigma, \pm 6\sigma, \pm 9\sigma, \ldots$ for panel (b), where $\sigma = 6.0$ and 11.7 mJy/beam, respectively. Figure 54 shows the spectra of each detected transition. The spectra were best fit with a $v_{\text{LSR}}$ of $\sim 8.0 \text{ km s}^{-1}$ and FWHM of $\sim 2.0 \text{ km s}^{-1}$, similar to that of CH$_3$OCH$_3$. Each transition was individually fit. The spectra from 34.1581 GHz shows two CH$_3$OCHO transitions.
All detected transitions were very low energy (<16 K) and could not be fit by a rotation temperature diagram, due to the small spread in energies. Friedel (2005) found a total column density of $3.3(1) \times 10^{17} \text{ cm}^{-2}$ and a rotation temperature of 344(55) K. Using this temperature yields a column density nearly an order of magnitude higher. Given that these are very low energy lines, and that the rotation temperature in Friedel (2005) is dominated by high energy lines, it is likely that the emission region detected by this survey is dominated by cooler, more extended gas. Using a rotation temperature of 200 K yields a column density of $\sim 4 \times 10^{17} \text{ cm}^{-2}$. Using this temperature and column density, there are no missing lines.

## 3.2.11. Dimethyl Ether \([\text{CH}_3\text{OCH}_3]\)

A total of 17 dimethyl ether lines were detected in this survey, 14 with the C configuration and 3 with combined C and D configuration data. Typically each transition is composed of four torsional states: $EE$, $AA$, $AE$, and $EA$, where $EE$ is at the central frequency and $AA$ and a combined $AE/EA$ are equally spaced on either side. Three of the transitions (12 lines) in this work fit this description. However, the lines near 31.999 GHz and 33.943 GHz do not. In these transitions, only a partial set of the four lines are detected. In the case of the 31.999 GHz lines, the $AE$ and $EA$ components are not stacked and are below the detection threshold. In the case of the 33.943 GHz lines, the $AA$ or $EE$ are blended; the $EA$ is detected but the separate $AE$ component is below the detection threshold. Friedel (2005) found a rotation temperature of $\sim 84$ K and a total column density of $\sim 4 \times 10^{17} \text{ cm}^{-2}$. Using this temperature we find a total column density of $\sim 4 \times 10^{18} \text{ cm}^{-2}$. This could be reconciled with the (Friedel 2005) column density by using either a higher temperature or a source size of $\sim 5''^2$. Given the
column densities and temperatures, there are no missing transitions.

Figure 57 shows the C and D configuration maps of CH$_3$OCH$_3$. In the C configuration map (panel (a)), emission is detected near the Compact Ridge and near IRC6, similar to Widicus Weaver & Friedel (2012) and Friedel & Snyder (2008). In all instances the emission is unresolved. Figure 58 shows the spectra from all detected CH$_3$OCH$_3$ lines. They were best fit with single Gaussians with a $v_{LSR}$ of $\sim$8.0 km s$^{-1}$ and FWHM of $\sim$1.6 km s$^{-1}$. Each group of transitions ($EE$, $AA$, $AE$, and $EA$) was fit together, with a common $v_{LSR}$ and FWHM for each group. In panels (a), (b), (e), and (f), there are multiple CH$_3$OCH$_3$ lines, and the $v_{LSR}$ references the strongest ($EE$) rest frequency.

Figure 46. Spectra of the six detected SO$_2$ transitions from the southern peak. The abscissa is $v_{LSR}$ in km s$^{-1}$, and the ordinate is intensity in Jy/beam. The rest frequency for each transition is given in each panel, and the “I” bars denote the 1$\sigma$ rms noise.

Figure 47. The single detected $^{34}$SO$_2$ transition from the southern peak. The abscissa is $v_{LSR}$ in km s$^{-1}$, and the ordinate is intensity in Jy/beam. The rest frequency for each transition is given in each panel, and the “I” bars denote the 1$\sigma$ rms noise.

Figure 48. Map of ammonia emission overlaid on the continuum. The contours are ±3$\sigma$, ±15$\sigma$, ±27$\sigma$, ..., where $\sigma$ = 2.0 mJy/beam. The synthesized beam is shown in the lower left corner.
A total of three transitions of CH$_3$CH$_2$CN were detected in our survey, one of which is blended with a transition of $^{13}$CH$_3$OH. While CH$_3$CH$_2$CN is one of the most ubiquitous emitters at higher frequencies \cite{Friedel2005}, it is a much poorer emitter at lower frequencies, due to notably lower line strengths. Figure 59 shows the three detected CH$_3$CH$_2$CN lines. Panel (a) shows the blended CH$_3$CH$_2$CN/$^{13}$CH$_3$OH line, panel (b) shows the $3_{1,2}-2_{1,1}$ transition, and panel (c) shows the $4_{1,4}-3_{1,3}$ transition. Both unblended CH$_3$CH$_2$CN transitions were best fit by two Gaussian components, a narrower one near 5 km s$^{-1}$, and a wider one near $-6$ km s$^{-1}$. Friedel (2005) also found that most CH$_3$CH$_2$CN lines at $\lambda = 3$ mm were best fit with two components. Based on the maps of Widicus Weaver & Friedel (2012), we find this work fully encompasses the CH$_3$CH$_2$CN emission and are thus sampling the same gas. Based on the rotation temperatures from Friedel (2005) of 314 K, for the narrow component, and 118 K, for the wide component, we find total column densities of $(1.5-2.9) \times 10^{17}$ and $8.4 \times 10^{15}-4.5 \times 10^{16}$ cm$^{-2}$, for the narrow and wide components, respectively. The column density for the narrow component is a factor of two to three above that reported in Friedel (2005), but the column density for the wide component agrees well with the value from Friedel (2005). Given these column densities and rotation temperatures, no CH$_3$CH$_2$CN transitions are missing from our survey. Also, given these values, we determine that the blended CH$_3$CH$_2$CN/$^{13}$CH$_3$OH line is at most 10% CH$_3$CH$_2$CN.
Figure 51. Array average intensity map of the 9_{00}−9_{00} transition of NH$_3$ (contours) overlaid on the single dish average intensity map of the same. Contours are ±3σ, ±6σ, ±9σ, where σ = 8.9 mJy/beam.

Figure 52. Spectra of the single dish (black) and array (red) observations of the 9_{00}−9_{00} transition of NH$_3$. The array data have been scaled by a factor of 3.0. The abscissa is v$_{LSR}$ in km s$^{-1}$, the ordinate is intensity in Jy/beam, and the ‘T’ bars denote the 1σ rms noise.

Figure 60 shows maps of the two unblended detected CH$_3$CH$_2$CN transitions, peaking near the Hot Core. Panel (a) shows the 3$_{1,2}$−2$_{1,1}$ transition, and panel (b) shows the 2$_{1,4}$−3$_{1,3}$ transition. Panel (c) shows the 4$_{1,4}$−3$_{1,3}$ in black contours overlaid with a λ = 3 mm CH$_3$CH$_2$CN transition from Widicus Weaver & Friedel (2012) in red. While the 3 mm emission was observed with a notably smaller beam, the 3$_{1,2}$−2$_{1,1}$ transition of CH$_3$CH$_2$CN, observed in single dish mode, was not detected above our 3σ threshold (1σ = 370 mJy/beam). Combining this non-detection with the fact that the 1 cm contours only show emission from the same region as the 3 mm emission, we can conclude that CH$_3$CH$_2$CN has little or no extended structure. This leads to the conclusion that CH$_3$CH$_2$CN is formed/liberated from the grains only in the hottest, densest, and most turbulent regions.

### 3.2.13. Cyanocetylene [HC$_3$N]

The only ground state HC$_3$N transition in our frequency coverage was detected, from two distinct sources. Figure 61 shows the map of the emission overlaid on the continuum. The strongest peak is centered near Source I, and the weaker peak extends toward CS1. This structure is similar to other molecules like H$_2$CO, H$_2$CS, and CH$_3$CCH, but does not quite match any of them. The only molecule that has notable peaks in both locations is H$_2$CS, but its strongest peak is near CS1, unlike HC$_3$N, which has its strongest peak near source I. Figure 62 shows the spectra from the two emission regions. The spectrum toward Source I is in panel (a), while the spectrum from the CS1 region is in panel (b). The Source I spectrum was best fit with three Gaussian components, with v$_{LSR}$’s of 2.2(15), 5.8(2), and 18.2(8) km s$^{-1}$ and FWHM of 16.8(16), 5.5(9), and 4.7(21) km s$^{-1}$. The CS1 peak was best fit by a single Gaussian with a v$_{LSR}$ of 10.0(0) km s$^{-1}$ and a FWHM of 1.8(0) km s$^{-1}$. The fits were performed by assuming the expected, optically thin, ratio of hyperfine components.$^7$ Using a temperature range of 20–200 K, we find column densities of 1.9 $\times$ 10$^{14}$–7.7 $\times$ 10$^{15}$ cm$^{-2}$ for Source I and 3.0 $\times$ 10$^{15}$–3.3 $\times$ 10$^{16}$ for the northeast component.

This transition of HC$_3$N was observed in single dish mode. Figure 63 shows the single dish average intensity color scale map overlaid by the array average intensity map as contours, and Figure 64 shows the single dish (black) and array (red) spectra. Like NH$_3$, the peaks do not fully correspond, and the array spectrum has to be scaled by a factor of 7.0. The array data were best fit by a pair of Gaussians with v$_{LSR}$’s of 5.4(5) and 9.8(1) km s$^{-1}$ and FWHM of 3.1(13) and 1.4(6) km s$^{-1}$. The single dish data were best fit by a single Gaussian with a v$_{LSR}$ of 9.1(0) km s$^{-1}$ and FWHM of 2.8(0) km s$^{-1}$. This indicates that HC$_3$N has a notable extended component, which is not surprising, as it is easily detected in many sources from hot cores to cold dark clouds.

### 4. Bringing It All Together

In the previous sections we described the distribution of the molecular species detected in this survey. These data paint a picture of complex molecules (CH$_3$CH$_2$CN, CH$_3$OCH$_3$, and CH$_3$OCHO), and CH$_3$OH being confined to the warmest, densest part of the region near the SiO outflow and highly extinguished infrared sources in Orion-KL. H$_2$CO and NH$_3$ also show significant compact emission, but have both large scale features and emission from more distant regions (e.g., HC-NW), which should also be cooler. SO and SO$_2$ appear to have emission that is clumpy but still shell-like around the hottest part of the region. H$_2$CS is the next most extended, followed by CH$_3$CCH, both of which occupy regions that are much cooler $\sim$30 K. CH$_3$CCH also has significant extended structure on the order of arcminutes. HC$_3$N is the only molecular species in this survey that occupies both the hottest

$^7$ Only five of the six hyperfine components were used in the fit, as the sixth has a line strength over two orders of magnitude smaller than any other.
and densest region (HC) and the more extended cooler regions (e.g., CS1).

Figure 65(a) illustrates the temperature gradient from the warmest region of the Hot Core (∼250 K), moving outward to the coolest region, CS1 (∼30 K). Note that none of the displayed molecules peak on top of the outflow, but rather at its edges or extremes. This shows how the outflow is energizing the region and driving the chemistry, with molecules formed dominantly in the gas phase occupying the coldest parts, through to the complex molecules, which require the higher temperatures and densities to form and/or be desorbed from icy dust grain mantles.

5. Conclusion

We have presented the results of the first λ = 1 cm spectral line survey of Orion-KL. We detected a total of 89 transitions from 14 molecular species, and no unidentified lines. The observations were conducted with Combined Array for Research in Millimeter-wave Astronomy (CARMA) in both array and single dish modes.

SO and SO2 (and their isotopomers) were found to have a shell-like structure near Source I, with three distinct subcores on the edge. There also appears to be a hole in the SO emission that was created by BN as it exited the main core. This structure is not seen in any other detected molecular

Figure 53. Methyl formate maps, one each from (a) C and (b) D configurations. The emission contours are overlaid on the respective continuum. The contours are ±3σ, ±5σ, ±7σ, ..., for panel (a) and ±3σ, ±6σ, ±9σ, ... for panel (b), where σ = 6.0 and 11.7 mJy/beam, respectively. The respective synthesized beams are in the lower left corner of each panel.

Figure 54. Methyl formate spectra from each detected transition. Each transition is labeled by its rest frequency. The spectrum from 34.1581 GHz shows two CH3OCHO transitions. The abscissa is $v_{LSR}$ in km s$^{-1}$, the ordinate is intensity in Jy/beam, and the "I" bars denote the 1σ rms noise.
species because SO and SO$_2$ occupy a different physical region from the other detected species. Each of the SO/SO$_2$ clumps borders on one or more of the primary emission regions of complex organic molecules (Hot Core, Compact Ridge, IRC6, etc.), giving a picture of SO/SO$_2$ encasing the compact emission of these species. A majority of the emission comes from the compact source detected by the

array, but there is a significant component that is more extended but $<165''$ in total extent.

Methanol had the most detected transitions of any species and exhibits a primarily compact emission, with three distinct velocity components. Each of these components comes from a different set of physical conditions. The highest temperature component comes from the smallest structure, and the lowest temperature comes from the largest structure. This may indicate either a shell-like structure or multiple individual cores.

Ammonia [NH$_3$] is also primarily compact, with two detected components, but like SO, it has an extended component that is $<165''$. Both H and He recombination lines were detected, but were very dependent on the size of the synthesized beam. While there were notable knots of emission detected, the primary component was found to be extended.

Several molecular species, specifically formaldehyde [H$_2$CO], thioformaldehyde [H$_2$CS], methyl acetate [CH$_3$CCH], and HC$_3$N show several regions of emission that are not compact. CH$_3$CCH has compact and extended emission regions that appear to be at the extreme ends of the SiO outflow, and H$_2$CO and HC$_3$N emission are concentrated near Source I, but also have emission at the northeast edge of the SiO emission, while H$_2$CS has its strongest peak at the northeast edge of the SiO outflow and weak emission near the Compact Ridge. Ethyl cyanide [CH$_3$CH$_2$CN], methyl formate [CH$_3$OCHO], and, by proxy, dimethyl ether [CH$_3$OCH$_3$] showed only compact emission from the central core.

Based on data from this work and those of Friedel (2005), Plambeck et al. (2009), Favre et al. (2011), Friedel and Widicus Weaver (2011), Goddi et al. (2011), Friedel and Widicus Weaver (2012), Widicus Weaver & Friedel (2012), and Brouillet et al. (2013), we suggest the following general picture: SO and SO$_2$ were formed or liberated from grains by the initial shock from the Source I/BN interaction. Either at the same time or shortly after, the interaction the SiO outflow from Source I began, which in turn heated up the region and sent further, more powerful shocks through the gas and dust. At the extreme ends of the outflow, several molecular species were formed/liberated into the gas phase (e.g., CH$_3$CCH, HCOOH, CH$_3$OCH$_3$, CH$_3$OCHO, and H$_2$CS). Further in, where the outflow is interacting with slightly denser material, molecules such as (CH$_3$)$_2$CO are formed/liberated. In the densest region of the outflow, molecules such as CH$_3$CH$_2$CN, NH$_3$, and H$_2$CO are formed/liberated. CH$_3$OH is the only molecule that is detected throughout the outflow, from the extremes to the densest parts. The outflow and BN formed “holes” in the SO shell as they escaped the inner region.

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Figure 57. Average intensity maps of CH$_3$OCH$_3$ from the (a) C configuration and (b) both configurations. The contours are ±3σ, ±6σ, ±9σ, ..., where σ = 4.6 and 7.7 mJy/beam, respectively.

Figure 58. Spectra of the detected CH$_3$OCH$_3$ transitions. The abscissa is $\nu_{\text{LSR}}$ in km s$^{-1}$ and the ordinate is intensity in Jy/beam. The rest frequency for each transition is given in each panel, and the “I” bars denote the 1σ rms noise.
Figure 59. Three detected CH$_3$CH$_2$CN transitions. (a) is the blended CH$_3$CH$_2$CN/13CH$_3$OH line, (b) is the 3$_{21}$,2$_{11}$ transition, and (c) is the 4$_{31}$,4$_{13}$ transition. The abscissa is $v_{\text{LSR}}$ in km s$^{-1}$, and the ordinate is intensity in Jy/beam. The rest frequency for each transition is given in each panel, and the “I” bars denote the 1σ rms noise.

Figure 60. Ethyl cyanide maps. (a) shows the 3$_{21}$,2$_{11}$ transition, and (b) shows the 4$_{31}$,4$_{13}$ transition. Contours are $\pm 3\sigma$, $\pm 6\sigma$, $\pm 9\sigma$, ..., where $\sigma = 2.7$ and 2.1 mJy/beam, respectively. (c) show the 4$_{31}$,4$_{13}$ in black contours overlaid with a $\lambda = 3$ mm CH$_3$CH$_2$CN transition from Widicus Weaver & Friedel (2012) in red.

Figure 61. Map of the HC$_3$N transition overlaid on the associated continuum. The contours are $\pm 3\sigma$, $\pm 6\sigma$, $\pm 9\sigma$, ..., where $\sigma = 17.6$ mJy/beam.
Figure 62. Spectrum of the detected HC₃N transition ($\nu = 27.2943$ GHz). The abscissa is $v_{\text{LSR}}$ in km s$^{-1}$, the ordinate is intensity in Jy/beam, and the "I" bars denote the 1$\sigma$ rms noise. (a) shows the spectrum toward the hot core, and (b) shows the spectrum toward the northwest peak.

Figure 63. Array average intensity map of the 3–2 transition of HC₃N (contours) overlaid on the color scale average intensity map of the same. Contours are ±3$\sigma$, ±6$\sigma$, ±9$\sigma$, ..., where $\sigma = 17.6$ mJy/beam.

Figure 64. Spectra of the single dish (black) and array observations (red) of the 3–2 transition of HC₃N. The array data have been scaled by a factor of 7.0. The abscissa is $v_{\text{LSR}}$ in km s$^{-1}$, the ordinate is intensity in Jy/beam, and the "I" bars denote the 1$\sigma$ rms noise.
Figure 65. A schematic of the temperature gradient, from the Hot Core where it is warmest (∼250 K) moving outward to the coolest region, CS (∼30 K). The contours are from H$_2$CO (magenta), SO (green), H$_2$CS (blue), and CH$_3$CCH (orange). The arrows denote the temperature gradient and are labelled with temperatures derived from this work and Friedel (2005). The dashed line connects the center of the gradient line with the Hot Core, and the red + indicate CS1, BN, I, and CR positions. Figure 65(b) shows a zoom in of panel (a) with SiO contours (gray) added in.

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References

Becklin, E. E., & Neugebauer, G. 1967, ApJ, 147, 799
Beuther, H., Zhang, Q., Greenhill, L. J., et al. 2004, ApJL, 616, L31
Bisschop, S. E., Jørgensen, J. K., van Dishoeck, E. F., & de Wachter, E. B. M. 2007, A&A, 465, 913
Blake, G. A., Sutton, E. C., Masson, C. R., & Phillips, T. G. 1987, ApJ, 315, 621
Brouillet, N., Despois, D., Baudry, A., et al. 2013, A&A, 550, A46
Charnley, S. B., Tielens, A. G. G. M., & Millar, T. J. 1992, ApJL, 399, L71
Cuppen, H. M., van Dishoeck, E. F., Herbst, E., & Tielens, A. G. G. M. 2009, A&A, 508, 275
Eisner, J. A., & Carpenter, J. M. 2006, ApJ, 641, 1162
Esplugues, G. B., Tercero, B., Cernicharo, J., et al. 2013, A&A, 556, A143
Favre, C., Wootten, H. A., Remijan, A. J., et al. 2011, ApJL, 739, L12
Friedel, D. N. 2005, PhD thesis, Univ. Illinois
Friedel, D. N., & Snyder, L. E. 2008, ApJ, 672, 962
Friedel, D. N., & Widicus Weaver, S. L. 2011, ApJ, 742, 64
Friedel, D. N., & Widicus Weaver, S. L. 2012, ApJS, 201, 17
Garrod, R. T., Widicus Weaver, S. L., & Herbst, E. 2008, ApJ, 682, 283
Ghosh, K. K., & Ghosh, S. N. 1979, IJRSP, 8, 219
Goddi, C., Humphreys, E. M. L., Greenhill, L. J., Chandler, C. J., & Matthews, L. D. 2011, ApJ, 728, 15
Goicoechea, J. R., Pety, J., Cuadrado, S., et al. 2016, Natur, 537, 207
Gong, Y., Henkel, C., Thorwirth, S., et al. 2015, A&A, 581, A48
Groner, P., Albert, S., Herbst, E., et al. 2002, ApJS, 142, 145
Groner, P., Herbst, E., De Lucia, F. C., Drouin, B. J., & Mäder, H. 2005, in 60th Int. Symp. Molecular Spectroscopy, Rotational Spectrum of the First Torsional Exited State of Acetone, CH$_3$COCH$_3$, abstract #RA03, https://molspect.chemistry.ohio-state.edu/symposium
Horiiuchi, S., & Kameya, O. 2000, PASJ, 52, 545
Jacox, M. E. 2005, Vibrational and Electronic Energy Levels of Polyatomic Transient Molecules in NIST Chemistry WebBook, NIST Standard Reference Database Number 69 (Gaithersburg, MD: National Institute of Standards and Technology), 20899
Kuiper, T. B. H., Kuiper, E. N. R., Dickinson, D. F., Turner, B. E., & Zuckerman, B. 1984, ApJ, 276, 211
Leurini, S., Despois, D., Baudry, A., et al. 2013, A&A, 550, A46
Liu, S.-Y., Remijan, A., Friedel, D. N., Meier, D. S., & Snyder, L. E. 2004, ApJ, 617, 384
Logsdon, D. M., & Brown, R. 2000, ApJ, 545, 551
Mehringer, D. M., Pearson, J. C., Keene, J., & Phillips, T. G. 2004, ApJ, 608, 306
Menten, K. M., Reid, M. J., Forbrich, J., & Brunthaler, A. 2007, A&A, 474, 515
Munder, L. G., Scoville, N. Z., Baath, L. B., Masson, C. R., & Woody, D. P. 1986, ApJL, 304, L51
Murata, Y., Kawabe, R., Ishiguro, M., et al. 1990, ApJ, 359, 125
Nummelin, A., & Bergman, P. 1999, A&A, 341, L59
O’Dell, C. R., Kollatschny, W., & Ferland, G. J. 2017, ApJ, 835, 171
Oesterling, L. C., Albert, S., de Lucia, F. C., Sastry, K. V. L. N., & Herbst, E. 1999, ApJ, 521, 255
Pickett, H. M., Poynter, R. L., Cohen, E. A., et al. 1998, JQSRT, 60, 883
Plambeck, R. L., Bolatto, A. D., Carpenter, J. M., et al. 2013, ApJ, 765, 40
Plambeck, R. L., & Wright, M. C. H. 1988, ApJL, 330, L61
Plambeck, R. L., Wright, M. C. H., Friedel, D. N., et al. 2009, ApJL, 704, L25
Plambeck, R. L., Wright, M. C. H., Welch, W. J., et al. 1982, ApJL, 259, 617
Remijan, A., Shiao, Y.-S., Friedel, D. N., Meier, D. S., & Snyder, L. E. 2004, ApJ, 617, 384
Remijan, A., Snyder, L. E., Friedel, D. N., Liu, S.-Y., & Shah, R. Y. 2003, ApJ, 590, 314
Remijan, A. J., Wyrowski, F., Friedel, D. N., Meier, D. S., & Snyder, L. E. 2005, ApJ, 626, 233
Sault, R. J., Teuben, P. J., & Wright, M. C. H. 1995, in ASP Conf. Ser. 77, Astronomical Data Analysis Software and Systems IV, ed. R. A. Shaw, H. E. Payne, & J. J. E. Hayes (San Francisco, CA: ASP), 443
Sutton, E. C., Blake, G. A., Masson, C. R., & Phillips, T. G. 1985, ApJS, 58, 341
Tielens, A. G. G. M., & Allamandola, L. J. 1987, in Interstellar Processes, ed. D. Hollenbach & H. Thronson (Dordrecht: Reidel), 397
Turner, B. E. 1989, ApJS, 70, 539
Turner, B. E. 1991, ApJS, 76, 617
Widicus Weaver, S. L., Butler, R. A. H., Drouin, B. J., et al. 2005, ApJS, 158, 188
Widicus Weaver, S. L., & Friedel, D. N. 2012, ApJS, 201, 16

Wilson, T. L., Gaume, R. A., Gensheimer, P., & Johnston, K. J. 2000, ApJ, 538, 665
Wilson, T. L., Henkel, C., Huttemeister, S., et al. 1993, A&A, 276, L29
Wright, M. C. H., Plambeck, R. L., Mundy, L. G., & Looney, L. W. 1995, ApJL, 455, L185
Wright, M. C. H., Plambeck, R. L., Vogel, S. N., Ho, P. T. P., & Welch, W. J. 1983, ApJL, 267, L41
Wright, M. C. H., Plambeck, R. L., & Wilner, D. J. 1996, ApJ, 469, 216