HIGH-RESOLUTION EXPANDED VERY LARGE ARRAY IMAGE OF DIMETHYL ETHER \((\text{CH}_3)_2\text{O}\) IN ORION–KL

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ABSTRACT

We report the first subarcsecond \((0.′65 \times 0.′51)\) image of the dimethyl ether molecule, \((\text{CH}_3)_2\text{O}\), toward the Orion Kleinkmann–Low nebula. The observations were carried at 43.4 GHz with the Expanded Very Large Array (EVLA). The distribution of the lower energy transition \(\sigma_1,\delta=0_0,6\), EE \((E_u = 21 \text{ K})\) mapped in this study is in excellent agreement with the published dimethyl ether emission maps imaged with a lower resolution. The main emission peaks are observed toward the Compact Ridge and Hot Core southwest components, at the northern parts of the Compact Ridge and in an intermediate position between the Compact Ridge and the Hot Core. A notable result is that the distribution of dimethyl ether is very similar to that of another important larger O-bearing species, the methyl formate (HCOOCH\(_3\)), imaged at a lower resolution. Our study shows that higher spectral resolution (WIDAR correlator) and increased spectral coverage provided by the EVLA offer new possibilities for imaging complex molecular species. The sensitivity improvement and the other EVLA improvements make this instrument well suited for high sensitivity, high angular resolution, and molecular line imaging.

Key words: ISM: individual objects (Orion–KL) – ISM: jets and outflows – ISM: molecules

Online-only material: color figures

1. INTRODUCTION

The Orion complex is among the most studied sources in our Galaxy. At a distance of \(\sim 420\) pc (see, e.g., Sandstrom et al. 2007; Hirota et al. 2007; Menten et al. 2007), this is the nearest site of recent high-mass star formation. The prominent \(\text{H}\)\(\text{ii}\) regions NGC 1976 or M42 and NGC 1977 are on the near side of a large molecular cloud associated with Lynds dark cloud L1640 (see O’Dell 2001). At the rear of the \(\text{H}\)\(\text{ii}\) region is the Orion Molecular Cloud, OMC-1. The brightest molecular emission in OMC-1 is near the H\(\text{ii}\) region NGC 1976 (see, e.g., Tatematsu et al. 1993). Plume et al. (2000) measured the \(J=5-4\) transition of \(^1\text{CO}\) over a \(0.′5\) resolution area with a 3:2 resolution. The brightest emission has an extent of \(\sim 15′\) in the north–south by \(\sim 5′\) in the east–west direction. Within this region of extended emission is a prominent maximum, the Kleinkmann–Low (KL) infrared nebula (see, e.g., Dougados et al. 1993; Gezari et al. 1998), which exhibits emission from complex molecules, masers, outflows, and warm dust. In addition to extended IR emission from warm dust, there are \(\sim 20\) compact near-IR sources found toward Orion–KL (Dougados et al. 1993).

In quasi-thermal continuum emission from dust grains, Orion–KL shows an overall extent of \(10′\) in \(\alpha\) by \(15′\) in \(\delta\). With a higher angular resolution, the form has a “V” shape, with the symmetry axis at a position angle (P.A.) \(\sim 20′\) east of north. Within this region, there is fine structure, with molecular species peaking at different positions. This reflects abundance differences, not excitation effects.

In the methyl formate (HCOOCH\(_3\)) image (see Figure 4 of Favre et al. 2011) and in the frequency-integrated maps of several molecular tracers (see Figure 5 of Guélin et al. 2008), the molecular distribution is seen as a V-shape with each arm having an observed length of \(12′′ \times 3′′\), with the major axis at a P.A. \(\sim 20′\) east of north having an opening angle of \(38′\). From Plateau de Bure Interferometer (PdBI; Favre et al. 2011) and Expanded Very Large Array (EVLA) data (A. Remijan, unpublished), the methyl formate emission taken with resolutions of \(0.′8 \times 0.′8\) and \(5″\) peaks at \(\delta_{2000} = 05^h35^m14′09″\), \(\delta_{2000} = -05°22′36″7^7\). This is the center position of the compact ridge region. The compact ridge shows a large abundance of oxygen-containing species. In \(\text{CH}_3\text{CH}_2\text{CN}\), ethyl cyanide, the center of the Hot Core peaks at \(\delta_{2000} = 05^h35^m14′6″\), \(\delta_{2000} = -05°22′29″\), with observed sizes of \(9′′ \times 4′′\) at a P.A. \(\sim 20′\) east of north. This region shows an excess of nitrogen-bearing species (see, e.g., Blake et al. 1996; Friedel & Snyder 2008; Wilson et al. 2000; Wright et al. 1996). The chemistry of Orion–KL is rich, with rather large abundances of complex molecules. There are two possibilities: (1) gas-phase reactions between ionized and neutral species and (2) formation on dust grains, followed by liberation from grains by radiation from nearby IR sources.

In addition to extended dust and molecular emission, Orion–KL also has a number of radio continuum sources (Garay et al. 1987; Churchwell et al. 1987; Menten & Reid 1995; Rodríguez et al. 2005). Accurate high angular resolution radio data show that the highly obscured source “I” and the Becklin–Neugebauer object (BN; Becklin & Neugebauer 1967) show large proper motions (Plambeck et al. 1995). Subsequently, Rodríguez et al. (2005), Gómez et al. (2005, 2008), and Goddi et al. (2011) have found proper motions of source I, BN, and the radio counterpart of source “n.”

Given the large amount of activity in the Orion–KL region, a high angular resolution is needed to separate the various influences. There are two coupled problems to be solved. The first is the chemistry of the Hot Core and the Compact Ridge. Although the centers of these regions are separated by only \(\sim 10′\) (0.02 pc), their chemistry is quite different. In addition, models...
must accurately predict the abundances of complex species and their survival in the presence of the activity as shown by the large proper motions of sources BN, I, and n. Given these questions, the first task is to image complex molecular species with arcsecond or better angular resolutions to test chemistry models. For this purpose, we have imaged the KL nebula in the “C” configuration (proposal code: 10B-223). Dual polarization observations were made toward a single object and the radio source I, are detected above 5σ with a peak flux density per synthesized beam, $S_\nu$, of 22.3 mJy beam$^{-1}$ and 9.8 mJy beam$^{-1}$, respectively. Some of the structure of the Hot Core source is resolved. Emission from the BN object also appears quite compact. The total flux densities, $S_\nu$, are given in Table 2.

### 3. RESULTS

#### 3.1. Continuum Emission

The 43 GHz continuum emission observed toward Orion BN/KL is shown in Figure 1. Two continuum sources, the BN object and the radio source I, are detected above 5σ with a peak flux density per synthesized beam, $S_\nu$, of 22.3 mJy beam$^{-1}$ and 9.8 mJy beam$^{-1}$, respectively. Some of the structure of the Hot Core source is resolved. Emission from the BN object also appears quite compact. The total flux densities, $S_\nu$, are given in Table 2.

#### 3.2. Dimethyl Ether (CH$_3$)$_2$O

The dimethyl ether emission map at 43.447 GHz is shown in Figure 2. The observed four main molecular emission peaks, hereafter DME1, DME2, DME3, and DME4, are located toward the Compact Ridge, the Hot Core southwest (Hot Core-SW), in an intermediate position between the Compact Ridge and the Hot Core-SW, and in the north of the Compact Ridge, respectively. Most of the peaks appear with a local standard of rest (LSR) velocity of 7.4 km s$^{-1}$. As for many O-bearing species, the emission distribution presents an extended V-shape linking the radio source I to the BN object (see, e.g., Guélin et al. 2008).

The high spectral resolution provided by the WIDAR correlator allows us to distinguish between the AA and EE transitions, although the AE and EA transitions are blended (see Table 1). Spectra of the lower energy transitions $6_{1}–6_{0,6}$, AA, EE, and AE/EA ($E_{\nu}$ = 21 K) observed toward the regions DME1 to DME4 are presented in Figure 2. The observed line parameters (velocity, intensity) of the detected (CH$_3$)$_2$O $6_{1}–6_{0,6}$, EE transition are summarized in Table 3.

### Table 1

| Frequency (MHz) | Transition | $\langle S_{\nu} \mu^2 \rangle$ (mJy) | $\sigma$ (mJy) | $E_{\nu}$ (K) | $\delta_{\nu2000}$ (h) | $\sigma_{\nu2000}$ (h) | $\Delta_{\nu2000}$ (h) |
|----------------|------------|-----------------------------------|----------------|--------------|------------------------|------------------------|-----------------------|
| 43446.4708(12) | $6_{1}–6_{0,6}$ AE | 14.0 | 21.1 | | | | |
| 43446.4713(12) | $6_{1}–6_{0,6}$ EA | 28.1 | 21.1 | | | | |
| 43447.5415(11) | $6_{1}–6_{0,6}$ EE | 112.2 | 21.1 | | | | |
| 43448.6120(14) | $6_{1}–6_{0,6}$ AA | 42.1 | 21.1 | | | | |

**Notes.**

a All spectroscopic data from (CH$_3$)$_2$O taken from Groner et al. (1998) are available from the JPL molecular line catalog (Pickett et al. 1998) at Splatalogue (http://www.splatalogue.net; Remijan et al. 2007).

b Errors are 2σ.

### Table 2

| Source | $\delta_{\nu2000}$ (h) | $\sigma_{\nu2000}$ (h) | Uncertainty$^b$ (mJy) | $S_\nu$ (mJy) |
|--------|------------------------|------------------------|-----------------------|--------------|
| BN     | 05 35 14.1094 | $–05 22 22.724$ | 3 | 29 |
| I      | 05 35 14.5141 | $–05 22 30.575$ | 3 | 16 |

### Table 3

| Region | Peak Label | $v_{LSR}$ (km s$^{-1}$) | $\Delta v_{LSR}$ (km s$^{-1}$) | $I_0$ (Jy beam$^{-1}$) |
|--------|------------|------------------------|------------------------|-----------------------|
| Compact Ridge (CR) | DME1 | 7.4 | 0.9 | 64 |
| Hot Core-SW (HC-SW) | DME2 | 7.4 | 1.9 | 14 |
| Intermediate of CR and HC-SW | DME3 | 7.4 | 1.7 | 35 |
| Compact Ridge North (CRN) | DME4 | 6.9 | 1.5 | 40 |

The continuum emission was subtracted from the January data set and imaged. The final continuum and continuum-subtracted images for analysis have been corrected for the response of the primary beam.

The final naturally weighted maps reached a (5σ) sensitivity of 20 mJy beam$^{-1}$ (39 K) in the line images and 3 mJy beam$^{-1}$ in the continuum images, as expected. The beam size is 0′′65 × 0′′51 at a P.A. 38°.
4. COMPARISON WITH OTHER RESULTS AND ANALYSIS

4.1. Comparison with Continuum Maps

The total flux densities, $S_\nu$ (see Table 2), obtained toward source I, in the Hot Core region, and the BN object are in very good agreement with the 43 GHz Very Large Array values reported by Menten & Reid (1995), Chandler & Wood (1997), Reid et al. (2007), and Goddi et al. (2011).

4.2. Single Dish Observations

Green Bank Telescope (GBT) molecular surveys have been undertaken from 42.3 GHz to 43.6 GHz (Goddi et al. 2009) and from 42.7 GHz to 45.6 GHz (H. A. Wootten, unpublished; Guélin et al. 2008). A comparison between these surveys and our EVLA spectra has allowed us to conclude to within the uncertainties that all flux measured in either GBT survey for the (CH$_3$)$_2$O, $6_{1,5}$–$6_{0,6}$ transition is recovered in our EVLA images.

The excitation of the dimethyl ether emission may be estimated from fitting a rotational temperature to the three lines spanning an energy range 21–147 K from Goddi et al. (2009) or from the two lines spanning the same range from Guélin et al. (2008). From these data, line sets observed simultaneously on the GBT; we estimate $T_{\text{rot}}$((CH$_3$)$_2$O) $\sim$ 120 K, in agreement with estimates from transitions of HCOOCH$_3$ of Favre et al. (2011). Note that the brightness temperature of the dimethyl ether line reported here toward the peak of the compact ridge (DME1; see Figure 2) is $\sim$140 K and that this line is optically thick ($\tau$ estimated to be 2.9), consistent with the rotational temperature in the broader (16") GBT beam. Using lines of acetone (CH$_3$)$_2$CO in the same GBT spectrum, Goddi et al. (2009) found a rotational temperature twice this value, suggesting an origin in the Hot Core. Higher resolution images are needed to understand how the distributions of otherwise similar O-bearing molecules differ and to glean lessons on how large molecules may form and vanish in molecular clouds.

4.3. Interferometric Observations

Using the Combined Array for Research in Millimeter-Wave Astronomy (CARMA), Friedel & Snyder (2008) have imaged the dimethyl ether transition $13_0,13$–$12_1,12$ ($E_u = 86$ K) with a beam size of 2.5" $\times$ 0.85. Our observed (CH$_3$)$_2$O emission peaks (DME1, DME2, and DME4; see Figure 2) are present...
Figure 2. Dimethyl ether (CH$_3$)$_2$O emission map observed with the EVLA toward Orion BN/KL. The synthesized beam, 0\,′′.65 × 0\,′′.51, is shown in red in the lower left corner. The red contours show the 43 GHz continuum emission of the BN object and the radio source I (see Figure 1). Spectra displayed in this figure are observed toward the four main (CH$_3$)$_2$O emission peaks (DME1 to DME4), i.e., in the following directions: the Compact Ridge (bottom right), the Hot Core-SW (top left), the intermediate region linking the Hot Core to the Compact Ridge (bottom left), and the north of the Compact Ridge (top right).

(A color version of this figure is available in the online journal.)

in their lower resolution data.\(^6\) CARMA observations reveal a similar LSR velocity at 7.6 km s\(^{-1}\). However, their lower spectral resolution (by a factor of 1.4 compared to that of ours) did not allow them to resolve the AA, EE, and AE/EA lines.

A comparison between our EVLA map and the PdBI dimethyl ether transition 122\,10−113\,9 (\(E_u = 78\) K) imaged by Guélin et al. (2008),\(^7\) with a synthesized beam of 3′′.3 × 1′′.7, shows very good agreement. With a higher angular resolution, the distribution of the (CH$_3$)$_2$O mapped with EVLA presents the same main strongest emission peaks within the entire region: DME1, DME2, and DME4 (regions A, B, and C, respectively, in Figure 5 of Guélin et al. 2008).

Our EVLA subarcsecond (0′′.65 × 0′′.51) image of the dimethyl ether clearly reveals a new emission peak DME3, located between the Hot Core-SW and the Compact Ridge (see Figure 2).

4.4. Relation to Methyl Formate (HCOOCH$_3$) and Shocks

There is a debate whether dimethyl ether is formed on grain surfaces or in the gas phase via a path involving methanol as a precursor (Garrod et al. 2008; Peeters et al. 2006). This largest O-bearing molecule is highly abundant in star formation regions, particularly in hot cores (Nummelin et al. 2000; Sutton et al. 1995; Turner 1991). Studies of the astrochemistry of this molecule, as well as its spatial distribution, will bring important data for understanding high-mass star-forming regions.

A comparison between the dimethyl ether distribution with that of another important O-bearing molecule, methyl formate HCOOCH$_3$ (see, e.g., Favre et al. 2011), shows that both of these species peak at the same locations within the same velocity range. In particular, these share common emission peaks in the north of the Compact Ridge, in the Compact Ridge itself, toward the Hot Core-SW, and toward an intermediate region linking the Hot Core to the Compact Ridge. These four emission regions are shown in Figure 2 (see labels DME1 to DME4 in the present Letter and MF1 to MF4/5 in Favre et al. 2011). Hence the formation of these two molecules must have some relation, regardless whether the mechanism involves gas phase or grain surface formation.

Favre et al. (2011) have shown that shocks could be responsible for the HCOOCH$_3$ production in the Compact Ridge region. In particular, the clear association observed between the emissions of the 2.12 \(\mu\)m vibrationally excited H$_2$ (Lacombe et al. 2004) and methyl formate could result from shocks between the interstellar material and bullets owing to the close encounter of the sources I, n, and BN 500 years ago (Zapata et al. 2009; Bally et al. 2011). The similar spatial distribution observed suggests that the same mechanisms could be at the origin of the release of (CH$_3$)$_2$O (itself or a precursor) from ice grain mantles.

5. CONCLUSION

We have imaged the distribution of the dimethyl ether $^6_{1.5}$-$^6_{0.6}$, EE (\(E_u = 21\) K) transition with the high angular resolution of 0′′.65 × 0′′.51 using the EVLA. The high resolution provided by the WIDAR correlator allowed us to spectrally separate transitions AA, EE, and AE/EA. Our study shows the

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\(^6\) Note that the Compact Ridge position defined in Friedel & Snyder (2008) is not the same as that used in this study (e.g., reference taken from Beuther et al. 2005). Their IRc5 position is closer to our Compact Ridge position (1′′ away).

\(^7\) Note that a misprint with the dimethyl ether quantum numbers appears in Table 1 of Guélin et al. (2008).
great capabilities offered by this new interferometer at such a high spatial and spectral resolution.

Our results confirm the three main emission peaks of (CH$_3$)$_2$O observed in the previous studies with a lower angular resolution. A new dimethyl ether emission peak has been identified thanks to the high spatial resolution of these EVLA observations. The similarity between spatial distributions of this molecule and HCOOCH$_3$ and vibrationally excited H$_2$ toward the Compact Ridge suggests that the same production mechanisms, that is, shocks, may be involved.

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REFERENCES

Bally, J., Cunningham, N. J., Moeckel, N., et al. 2011, _ApJ_, 727, 113
Becklin, E. E., & Neugebauer, G. 1967, _ApJ_, 147, 799
Beuther, H., Zhang, Q., Greenhill, L. J., et al. 2005, _ApJ_, 632, 355
Blake, G. A., Mundy, L. G., Carlstrom, J. E., et al. 1996, _ApJ_, 472, L49
Chandler, C. J., & Wood, D. O. S. 1997, _MNRAS_, 287, 445
Churchwell, E., Fell, M., Wood, D. O. S., & Massi, M. 1987, _ApJ_, 321, 516
Dougados, C., Lena, P., Ridgway, S. T., Christou, J. C., & Probst, R. G. 1993, _ApJ_, 406, 112
Favre, C., Despois, D., Brouillet, N., et al. 2011, _A&A_, in press
Friedel, D. N., & Snyder, L. E. 2008, _ApJ_, 672, 962
Garay, G., Moran, J. M., & Reid, M. J. 1987, _ApJ_, 314, 535
Garrod, R. T., Weaver, S. L. W., & Herbst, E. 2008, _ApJ_, 682, 283
Gezari, D. Y., Backman, D. E., & Werner, M. W. 1998, _ApJ_, 509, 283
Goddi, C., Greenhill, L. J., Humphreys, E. M. L., et al. 2009, _ApJ_, 691, 1254
Goddi, C., Humphreys, E. M. L., Greenhill, L. J., Chandler, C. J., & Matthews, L. D. 2011, _ApJ_, 728, 15
Gómez, L., Rodríguez, L. F., Loinard, L., et al. 2008, _ApJ_, 685, 333
Gómez, L., Rodríguez, L. F., Loinard, L., et al. 2005, _ApJ_, 635, 1166
Groner, P., Albert, S., Herbst, E., & De Lucia, F. C. 1998, _ApJ_, 500, 1059
Guélin, M., Brouillet, N., Cernicharo, J., Combes, F., & Wooten, A. 2008, _Ap&SS_, 313, 45
Hirotta, T., Bashamata, T., Choi, Y. K., et al. 2007, _PASJ_, 59, 897
Lacombe, F., Gendron, E., Rouan, D., et al. 2004, _A&A_, 417, L5
Menten, K. M., & Reid, M. J. 1995, _ApJ_, 445, L157
Menten, K. M., Reid, M. J., Forbrich, J., & Brunthaler, A. 2007, _A&A_, 474, 515
Nummelin, A., Bergman, P., Hjalmarson, Å., et al. 2000, _ApJS_, 128, 213
O’Dell, C. R. 2001, RevMexAA Conf. Ser., 10, 1
Peeters, Z., Rodgers, S. D., Charnley, S. B., et al. 2006, _A&A_, 445, 197
Perley, R. A., Chandler, C. J., Butler, B. J., & Wrobel, J. M. 2011, _ApJ_, 739, L1
Pickett, H. M., Poynter, I. R. L., Cohen, E. A., et al. 1998, _J. Quant. Spectrosc. Radiat. Transfer_, 60, 883
Plambeck, R. L., Wright, M. C. H., Mundy, L. G., & Looney, L. W. 1995, _ApJ_, 455, L189
Plume, R., Bensch, F., Howe, J. E., et al. 2000, _ApJ_, 539, L133
Reid, M. J., Menten, K. M., Greenhill, L. J., & Chandler, C. J. 2007, _ApJ_, 664, 950
Remijan, A. J., & Markwick-Kemper, A. (ALMA Working Group on Spectral Line Frequencies) 2007, _BAAS_, 38, 963
Rodríguez, L. F., Poveda, A., Lizano, S., & Allen, C. 2005, _ApJ_, 627, L65
Sandstrom, K. M., Peek, J. E. G., Bower, G. C., et al. 2007, _ApJ_, 667, 1161
Sutton, E. C., Peng, R., Danchi, W. C., et al. 1995, _ApJS_, 97, 455
Tatematsu, K., Umemoto, T., Kameya, O., et al. 1993, _ApJS_, 76, 617
Wilson, T. L., Gaume, R. A., Gensheimer, P., & Johnston, K. J. 2000, _ApJ_, 538, 665
Wright, M. C. H., Plambeck, R. L., & Wilner, D. J. 1996, _ApJ_, 469, 216
Zapata, L. A., Schmid-Burgk, J., Ho, P. T. P., Rodríguez, L. F., & Menten, K. M. 2009, _ApJ_, 704, L45