HCOOCH₃ as a probe of temperature and structure in Orion-KL★,★★,★★★

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ABSTRACT

Context. The Orion Kleinmann-Low nebula (Orion-KL) is a complex region of star formation. Whereas its proximity allows studies on a scale of a few hundred AU, spectral confusion makes it difficult to identify molecules with low abundances.

Aims. We studied an important oxygenated molecule, HCOOCH₃, to characterize the physical conditions, temperature, and density of the different molecular source components. Methyl formate presents strong close rotational transitions covering a wide range of energy, and its emission in Orion-KL is not contaminated by the emission of N-bearing molecules. This study will help in the future 1) to constrain chemical models for the formation of methyl formate in gas phase or on grain mantles and 2) to search for more complex or prebiotic molecules.

Methods. We used high-resolution observations from the IRAM Plateau de Bure Interferometer to reduce spectral confusion and to better isolate the molecular emission regions. We used twelve data sets with a spatial resolution down to 1.8'' × 0.8''. Continuum emission was subtracted by selecting apparently line-free channels.

Results. We identify 28 methyl formate emission peaks throughout the 50'' field of observations. The two strongest peaks, named MF1 and MF2, are in the Compact Ridge and in the southwest of the Hot Core, respectively. From a comparison with single-dish observations, we estimate that we miss less than 15% of the flux and that spectral confusion is still prevailing as half of the expected transitions are blended over the region. Assuming that the transitions are thermalized, we derive the temperature at the five main emission peaks. At the MF1 position in the Compact Ridge we find a temperature of 80 K in a 1.8'' × 0.8'' beam size and 120 K on a larger scale (3.6'' × 2.2''), suggesting an external source of heating, whereas the temperature is about 130 K at the MF2 position on both scales. Transitions of methyl formate in its first torsionally excited state are detected as well, and the good agreement of the positions on the rotational diagrams between the ground state and the $v_t = 1$ transitions suggests a similar temperature. The LSR velocity of the gas is between 7.5 and 8.0 km s⁻¹ depending on the positions and column density peaks vary from 1.6 × 10¹⁶ to 1.6 × 10¹⁷ cm⁻². A second velocity component is observed around 9–10 km s⁻¹ in a north-south structure stretching from the Compact Ridge up to the BN object, and this component is warmer at the MF1 peak. The two other C₂H₄O₂ isomers are not detected, and the derived upper limit for the column density is ≤ 3 × 10¹⁴ cm⁻² for glycolaldehyde and ≤ 2 × 10¹⁵ cm⁻² for acetic acid. From the 223 GHz continuum map, we identify several dust clumps with associated gas masses in the range 0.8 to 5.8 M_⊙. Assuming that the methyl formate is spatially distributed as the dust is, we find relative abundances of methyl formate in the range ≤ 0.1 × 10⁻⁸ to 5.2 × 10⁻⁸. We suggest a relation between the methyl formate distribution and shocks as traced by 2.12 μm H₂ emission.

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

1. Introduction

The Orion Nebula is one of the most studied regions in the sky. It contains remarkable groups of bright, visible stars and, at the same time, it is an extremely rich region of star formation, up to very high masses. In addition, it is the closest high-mass star formation region to the Sun (414 ± 7 pc, Menten et al. 2007). It is thus the best source for investigating the processes leading to star formation with very high spatial resolution. However, Orion cannot be considered as the prototypical star-forming region in

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** A fits image of the HCOOCH₃ integrated intensity map (Fig. 4) is only available at the CDS via anonymous ftp to cdsarc.u-strasbg.fr (130.79.128.5) or via <http://cdsarc.u-strasbg.fr/viz-bin/qcat?J/A+A/532/A32>. All spectra can be obtained upon request to the authors.

*** Table 10 and Appendix A are available in electronic form at <http://www.aanda.org>

our Galaxy because it exhibits some unique characteristics that need to be understood before any generalization is made.

The Orion Kleinmann-Low nebula is an atypical region of the Orion Molecular Cloud 1 (OMC-1), which harbors one of the most luminous embedded IR sources of this region (luminosity $\sim 10^5 L_\odot$, Wynn-Williams et al. 1984). Several molecular components (referred to as the Hot Core, Compact, and Extended Ridges) and several IR sources or radio sources are associated with Orion-KL. The nature of the source(s) responsible for this IR emission is still poorly known and much debated. Many young stellar objects are still embedded in the dusty gas, including radio source I, a deeply embedded, high-mass young stellar object, which drives a bipolar outflow along a northeast-southwest axis (Beuther et al. 2005; Goddi et al. 2009; Plambeck et al. 2009) and presents a disk perpendicular to it (Matthews et al. 2010).

Another specificity of the Orion protocluster region is the presence of high-speed shocks generated in the center of Orion-KL, reminiscent of an explosive event. From VLA velocity measurements, it has been proposed that a very unique phenomenon had taken place some 500–1000 years ago: the close encounter, or collision, of two or more rather massive stars. The objects involved in such a dynamical interaction could have included the Becklin-Neugebauer object (BN) and sources I and n (Gómez et al. 2005; Rodríguez et al. 2005; Goddi et al. 2011). We might be observing a very recent and energetic event at the heart of the nebula, providing unique conditions for studying a rich interstellar chemistry. With this scheme in mind, many molecules could have been released from the grain mantles because of dust heating or multiple shocks.

The search for complex or prebiotic molecules is difficult because of their relatively low abundance and line intensity. Especially in a very rich molecular source such as Orion-KL, high spectral confusion makes it difficult to detect the weakest lines. Among them, glycine ($\text{NH}_2\text{CH}_2\text{COOH}$, the simplest amino acid) has been searched for in the interstellar medium by many groups but has not been detected, and only upper limits are given by the most sensitive studies (e.g. Combes et al. 1996; Guélin et al. 2008; Snyder et al. 2005). On the other hand, observing abundant complex molecules is necessary for characterizing the gas temperature and density of the various Orion-KL molecular source components. Observations of O- and N-bearing molecules show a clearly different spatial distribution. The N-bearing molecules tend to peak to the north of the Hot Core, while O-bearing molecules cover the Hot Core and the Compact Ridge (Guélin et al. 2008; Beuther et al. 2005; Friedel & Snyder 2008).

Rotational temperature maps have been derived from interferometric observations of CH_3OH (Beuther et al. 2005) and NH_3 (Wilson et al. 2000), both essentially focused on the Hot Core, and of CH_3CN (Wang et al. 2010); however the intense lines of these abundant species require correcting for opacity effects. Several single-dish observations (e.g. Blake et al. 1987; Comito et al. 2005) have also been used to derive rotational temperatures towards the Hot Core and the Compact Ridge, which are supposed to be differentiated from their velocity structure. However, the spatial structure lacks in these data.

In this paper we investigate the spatial structure and temperature distribution of Orion-KL from observations of the O-bearing methyl formate (HCOOCH_3) molecule, which is relatively abundant in several interstellar hot cores and corinos, and especially abundant in Orion-KL (Blake et al. 1987; Kobayashi et al. 2007; Friedel & Snyder 2008). In Sect. 2 we present our observations and the methyl formate frequency data base used in

this work, and we briefly describe the data reduction methodology. The results of our maps are presented in Sect. 3, together with details on the various molecular emission peaks identified in our maps. In Sect. 4, the temperature and molecular abundance across the entire V-shaped molecular structure linking IRC2 to BN are deduced from the rotational diagrams of the methyl formate molecule. In Sect. 5, upper limits on the abundance of methyl formate isomers are given. The dust and total mass and the mean gas density of the most prominent dust emission peaks are estimated from our continuum data in Sect. 6. The methyl formate fractional abundance is also estimated and briefly discussed in this same section. We compare our results to previous studies in Sect. 7. In Sect. 8, the methyl formate distribution is discussed in the light of the complex structure of the Orion nebula. Conclusions are presented in the last section.

2. Observations and methyl formate frequencies

We used twelve observational data sets obtained with the IRAM Plateau de Bure Interferometer (PdBI) towards the IRC2 region and its surroundings between 1996 and 2007. The bulk of the observations were obtained between 1999 and 2007. Table 1 lists the different parameters for each data set. The highest spatial resolution ($1.79'' \times 0.79''$) was achieved in the period 2003 to 2007. Most observations used five antennas that were equipped with two SIS receivers operated simultaneously at 3 mm and 1 mm until 2006, then independently. 0420-014, 0458-020, 0528+134, 0605-085, and 0607-157 were used as phase and amplitude calibrators. The short-term atmospheric phase fluctuations were corrected at 1.3 mm on line. Tropospheric and radiometric phase corrections have been used since 1995 and October 2001, respectively, at the IRAM PdBI, based on the measured water line wings in the continuum emission observed with the 1.3 mm receiver and on the 22 GHz water line radiometers. The six units of the correlator allowed us to observe several data subsets with different bandwidths and spectral resolution, which are also given in Table 1. For the highest spatial resolution, the spectral resolution was around 0.84 km s^{-1} , while some lower spatial resolution maps were obtained with 0.42 km s^{-1} spectral resolution. The *uv* coverage of these two data sets is shown in Fig. 1.

2.1. Data reduction

We used the GILDAS package¹ for data reduction. The continuum emission was subtracted in the data cubes by selecting line-free channels, discarding any contaminated (or doubtful) channels. Continuum emission in Orion-KL is essentially due to the thermal emission from the dust and to a weaker contribution from the free-free radiation of the gas. However, the contribution from the pseudo-continuum resulting from the superposition of many weak lines cannot be easily removed because it may depend on the spectral range analyzed. The continuum emission is strong and spatially extended, varies with frequency, and reveals a clumpy structure at the highest spatial resolutions (see Figs. 2 and 16). As the center of the observations is not the same for all data sets, the continuum emission is better mapped toward the south at 223 GHz and toward the north at 225 GHz. Mapping the continuum emission is not obvious because of the high density of lines. It is difficult to isolate channels devoid of molecular lines. Nevertheless, we were able to identify several channels (typically 4 to 22 by data sets) without line emission

¹ <http://www.iram.fr/IRAMFR/GILDAS>

Table 1. Main parameters of IRAM Plateau de Bure interferometer observations.

Set ^a	Bandwidth (GHz)	Date of observation ^b	Confi- guration	HPBW ($''$)	Spectral resolution (MHz)	(km s ⁻¹)	Flux conversion (1 Jy beam ⁻¹)	Synthesized beam ($'' \times ''$)	PA ($^\circ$)	Pixel size ($'' \times ''$)
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)
1	80.502–80.574	10-11/1999	CD	60	0.625	2.33	4.6 K	7.63×5.35	15	0.80×0.80
2	80.582–80.654	10-11/1999	CD	60	0.625	2.33	4.7 K	7.62×5.23	16	0.96×0.96
3	101.178–101.717	^c	BC	50	0.625	1.85	15.8 K	3.79×1.99	22	0.50×0.50
4	105.655–105.726	08-11/2005	D	48	0.3125	0.89	2.9 K	7.13×5.36	9	1.40×1.40
5	105.785–105.856	08-11/2005	D	48	0.3125	0.89	2.9 K	7.12×5.36	9	1.40×1.40
6	110.125–110.181	10/1996	C	46	0.15625	0.43	8.5 K	5.85×2.02	8	0.54×0.54
7	203.331–203.403	10-11/1999	CD	25	0.625	0.92	7.0 K	2.94×1.44	27	0.38×0.38
8	203.411–203.483	10-11/1999	CD	25	0.625	0.92	7.0 K	2.94×1.44	27	0.32×0.32
9	223.402–223.941	^d	BC	23	0.625	0.84	17.3 K	1.79×0.79	14	0.25×0.25
10	225.675–225.747	09-11/2005	D	22	0.3125	0.42	2.9 K	3.63×2.26	12	0.70×0.70
11	225.805–225.942	09-11/2005	D	22	0.3125	0.42	2.9 K	3.63×2.26	12	0.70×0.70
12	225.990–226.192	09-11/2005	D	22	0.3125	0.42	2.9 K	3.63×2.25	12	0.70×0.70

Notes. ^(a) Sets 3 and 9 were centered on coordinates ($\alpha_{J2000} = 05^h35^m14^s.20$, $\delta_{J2000} = -05^\circ22'36''.00$). Sets 1, 2, 4, 5, 6, 7, 8, 10, 11, and 12 were centered on coordinates ($\alpha_{J2000} = 05^h35^m14^s.46$, $\delta_{J2000} = -05^\circ22'30''.59$). The observation velocity was 6 km s⁻¹ for sets 1, 2, 6, 7, and 8, and 8 km s⁻¹ for the other sets. ^(b) Format: Month-Month/Year. ^(c) Dates of observation: 12/2003, 01-12/2004, 03/2005, 01/2006. ^(d) Dates of observation: 12/2003, 01-12/2004, 03/2005, 01/2006, 11-12/2007.

Fig. 1. Resulting uv coverage from the six tracks at 223 GHz (top panel) and four tracks at 225 GHz (bottom panel).

in our observations. All of these channels were averaged and the average was subtracted from each channel in the data cubes.

Finally, we cleaned the data cubes, channel by channel, using the Clark method. Columns 9–11 in Table 1 summarize the synthesized beam parameters for each dataset.

Fig. 2. Continuum maps obtained toward Orion-KL with the Plateau de Bure Interferometer. The clean beam is shown in the bottom left corner of each map. The first contour and the level step are 15 mJy beam⁻¹, 170 mJy beam⁻¹, and 100 mJy beam⁻¹ at 101.45 GHz, 203.41 GHz, 223.67 GHz, and 225.90 GHz, respectively. In each map, positions of the BN object ($\alpha_{J2000} = 05^h35^m14^s.1094$, $\delta_{J2000} = -05^\circ22'22''.724$) and the radio source I ($\alpha_{J2000} = 05^h35^m14^s.5141$, $\delta_{J2000} = -05^\circ22'30''.575$) (Goddi et al. 2011) are indicated. The maps have not been observed with the same center (see Table 1).

2.2. Interest of methyl formate observations

Methyl formate, one of three [C₂H₄O₂] isomers, is relatively abundant towards Orion-KL, in view of its complexity. High angular resolution allows us 1) to isolate the different emission peaks of methyl formate and to investigate the gas structure; 2) and with large-scale maps, to understand the overall Orion nebula structure (as discussed later in Sect. 8 of this work). High angular resolution also lowers the risk of spectral contamination by line-rich species such as C₂H₅CN, because the methyl formate distribution is different from that of N-bearing molecules

Fig. 3. Methyl formate (HCOOCH_3) line intensities assuming LTE and a temperature of 300 K (sources: JPL database and Ilyushin et al. 2009).

(Blake et al. 1987; Kobayashi et al. 2007; Friedel & Snyder 2008).

Methyl formate presents close rotational transitions (see Fig. 3) with strong line strengths ($S\mu^2$ up to 50.2 D^2 in our selection, see Tables 10 and A.1 to A.4). Several transitions covering a wide range of energy can be observed at the same time. Comparison of these data obtained with identical spatial and spectral resolutions will allow an optimal estimate of the molecular gas physical conditions. The observed lines are all optically thin, which eases their interpretation considerably.

From a chemical point of view, formation of methyl formate on grain surfaces or in gas phase is still being debated, as for many other complex species. The study of its spatial distribution and its relative abundance with respect to other O-bearing molecules like methanol CH_3OH , dimethyl ether CH_3OCH_3 , and the two methyl formate isomers, glycolaldehyde CH_2OHCHO and acetic acid CH_3COOH , could help evaluate the different chemical models (Charnley & Rodgers 2005; Bisschop et al. 2007; Garrod & Herbst 2006; Garrod et al. 2008).

2.3. Methyl formate and isomers frequencies

Recently, Ilyushin et al. (2009) recalculated the rotational transitions of HCOOCH_3 for the ground and first excited torsional states of this molecule. The JPL database² (Pickett 1991; Pickett et al. 1998) is now updated (since April 2009) to include both the newly recalculated methyl formate frequencies and their own predictions (Drouin, B.J.). Because of its threefold internal rotation, the methyl group leads to a series of thermally populated torsional levels that are split into two torsional substates with A and E symmetries. Previous data separated these two states, while current data treat both substates simultaneously. In our study, we used the measured and predicted transitions coming from both Ilyushin's table and the JPL database up to $E_{\text{upper}} \lesssim 650 \text{ K}$. Assuming HCOOCH_3 lines are thermalized, we considered transitions in their fundamental and first excited torsional states $v_t = 0$ and $v_t = 1$, respectively. Our observations confirm the detection of transitions of methyl formate in the first torsionally excited state (Kobayashi et al. 2007).

We also searched for the methyl formate isomers (see Sect. 5) and used Ilyushin et al. (2008) for the acetic acid and the CDMS database³ (Müller et al. 2001, 2005) for the glycolaldehyde transitions.

² <http://spec.jpl.nasa.gov/home.html>

³ <http://www.astro.uni-koeln.de/cdms>

3. Mapping methyl formate emission (HCOOCH_3) with the IRAM interferometer

The methyl formate molecule, HCOOCH_3 , allows us to trace the spatial distribution of one major oxygenated molecule in Orion-KL, especially in the direction of the Compact Ridge where high spatial resolution data are missing. We adopted the Hot Core and Compact Ridge positions labeled in Beuther et al. (2005). Figure 4 shows our large-scale, $1.79'' \times 0.79''$ beam size interferometric map of the HCOOCH_3 line emission integrated over the line profile and on three different transitions: $11_{4,8}-10_{3,7}$ A and E in $v_t = 0$ and $18_{5,14}-17_{5,13}$ E in $v_t = 1$ (at 223 465.340 MHz, 223 500.463 MHz, and 223 534.727 MHz, respectively) to improve the signal-to-noise ratio. It shows (a) several main emission peaks labeled MF1 to MF28; and (b) an extended, V-shaped molecular emission linking the radio source I to the BN object.

3.1. Molecular emission peaks

We used the whole data set obtained with different frequencies and angular resolutions to model and investigate the properties of the methyl formate emission. The molecular emission peaks (MF1 to MF28) were determined from our highest angular resolution data ($1.79'' \times 0.79''$) on the channel maps when they are present on *at least three adjacent channels*; they are listed in Table 2. The individual positions can vary by one pixel ($0.25''$) depending on the HCOOCH_3 transition. Two main molecular peaks, MF1 and MF2, are located toward the Compact Ridge and the Hot Core-SW respectively (e.g. references taken from Beuther et al. 2005; Friedel & Snyder 2008). Emission peaks are present throughout the observed field and exhibit more or less extended structures. At some frequencies a molecular emission is also detected at the position of the millimeter source MM23 (Eisner et al. 2008).

The molecular emission peaks MF1, MF2, MF4-5, and MM23 are associated with the four main dust peaks identified at 223 GHz (see Fig. 16 in Sect. 6). However the continuum emission does not coincide exactly with the associated molecular line peak ($\Delta\alpha \sim 0.1''$ to $1.2''$ and $\Delta\delta \sim 0.03''$ to $1.8''$, except for MF2 where $\Delta\alpha = 1.8''$ and $\Delta\delta = 2.9''$, for a beam size of $1.8'' \times 0.8''$). Since both continuum and line maps come from the same data sets, the observed spatial separations cannot be ascribed to instrumental effects. De Vicente et al. (2002) report the same effect from their HC_3N (10–9) lines observed on different vibrational levels. We conclude that even our best resolution is probably not sufficient to determine the relative positions of molecular and dust emissions exactly.

3.2. Velocity structure

Figure 5 presents the channel maps of the 223 465.340 MHz line. Most of the peaks appear between 6 and 9 km s^{-1} ; however, a linear structure is seen mainly toward the north at higher velocities (see discussion on MF1 and MF4 peaks in Sect. 3.5), going from MF5 to MF8. There is no methyl formate emission at the Hot Core position at the usual 5 km s^{-1} velocity.

3.3. Critical density

We assumed that the HCOOCH_3 transitions are thermalized at the five molecular emission peaks MF1 to MF5. From the H_2 column densities measured at the continuum peaks

Fig. 4. Methyl formate integrated intensity maps obtained with the Plateau de Bure Interferometer (sum of emission at 223 465.340 MHz, 223 500.463 MHz, and 223 534.727 MHz between 5 and 12 km s⁻¹). The bottom image is a blowup of the Hot Core/Compact Ridge map area. The beam is 1.79'' × 0.79''; the level step and first contour are 3.2 K km s⁻¹. The BN object position is ($\alpha_{J2000} = 05^{\text{h}}35^{\text{m}}14^{\text{s}}.1094$, $\delta_{J2000} = -05^{\circ}22'22''.724$), the radio source I position is ($\alpha_{J2000} = 05^{\text{h}}35^{\text{m}}14^{\text{s}}.5141$, $\delta_{J2000} = -05^{\circ}22'30''.575$), and the IR source n position is ($\alpha_{J2000} = 05^{\text{h}}35^{\text{m}}14^{\text{s}}.3571$, $\delta_{J2000} = -05^{\circ}22'32''.719$) (Goddi et al. 2011). The position of the millimeter source MM23 (Eisner et al. 2008) is also indicated. The main different HCOOCH₃ emission peaks identified on channel maps are marked by a cross and labeled MF_{NUMBER}.

associated to those positions (see Sect. 6 and Table 7), we indeed find $n_{\text{H}_2} \gg n_{\text{cr}} \sim 10^{4-7} \text{ cm}^{-3}$ for the detected lines at frequencies between 80 GHz and 226 GHz. To compute n_{cr} , we adopted the collision coefficients of H₂O (Faure & Josselin 2008) because of a similar dipole moment to HCOOCH₃ ($\mu = 1.8 \text{ D}$), and we took a multiplicative factor between 1 and 10 into account because HCOOCH₃ is a larger molecule. Even if n_{cr} could reach 10^7 cm^{-3} , the critical density remains well below n_{H_2} (see Table 7).

Fig. 5. Methyl formate channel maps of emission at 223 465.340 MHz. The beam is 1.79'' × 0.79'' and the first contour and level step are 50 mJy beam⁻¹. The v_{LSR} velocity is indicated on each plot.

Table 2. Position of the main HCOOCH₃ emission peaks observed with the Plateau de Bure Interferometer toward Orion-KL.

Position name	RA (J2000) 05 ^h 35 ^m	Dec (J2000) -05°22'
MF1	14:09	36:7
MF2	14:44	34:4
MF3	14:31	37:2
MF4	14:15	29:3
MF5	14:12	27:7
MF6	14:50	32:6
MF7	14:05	42:3
MF8	14:20	46:1
MF9	14:11	43:3
MF10	14:68	28:9
MF11	14:45	30:6
MF12	14:18	34:6
MF13	14:09	32:5
MF14	14:16	37:0
MF15	13:72	14:0
MF16	13:73	19:1
MF17	14:44	24:0
MF18	13:46	30:8
MF19	13:66	31:5
MF20	13:46	36:6
MF21	13:64	39:3
MF22	13:61	41:3
MF23	15:01	34:8
MF24	14:68	36:7
MF25	15:20	38:7
MF26	14:38	49:4
MF27	13:92	50:3
MF28	14:00	35:3

3.4. Missing flux estimation

To estimate whether there is some flux missing in our data owing to spatial filtering with the PdBI interferometer, we compared our PdBI spectra at 3 mm and 1 mm with IRAM 30-m telescope spectra. The PdBI spectra were convolved with a Gaussian

Fig. 6. Spectra of molecular emission at 3 mm toward the Compact Ridge. *The lower panel* is a blow up of the upper one. Green lines show IRAM 30-m telescope data of [Combes et al. \(1996\)](#), and black lines illustrate PdBI data (set No. 3, see Table 1) convolved with the 30-m beam. A and E transitions of HCOOCH_3 are marked in the figure.

beam similar to the 30-m beam (25'' at 3 mm and 11'' at 1 mm). For all data sets, the convolution was performed at the positions observed with the 30-m telescope. Error bars arising from the calibration and the pointing of the 30-m antenna fall within the typical range of 5–10%.

In the Compact Ridge, comparison of our PdBI observations (which have a spatial resolution of $3.79'' \times 1.99''$ at the relevant frequencies) with the 30-m observations made at 101 GHz (Combes et al. 1996) indicates a ratio of missing flux of 3% measured from lines at 101 370.505 MHz ($13_{3,11}$ – $13_{2,12}$, E) and 15% at 101 414.746 MHz ($13_{3,11}$ – $13_{2,12}$, A). At 101 477.421 MHz, the $18_{3,15}$ – $18_{3,16}$ E line is strongly blended with an intense H_2CS transition (see Fig. 6).

Concerning the Hot Core position, we also compared our PdBI observations (spatial resolution: $1.79'' \times 0.79''$) with the 30-m observations made at 223 GHz (J. Cernicharo, priv. comm.). Chemically, this region exhibits a strong molecular diversity that implies a very high confusion level. All HCOOCH_3 lines are blended either with another strong molecule or with a multitude of weaker lines, which makes it difficult to measure the exact missing flux. Using the 223 500.463 MHz ($11_{4,8}-10_{3,7}$, A) line, we find that about 20% of the flux is missed. At 3 mm we estimate that we can miss between 4% and 15% of methyl formate emission flux. This is determined from the lines at 101 302.159 MHz ($25_{6,19}-25_{5,20}$, A) and 101 370.505 MHz ($13_{3,11}-13_{2,12}$, E).

3.5. Observed parameters of the different HCOOCH_3 peaks

Supposing that the gas rotational temperature does not exceed a few hundred Kelvin, we searched for the 64 methyl formate transitions with $E_{\text{upper}} \lesssim 650$ K. We used the MAPPING GILDAS software to map and model the methyl formate source sizes, and the CLASS GILDAS software to determine the line parameters. The line frequencies and spectroscopic and observed parameters (ν , $\Delta\nu_{1/2}$, T_{B} , W) at the MF1 to MF5 emission peaks are given in Tables 10, and A.1 to A.4. The observational results are briefly summarized below for the main molecular peaks shown in Fig. 4.

Fig. 7. Two HCOOCH_3 components observed on the emission peak MF1 toward the Compact Ridge. The black spectrum shows the 223 465.340 MHz line, the gray spectrum the 225 855.505 MHz transition and the dotted line spectrum the 203 435.554 MHz transition. The intensity of these 2 spectra is multiplied by a factor 1.5 and 2, respectively. Dashed lines mark $v_{\text{LSR}} = 7.5$ and 9.2 km s^{-1} .

MF1: is the main HCOOCH_3 emission peak toward the Compact Ridge. It is present in all maps of detected HCOOCH_3 transitions. The source sizes, estimated at half-peak flux density (see Table 10), increase with a lower spatial resolution from $3.0'' \times 2.0''$ at 223 GHz to $7.0'' \times 10.0''$ at 80 GHz. The line width clearly depends on the spatial and spectral resolutions. For instance, with the same beam ($\approx 3'' \times 2''$), but using two different spectral resolutions, 1.85 km s^{-1} and 0.42 km s^{-1} , we obtain $\Delta v \approx 3.6 \text{ km s}^{-1}$ and 1.1 km s^{-1} , respectively. Table 10 summarizes the line parameters for all detected, blended, or not detected transitions in all data sets. We detected 20 lines, and observed two partially blended and 33 blended lines. Nine transitions were too faint to be detected. At both high spatial and spectral resolutions the 203 GHz, 223 GHz, and 225 GHz methyl formate spectra display two components, one around 7.5 km s^{-1} and the other around 9 km s^{-1} (see Fig. 7). The 2-velocity fit parameters are presented in Table 3. Both components have a narrow average line width of $\Delta v_{1/2} \approx 1.7 \text{ km s}^{-1}$. For the transitions observed with less resolution, the second velocity component cannot be directly separated, and the line widths are broader ($\Delta v_{1/2} \approx 3.6 \text{ km s}^{-1}$).

MF2: is the main HCOOCH_3 emission peak toward the Hot Core region. This peak is present in all detected HCOOCH_3 transitions. The source sizes, estimated at half-peak flux density (see Table A.1 in Appendix A), increases with a lower spatial resolution from $2.5'' \times 1.2''$ at 223 GHz to $5.0'' \times 2.5''$ at 101 GHz⁴. This source appears to be more compact than MF1 in the Compact Ridge. Table A.1 (in Appendix A) summarizes the line parameters for all detected, blended, or not detected transitions in all data sets. We detected 14 lines and observed 3 partially blended and 40 blended lines, and seven transitions were too faint to be detected. The mean velocity is around 7.7 km s^{-1} . As for clump MF1, the line widths depend on the spatial and spectral resolutions. With the highest spatial resolution ($1.79'' \times 0.79''$), we find $\Delta v_{1/2} \approx 2.4 \text{ km s}^{-1}$, while for a resolution of $3.79'' \times 1.99''$, $\Delta v_{1/2} \approx 4.1 \text{ km s}^{-1}$; we did not

⁴ The lower spatial resolution of the detected lines at 80 565.210 MHz and 105 815.953 MHz does not allow us to identify individual sources.

Table 3. Two-component analysis of methyl formate transitions observed with the IRAM Plateau de Bure Interferometer toward position MF1 in the Compact Ridge.

Frequency (MHz)	Transition	E_{up} (K)	$S\mu^2$ (D ²)	sigma (K)	v_1 (km s ⁻¹)	Component 1			v_2 (km s ⁻¹)	Component 2		
						$(\Delta v_{1/2})_1$ (km s ⁻¹)	$T_{\text{B}1}$ (K)	W_1 (K km s ⁻¹)		$(\Delta v_{1/2})_2$ (km s ⁻¹)	$T_{\text{B}2}$ (K)	W_2 (K km s ⁻¹)
203 435.554	19 _{8,11} –19 _{7,12} A	155	5.3	0.09	7.6(0.9)	1.6(0.9)	6.40	10.6(1.6)	9.3(0.9)	2.2(0.9)	0.88	2.1(1.6)
203 471.840	19 _{8,11} –19 _{7,12} E	155	4.9	0.09	7.5(0.1)	1.6(0.1)	5.28	9.2(2.0)	9.0(0.7)	3.1(1.0)	1.29	4.3(2.2)
223 465.340	11 _{4,8} –10 _{3,7} E	50	2.1	0.17	7.6(0.1)	2.0(0.2)	10.74	22.5(1.9)	9.5(0.2)	1.5(0.3)	3.17	5.0(1.7)
223 500.463	11 _{4,8} –10 _{3,7} A	50	1.8	0.17	7.4(0.1)	1.8(0.1)	11.49	21.8(1.7)	9.2(0.3)	1.9(0.4)	2.85	5.8(1.2)
223 534.727	18 _{5,14} –17 _{5,13} E, ($v_t = 1$)	305	41.6	0.17	7.4(0.1)	1.7(0.1)	10.25	18.5(0.8)	8.9(0.1)	2.9(0.2)	4.16	13.0(8.2)
225 855.505	6 _{6,1} –5 _{5,1} E	36	3.1	0.10	7.6(0.1)	1.2(0.1)	6.84	9.1(0.1)	9.2(0.1)	1.1(0.1)	2.56	2.9(0.1)
225 999.145	30 _{7,23} –29 _{8,22} E	312	2.2	0.11	7.5(0.1)	0.9(0.3)	0.70	0.6(0.2)	9.1(0.1)	0.8(0.3)	0.45	0.4(0.1)

Notes. For the definition of the parameters see Table 10.

Table 4. Two-component analysis of methyl formate transitions observed with the IRAM Plateau de Bure Interferometer toward position MF4.

Frequency (MHz)	Transition	E_{up} (K)	$S\mu^2$ (D ²)	sigma (K)	v_1 (km s ⁻¹)	Component 1			v_2 (km s ⁻¹)	Component 2		
						$(\Delta v_{1/2})_1$ (km s ⁻¹)	$T_{\text{B}1}$ (K)	W_1 (K km s ⁻¹)		$(\Delta v_{1/2})_2$ (km s ⁻¹)	$T_{\text{B}2}$ (K)	W_2 (K km s ⁻¹)
223465.340	11 _{4,8} –10 _{3,7} E	50	2.1	0.17	8.0(0.1)	1.9(0.3)	3.83	7.7(2.5)	10.2(0.8)	3.7(1.0)	1.66	6.6(2.7)
223500.463	11 _{4,8} –10 _{3,7} A	50	1.8	0.17	8.0(0.1)	2.2(0.2)	1.90	4.4(0.4)	11.4(0.2)	2.2(0.3)	1.29	3.0(0.4)
223534.727	18 _{5,14} –17 _{5,13} E, ($v_t = 1$)	305	41.6	0.17	8.7(0.3)	3.0(0.4)	1.78	5.8(0.8)	11.0(0.4)	5.3(0.8)	1.34	7.6(0.9)

Notes. For the definition of the parameters see Table A.3 (in Appendix A).

take the partially blended line at 226 061.796 GHz into account. The linewidths observed here are slightly broader than those of components 1 and 2 at the MF1 peak. Because the lines are optically thin (see Sect. 4), this indicates a wider velocity spread in the source.

MF3: is a HCOOCH₃ emission peak located in-between the two previous clumps. It often appears as an extension of the emission, since most of our data do not allow us to isolate the emission peak. As for clumps MF1 and MF2, the linewidth is narrow; at 203 GHz and 223 GHz, $\Delta v_{1/2} \approx 1.7$ km s⁻¹. Table A.2 (in Appendix A) summarizes the line parameters for all detected, blended, or not detected transitions in all data sets. We detected 14 lines, and observed 3 partially blended and 26 blended lines, but 21 transitions were too faint to be detected. The methyl formate velocity is around 7.7 km s⁻¹.

MF4: is one of the main HCOOCH₃ emission peaks lying to the north of the Compact Ridge. Table A.3 (in Appendix A) summarizes the line parameters for all detected, blended, or not detected transitions in all data sets. We detected nine lines, and observed four partially blended and 28 blended lines, while 23 transitions were too faint to be detected. As for clump MF1, the high spectral resolution line profiles show two components (see Fig. 8). The 223 GHz methyl formate emission profiles are fitted with two components centered on 8.0 km s⁻¹ and 11.4 km s⁻¹ (Table 4). Both components have linewidths in the range ($\Delta v_{1/2} \approx 1.9$ –3.7 km s⁻¹).

MF5: lies near the emission peak MF4, and its size is similar to that of MF4. Two velocity components, visible with only high spectral resolution, are present in our data. However, we have not made any precise velocity identification of these

Fig. 8. Two HCOOCH₃ components observed toward the emission peak MF4. The black spectrum shows the 223 465.340 MHz transition and the gray spectrum the 223 500.463 MHz transition. Dashed lines mark $v_{\text{LSR}} = 8.0$ and 11.4 km s⁻¹.

components because they are more blended than those identified in the direction of MF4 and MF1. The unresolved emission is centered on 7.7 km s⁻¹. We detected nine methyl formate transitions and observed three partially blended and 28 blended lines, while 24 other lines were too faint to be detected. All results from all data sets are summarized in Table A.4 (in Appendix A).

3.6. Fraction of blended and detected lines

We mentioned earlier that spectral confusion is a major problem toward Orion-KL. Confusion increases with frequency, and it is more prevalent in our data at 223–225 GHz than at 101 GHz. Spectral confusion is present to some extent toward all the emission peaks identified in this work (MF1 to MF28).

We present here a rough estimate of the confusion level. From a visual inspection of our spectra, we believe that some line frequencies are contaminated by other lines, noted *a priori* as *blended*, whereas at other line frequencies the spectrum appears *free of contamination*. To determine which lines are detectable in our data set we used the simple one-temperature model derived in Sect. 4 and compared the expected line intensity to the noise level. Of the n_d *detectable lines*, a number, n_{db} , are *blended*, whereas $n_{df} = n_d - n_{db}$ others appear free of contamination.

For sources MF1, MF2, and MF3, all lines expected above 3 sigma and free of contamination are detected; this is a consistency check of the LTE model. To roughly quantify the effect of confusion in these sources we computed $\eta_D = n_{df}/n_d$. We obtain the following results for temperatures derived from our rotational diagrams (see following section):

- $\eta_D = 49\%$ at the MF1 peak for $T = 79$ K,
- $\eta_D = 40\%$ at the MF2 peak for $T = 130$ K,
- $\eta_D = 30\%$ at the MF3 peak for $T = 85$ K.

For sources MF4 and MF5, the presence of two velocity components makes the methyl formate lines broader and more difficult to detect. The number of detected lines is thus more imprecise, as for example some broad lines may be classified as blended instead of broadened by the dynamics. We get $\eta_D = 13\text{--}20\%$, which is coherent with an increase in the confusion for broader lines. Some of the fainter lines expected to be detectable from the LTE model are not seen, especially in the data cubes around 225 GHz, which we attribute to an increased interferometric filtering of the quasi vertical MF4-MF5 structure in these cubes (compare the two uv coverages in Fig. 1).

The meaning of η_D should not be overinterpreted because i) it depends on the LTE hypothesis, on the derived column density and temperature values, and on the expected line profile; ii) it is not intrinsic to a molecule in a given source as it also depends on the frequency range and other observation parameters (noise level, spectral, and spatial resolution, uv coverage). In addition that in the case of our dataset, the last parameters vary from one datacube to the next, so that η_D is only an average value. It is, however, a first indication of the relative importance of the confusion problem – a similar indicator was given by Belloche et al. (2008) for their search and detection of amino acetonitrile in Sgr B2(N).

4. Temperatures and abundance of methyl formate towards the whole molecular V-shape

From Rohlfs & Wilson (2000), the opacity at the line center can be calculated from

$$\tau = -\ln\left(1 - \frac{\Delta T_{mb}}{J(T_r) - J(T_{\text{continuum}}) - J(T_{bg})}\right), \quad (1)$$

where

- ΔT_{mb} is the excess brightness temperature observed on spectra,
- $J(T_r)$ the source function of the rotational brightness temperature,
- $J(T_{\text{continuum}})$ the source function of the continuum brightness temperature, and
- $J(T_{bg})$ the source function of the 2.7 K background brightness temperature.

We assumed that all the lines are optically thin (calculated opacities are generally less than 0.05 and at most 0.1) and that the

local thermodynamic equilibrium is reached for all positions (see Sect. 3.3), so that the kinetic temperature is equal to the excitation, rotational, and vibrational temperatures. We estimated the rotational temperature and the column density of HCOOCH₃ using the equation (Turner 1991):

$$\ln\left(\frac{3k_B W}{8\pi^3 \nu S \mu^2 g_i g_k}\right) = \ln\left(\frac{N}{Q}\right) - \frac{E_{up}}{k_B T}, \quad (2)$$

where

- W is the integrated line intensity (K km s^{-1}),
- ν the line frequency (Hz),
- $S \mu^2$ the line strength (D^2),
- g_i the reduced nuclear spin statistical weight,
- g_k the K -level degeneracy,
- N the total column density,
- Q the partition function,
- E_{up} the upper state energy, and
- T the excitation temperature.

Due to the CH₃ group, methyl formate is divided into two forms: A and E. Turner (1991) indicates that for A species: $g_i = 2$ and $g_k = 1$, and inversely for E species. We used $g_i g_k = 2$ for all the transition lines.

We made the rotational diagrams for two different spatial resolutions. One is based on the data with the highest spatial resolution (synthesized beam of $1.79'' \times 0.79''$ at 223 GHz). The other one includes data at 101 GHz, 203 GHz, and 225 GHz where the two first data sets are smoothed to the resolution of the third one (synthesized beam of $3.63'' \times 2.26''$) for the MF1 emission peak. The rotational temperatures and column density uncertainties, estimated by a least-square fit, are only based on the statistical weight of the detection measurements⁵ (upper limits are not taken into account by the fit). The derived column densities are corrected for the beam filling factor.

Rotational diagram at the MF1 peak. We made a rotational diagram for each velocity component. Figure 9 displays the diagrams obtained with the data at a $1.79'' \times 0.79''$ resolution (see Set No. 9 in Table 1) and Fig. 10 the diagrams obtained with the data at a $3.63'' \times 2.26''$ resolution (see Sets 7, 8, 10, 11 and 12 in Table 1). They show that the temperature of the 9.2 km s^{-1} component is higher (112 ± 50 K at high resolution and 168 ± 30 K at a lower resolution) than that of the 7.6 km s^{-1} component (79 ± 2 K at high resolution and 119 ± 10 K at a lower resolution). We also note for both components that the temperatures are lower with the high spatial resolution, suggesting an external heating of the clump. The rotational diagram taking both components into account leads to an average rotational temperature of 100 K.

The derived column densities are given in Table 5. The column density derived with a high spatial resolution is higher than derived with a lower spatial resolution.

Rotational diagram at the MF2 peak. Both rotational diagrams, for angular resolutions of $1.79'' \times 0.79''$ and $3.63'' \times 2.26''$ (see Sets 9 and 3, 7, 8, 10, 11, 12 in Table 1), give comparable rotational temperatures, within the uncertainties. We obtain 128 ± 9 K and 140 ± 14 K (see Fig. 11). The derived methyl formate column densities are given in Table 5.

⁵ Error bars only reflect the uncertainties in the Gaussian fit of the lines. Some points overlap because they correspond to lines with the same upper energy level E_{up} .

Fig. 9. Rotational diagram of the first (*top*) and the second (*bottom*) components toward the MF1 peak, based only on data observed with a synthesized beam of $1.79'' \times 0.79''$. Dots and squares with error bars mark detected and partially blended lines in the fundamental and first excited states $v_t = 0$ and $v_t = 1$, respectively, filled triangles mark undetected lines and open triangles blended lines. The red line is the fit according to the method described in Sect. 4. The derived temperatures are 79 ± 2 K and 112 ± 50 K.

Rotational diagram at the MF3 peak. The rotational temperature derived at a higher resolution is lower (85 ± 3 K) than at a lower resolution (103 ± 3 K) (see Fig. 12), suggesting external heating like for the MF1 peak. The derived methyl formate column densities are given in Table 5.

Rotational diagram at the MF4 peak. At 223 GHz, two velocity components are present as for the MF1 peak. Though two different upper energies are available, no rotational diagram at the resolution of $1.79'' \times 0.79''$ has been made because of the important error bars in the velocity decomposition. Figure 13 shows the rotational diagram at a $3.63'' \times 2.26''$ resolution. The derived gas temperature and column density are given in Table 5.

Rotational diagram at the MF5 peak. As for the MF4 peak and from the same above-mentioned argument, no rotational diagram was made at the resolution of $1.79'' \times 0.79''$. Figure 14 shows the rotational diagram at a $3.63'' \times 2.26''$ resolution. The derived gas temperature and column density are given in Table 5. These values are close to those found at the nearby MF4 position.

Fig. 10. Rotational diagram of the first (*top*) and the second (*bottom*) components toward the MF1 peak, based only on data observed with a synthesized beam of $3.63'' \times 2.26''$. Dots and squares with error bars mark detected and partially blended lines in the fundamental and first excited states $v_t = 0$ and $v_t = 1$, respectively, and filled triangles mark undetected lines and open triangles blended lines. The red line is the fit according to the method described in Sect. 4. The derived temperature is 119 ± 10 K and 168 ± 30 K, respectively.

The different temperatures obtained at different positions (MF1 to MF5) are most likely due to different physical conditions (see Sect. 8). When we compare the methyl formate emission from different energy levels (see Fig. 15), it is noticeable that the emission at the MF1 position is much stronger for low upper state energies than at MF2. The emission at MF2 becomes stronger at higher energy levels.

5. Comparison with the other C₂H₄O₂ isomers

Methyl formate (HCOOCH₃), acetic acid (CH₃COOH), and glycolaldehyde (CH₂OHCHO) are three isomers among which acetic acid is the most stable. In a recent paper, Lattalais et al. (2009) have argued that the abundance ratio of isomers could be linked to their relative stability, except for some species such as methyl formate. Indeed, whereas methyl formate is known to be abundant in many molecular cores, glycolaldehyde has only been detected toward Sgr B2 (e.g. Hollis et al. 2000; Halfen et al. 2006) and acetic acid is barely detected in hot cores (e.g. Shiao et al. 2010).

We searched for acetic acid and glycolaldehyde in our data sets (from upper energy levels of 18 K up to 452 K and of 25 K up to 646 K, respectively), using Ilyushin et al. (2008) for the acetic acid frequencies, but we detect neither of them. Assuming

Table 5. HCOOCH₃ beam-averaged column densities derived towards the emission peaks MF1 to MF5 for two angular resolutions.

Emission peaks	v^a (km s ⁻¹)	T_{rot}^b (K)		$N_{\text{HCOOCH}_3}^b$ (10 ¹⁶ cm ⁻²)	
		(1.79'' × 0.79'')	(3.63'' × 2.26'')	(1.79'' × 0.79'')	(3.63'' × 2.26'')
MF1	7.6	79 ± 2	119 ± 10	16.0 ± 1.0	3.0 ± 0.1
MF1	9.2	112 ± 50	168 ± 30	6.8 ± 2.1	1.6 ± 0.1
MF2	7.7	128 ± 9	140 ± 14	16.0 ± 2.0	7.0 ± 0.4
MF3	7.7	85 ± 3	103 ± 3	4.6 ± 0.3	5.5 ± 0.1
MF4	8.2	–	108 ± 4	–	4.5 ± 0.2
MF5	7.8	–	111 ± 4	–	5.8 ± 0.1

Notes. ^(a) Towards MF1 and MF4 two different velocity components are identified but separate rotational diagrams could only be made for MF1 (see text) – for the other sources, velocity is a mean value of detected lines (see Tables A.1, A.2, and A.4 for details).
^(b) Error bars reflect only the uncertainties in the Gaussian fit of the lines.

Fig. 11. Rotational diagrams toward the MF2 peak based only on data observed with a beam of 1.79'' × 0.79'' (top) and a beam of 3.63'' × 2.26'' (bottom). Dots and squares with error bars mark detected and partially blended lines in the fundamental and first excited states $v_t = 0$ and $v_t = 1$, respectively, and filled triangles mark undetected lines and open triangles blended lines. The red line is the fit according to the method described in Sect. 4. The derived rotational temperatures are 128 ± 9 K and 140 ± 14 K.

Fig. 12. Rotational diagrams toward the MF3 peak based only on data observed with a beam of 1.79'' × 0.79'' (top) and a beam of 3.63'' × 2.26'' (bottom). Dots and squares with error bars mark detected and partially blended lines in the fundamental and first excited states $v_t = 0$ and $v_t = 1$, respectively. Filled triangles mark undetected lines and open triangles blended lines. The red line is the fit according to the method described in Sect. 4. The derived rotational temperatures are 85 ± 3 K and 103 ± 3 K, respectively.

the rotational temperatures derived from our HCOOCH₃ study, we calculated upper limits for the column densities of these isomers at the MF1 and MF2 positions (Table 6). We find that the abundance of acetic acid is at least 50 times less than the methyl formate one and the abundance of glycolaldehyde at least 200–500 times less.

6. Dust emission and characteristics of main clumps

Figure 2 shows that the continuum emission in the 101 to 225 GHz range is strong, extended, and clumpy in places from the highest frequency. In this section we use the high spatial resolution and high signal-to-noise ratio achieved at 223 GHz (see Fig. 16) to estimate, for the main clumps of dust emission,

Fig. 13. Rotational diagram toward the MF4 peak based only on data observed with a synthesis beam of $3.63'' \times 2.26''$. Dots and squares with error bars mark detected and partially blended lines in the fundamental and first excited states $v_l = 0$ and $v_l = 1$, respectively. Filled triangles mark undetected lines and open triangles blended lines. The red line is the fit according to the method described in Sect. 4. The derived rotational temperature is 108 ± 4 K.

Fig. 14. Rotational diagrams toward the MF5 peak based only on data observed with a synthesis beam of $3.63'' \times 2.26''$. Dots and squares with error bars mark detected and partially blended lines in the fundamental and first excited states $v_l = 0$ and $v_l = 1$, respectively. Filled triangles mark undetected lines and open triangles blended lines. The red line is the fit according to the method described in Sect. 4. The derived rotational temperature T is 111 ± 4 K.

their masses, the mean projected H₂ column density, and the H₂ volume density. By combining our line results with our N_{H_2} estimates, we go on to derive the relative abundance of the methyl formate molecule.

There are four main dust clumps in our 223 GHz map (Fig. 16): two, Cb and Ca, lie in the Compact Ridge and the Hot Core near the methyl formate peaks MF1 and MF2, respectively; Cc, in the north lies near MF4 and MF5; another clump, Cd, lies in the south near MM23. Each clump exhibits a complex spatial structure that is not fully revealed even with our $1.79'' \times 0.79''$ spatial resolution. In the Compact Ridge, for instance, we have identified toward MF1 two clear continuum maxima (labeled Cb₁ and Cb₂ in Fig. 16), which we consider, however, as one “single clump” (Cb). Ca, Cc, and Cd are most probably not single entities either, but we will consider them as roughly Gaussian clumps in our subsequent analysis.

Fig. 15. HCOOCH₃ intensity maps integrated in velocity between 6 and 9 km s⁻¹. The line frequency and the upper state energy are indicated on each plot. The methyl formate emission is stronger towards MF1 than MF2 for low upper energy transitions, while the opposite is verified for high upper state energies.

Table 6. Upper limits of column densities derived for acetic acid and glycolaldehyde from our PdBI data sets.

Emission peak	Temperature (K)	Beam (″ × ″)	N (cm ⁻²)
CH₂OHCHO			
MF1	78	1.79×0.79	$\leq 2.4 \times 10^{14}$
MF1	120	3.79×1.99	$\leq 2.8 \times 10^{14}$
MF2	128	1.79×0.79	— ^a
MF2	140	3.79×1.99	$\leq 3.5 \times 10^{14}$
CH₃COOH			
MF1	78	1.79×0.79	$\leq 1.8 \times 10^{15}$
MF1	120	3.79×1.99	$\leq 1.2 \times 10^{15}$
MF2	128	1.79×0.79	$\leq 2.6 \times 10^{15}$
MF2	140	3.79×1.99	$\leq 1.4 \times 10^{15}$

Notes. (a) All the glycolaldehyde lines are blended, so that the upper limit is not significant.

We first give below details on the equations used to derive the mean clump properties.

The flux density, S_ν , from a dust cloud at frequency ν is given in the optically thin case by

$$S_\nu \approx \tau B_\nu(T_d)\Omega, \quad (3)$$

where τ is the dust opacity at frequency ν , $B_\nu(T_d)$ the Planck function, T_d the dust temperature, and Ω the dust cloud solid angle. Estimating the dust column density and mass from the observables S_ν and Ω requires a dust opacity model and knowledge of the variation in the extinction efficiency with frequency. This variation strongly depends on the wavelength range, the dust composition, and its temperature. Mathis et al. (1977) suggested that the visible and UV interstellar extinction can be reproduced with a mixture of graphite and silicate grains, and their model was extended to the infrared by Draine & Lee (1984). Draine & Lee (1984) showed that a mixture of silicate and graphite explains the NIR and FIR observations rather well and they showed

Table 7. Beam averaged density and methyl formate relative abundance at 223 GHz continuum and molecular peaks.

Continuum source	RA (J2000) 05 ^h 35 ^m	Dec (J2000) −05°22′	Adopted T_d (K)	s_ν^a (Jy beam ^{−1})	$\langle N_{H_2} \rangle^b$ (10 ²⁴ cm ^{−2})	$\langle n_{H_2} \rangle^c$ (10 ⁸ cm ^{−3})	$\langle N_{HCOOCH_3}/N_{H_2} \rangle^d$ (10 ^{−8})
Ca	14 ^h 56	31 ^m 50	200	0.49	5.4	7.3	at continuum peak
			130	0.18	3.1	4.2	at MF2 molecular peak
Cb	Cb ₁ 14 ^h 08	36 ^m 73	80	0.18	5.0	6.8	at continuum peak
	Cb ₂ 14 ^h 01	37 ^m 24	80	0.18	5.0	6.8	at MF1 molecular peak
Cc	14 ^h 08	27 ^m 50	110	0.12	2.4	3.3	≤0.6 at continuum peak
			110	0.08	1.6	2.2	≤0.2 at MF4 molecular peak
			110	0.08	1.6	2.2	≤0.5 at MF5 molecular peak
Cd	14 ^h 03	44 ^m 60	105	0.17	3.6	4.9	≤0.1 at continuum peak
			105	0.17	3.6	4.9	≤0.1 at MM23 molecular peak

Notes. ^(a) Flux density per beam or brightness temperature; ^(b) estimated in a beam size of 1.79'' × 0.79''; ^(c) estimated in a beam size of 1.79'' × 0.79'' at a distance of 414 pc (Menten et al. 2007); ^(d) estimated at continuum and associated molecular peaks. The methyl formate column densities are derived from this work.

Fig. 16. Continuum emission map obtained with the IRAM Plateau de Bure Interferometer at 223.67 GHz. The level step is 60 mJy beam^{−1} (3.5 σ) for a beam size of 1.8'' × 0.8''. Dark crosses label the 4 different continuum components, while points label the main molecular HCOOCH₃ emission peaks.

that the FIR opacity varies as λ^{-2} where λ is the wavelength. Of particular interest here is their estimate of the dust opacity at 125 μ m as a function of the visual absorption or the projected H gas density N_H . They obtain $\tau = 4.6 \times 10^{-25} N_H$ (cm^{−2}), which we extrapolate to the mm-wavelength regime, assuming that the extinction varies as λ^{-2} ,

$$\tau = 1.4 \times 10^{-26} \frac{N_{H_2}(\text{cm}^{-2})}{\lambda^2(\text{mm}^2)}, \quad (4)$$

where we further assume the relation holds for molecular hydrogen with $N_H \approx 2N_{H_2}$.

We are aware that the Draine & Lee (1984) data are fairly typical of diffuse interstellar clouds and that dust coagulation as described by Ossenkopf & Henning (1994) for protostellar cores could be more appropriate. For an assumed central luminosity and outer envelope radius, the dust mass derived from a 1D fit

of the derived fluxes to the observed spectral energy distribution of the massive protostellar object W3IRS5 is three times lower with the Ossenkopf & Henning (1994) opacity profile than with the Draine & Lee (1984) profile (Luis Chavarria, priv. comm.). However, the Ossenkopf & Henning (1994) opacities may be uncertain by a factor of at least 2 due to changes in the physical conditions and, given the additional dust to mass ratio uncertainty, derivation of the total gas mass in protostellar cores remains uncertain.

In this work we adopt a simple approach and combine Eqs. (3) and (4) to derive the H₂ projected density in a straightforward manner, hence the total mass. Using the observed peak flux density per synthesized beam, s_ν in Jy beam^{−1} (or source brightness temperature in K), and the Rayleigh-Jeans approximation, we derive, for the mean observing frequency of 223.65 GHz (1 Jy beam^{−1} = 17.3 K, for a HPBW of 1.79'' × 0.79''), the beam averaged projected density from

$$\langle N_{H_2} \rangle = 2.22 \times 10^{27} \frac{s_\nu(\text{Jy beam}^{-1})}{T_d(\text{K})}. \quad (5)$$

Assuming, for simplicity, that the dust clump is Gaussian with peak flux density s_ν and size $\theta_1 \times \theta_2$ determined from the 2D Gaussian fits to the source half peak flux density, we derive the total gas mass in the entire Gaussian clump from the following equation (taking a mean molecular weight of 2.33 and adopting 414 pc as the Orion KL distance):

$$M_{\text{gas}}(M_\odot) \approx 188.7 \times \frac{s_\nu(\text{Jy beam}^{-1})}{T_d(\text{K})} \times \theta_1('') \times \theta_2(''). \quad (6)$$

We use this equation to obtain the total gas mass present in our clumps (see Table 8).

All relevant gas clump parameters are gathered in Tables 7 and 8. They include the positions and names of the four main dust clumps, as well as the adopted dust temperature (see details below), the peak flux in Jy beam^{−1}, the projected and volumic densities, and see last 3 columns in Table 8, the clump sizes, total flux density, and estimated total gas mass within the identified clumps. The methyl formate relative abundance at continuum and molecular peaks is also given in the last column of Table 7.

The dust temperature is a crucial parameter in all of the above calculations. To estimate T_d we assume that (a) the gas-dust relaxation time is short (Draine 2010; Tielens 2005); and (b) the gas temperature is close to the rotational temperature T_r

Table 8. Dust clump half sizes, total flux density, and total gas mass within the dust clumps.

Continuum source	Nearby molecular peak	Adopted T_d (K)	Adopted clump surface ^a (″ × ″)	M_{gas} ($M_{\odot}$)	S_{total} (Jy)
Ca	MF2	200	5.0×2.5	5.8	3.9
Cb ^b	MF1	80	4.0×2.5	4.3	1
Cc	MF4, MF5	110	2.6×1.5	0.8	0.45
Cd	MM23	105	3.0×1.5	1.4	0.8

Notes. ^(a) Taken at half size; ^(b) overall structure including C_{b1} and C_{b2}.

deduced from our methyl formate data. The gas-dust relaxation time is roughly given by $4 \times 10^{16} \text{ s}/T_K^{0.5} n_{\text{H}_2} (\text{cm}^{-3})$, which is ≤ 130 years for $n_{\text{H}_2} \gtrsim 10^6 \text{ cm}^{-3}$ and T_K around 100 K; therefore, dust thermalization should be verified well in Orion. The value of T_r is determined fairly well from our LTE multi-line analysis. It is therefore reasonable to assume that both (a) and (b) are verified, hence $T_d \approx T_r$. Another complication arises because T_d is not uniform throughout Orion as demonstrated by our continuum maps, and our continuum and line peaks do not match exactly. The values of T_d adopted here are given in Tables 7 and 8. They are taken from the rotational temperature obtained for the main gas peaks MF1, MF2, MF4, MF5, and MM23. There is also some uncertainty at the continuum peaks near both MF2 and MM23 because only three and two methyl formate lines were unambiguously detected in these directions (while many lines are present at the molecular peaks). In this case we used our best judgement to estimate T_r and thus T_d .

The beam-averaged projected density N_{H_2} lies in the range 2 to $5 \times 10^{24} \text{ cm}^{-2}$ corresponding to very large visual extinctions. The latter density is used to derive the volumic H₂ density across the synthesized beam projected at the 414 pc distance of Orion-KL; it lies in the range 2 to $7 \times 10^8 \text{ cm}^{-3}$. Our derived densities are much higher than those found in the literature (e.g. Irvine et al. 1987; Persson et al. 2007; Mezger et al. 1990). However, our spatial resolution is higher and the densities are similar if we take the beam dilution into account. Moreover, we find similar H₂ density values when we use the continuum map of Beuther et al. (2004) and use their source and dust properties hypothesis.

Our individual clump masses vary from about 1 to 5 solar masses. We stress that these individual masses cannot be highly accurate for various reasons. First, any T_d uncertainty is directly translated into a mass uncertainty in our mass equations. Second, an uncertainty in the opacity wavelength dependence also results in a mass uncertainty; for instance, at 1.3 mm there is a 30% mass change when the extinction varies from a λ^{-2} dependence to λ^{-1} . Third, as explained earlier, our clumps might not be Gaussian, and our observed spatial structure might be even clumpier than reported here. Another way to estimate our mass uncertainty is to derive the total gas mass for the entire clump from the equation, $M_{\text{gas}}(M_{\odot}) \approx 270 \times \frac{S_{\nu}(\text{Jy})}{T_d(\text{K})}$, where S_{ν} is the flux density measured in Jy in our calibrated maps (see last column in Table 8). The derived masses differ from those obtained with Eq. (6) by about 9% to 30%. Despite these uncertainties, we estimate that the total mass derived for all clumps identified here, about 12 solar masses, is meaningful. This mass reservoir could well be used in future star-forming activity.

In the last column of Table 7 we also give the methyl formate relative abundance averaged over the synthesized beam in the direction of the 223 GHz dust emission peaks and of the molecular

peaks. The relative abundances lie in the range $\leq 0.1 \times 10^{-8}$ to 5×10^{-8} and show variations from one peak to another. Toward Cc and Cd, there are not enough detected molecular lines to estimate a precise methyl formate column density, and we only give upper limits of the relative abundance. Toward Cb there is no difference in abundance between the molecular and continuum peaks, while there is a marked difference in the relative abundances measured toward the Hot Core (Ca) and the associated Hot Core-SW molecular peak (MF2). The largest methyl formate relative abundances are observed toward MF2 and MF1.

7. Comparison with previous studies

In this section we try to relate our results to some of the most comparable and recent studies of Orion-KL. The large number of published works devoted to this region prevents us from being exhaustive. Therefore, we limit ourselves to the high ($<10''$) resolution studies of the continuum emission and methyl formate emission. There is general agreement on space and velocity distribution and on column densities derived; however, our data show more details due to higher spatial and/or spectral resolution.

Methyl formate temperatures were often not derived by previous authors from their interferometric studies so we also quote other temperature indicators at high resolution for reference: dust color temperature, and methanol (CH₃OH) and methyl cyanid (CH₃CN) rotational temperatures. Methanol is interesting because this O-bearing species may be formed on grains (e.g. van der Tak et al. 2000) like methyl formate, and as stated previously, it may also be a precursor of methyl formate. It may, however, suffer from opacity problems, and its excitation is often more complex than LTE (see e.g. Menten et al. 1988; Leurini et al. 2004). Methyl cyanide is a well-known probe of kinetic temperature (Boucher et al. 1980). But N-bearing species have a different distribution, so that temperatures derived from these molecules may thus differ from those derived from methyl formate.

Much work has been done, on the other hand, with single-dish telescopes towards Orion-KL, and large surveys allow for the determination of a temperature of the region averaged over the beam and sometimes for a decomposition into a few spectral features identified from their velocity profiles. We quote previous results on methyl formate and methanol but avoid, however, studies most affected by optical thickness effects. The HCOOCH₃ temperatures we derive fall in the 60–220 K range found in these studies.

7.1. High-resolution continuum maps

Our 1.3 mm continuum map differs from the Hot Core maps obtained with the SMA at 345 GHz and 690 GHz by [Beuther et al. \(2004, 2006\)](#) because we do not see any emission peak on source I and SMA1. [Beuther et al. \(2004\)](#) and [Beuther et al. \(2006\)](#) maps already show differences between each other. This could come from the different spatial resolutions and/or to the different *uv* coverages used in these two works. Finally, the SMA 870 μm dust continuum maps of [Tang et al. \(2010\)](#) is much similar to our 223 GHz map obtained with a $1.79'' \times 0.79''$ resolution. Our map covers a more extended region of the southern Compact Ridge, but all other clumps observed by us along the Ridge up to BN are also detected in the $0.8'' \times 0.7''$ SMA map. As also suggested by our 1.3 mm map, the 870 μm dust emission map shows that there are at least two clumps in the Hot Core region. From their polarization study of the Hot Core and Compact Ridge, [Tang et al. \(2010\)](#) suggest that the magnetic field is regulating star formation on large physical scales. As a result, all clumps identified here are probably intimately related to the Orion large-scale magnetic field.

7.2. High-resolution studies of methyl formate distribution and temperature

Our methyl formate emission peaks MF1, MF2, and MF4-5⁶ are also present in the interferometric maps of [Friedel & Snyder \(2008\)](#) and [Beuther et al. \(2005\)](#), but the MF3 and MF4 peaks are less obvious in their data. Their maps, like ours, do not show any emission of this molecule towards the Hot Core around 5 km s^{-1} .

The methyl formate observations of [Friedel & Snyder \(2008\)](#) made with the CARMA interferometer with a $2.5'' \times 0.85''$ beam size also reveal components at 7.6 km s^{-1} and 9.3 km s^{-1} towards the Compact Ridge region⁷. However, the authors do not separate the two velocity components to derive the temperature and the column density. Their results agree with ours if we do not separate the two HCOOCH_3 spectral components: $T_{\text{rot}} = 101 \text{ K}$ and $N_{\text{HCOOCH}_3} = 1.5 \times 10^{17} \text{ cm}^{-2}$. Moreover methyl formate emission towards the Compact Ridge region has also been observed with BIMA by [Liu et al. \(2002\)](#) and [Remijan et al. \(2003\)](#). Their spatial and spectral resolutions do not allow them to see the two velocity components, and they derive a temperature and a column density similar to those found by [Friedel & Snyder \(2008\)](#) and to ours when we combine the two components into one.

[Hollis et al. \(2003\)](#) also imaged methyl formate at high resolution ($2.9'' \times 1.6''$) using the VLA at 45 GHz. The very low ($E_u = 6 \text{ K}$) energy of the upper state of the transition they observed shows that emission from the Compact Ridge is dominant, thus confirming the trend shown in our Fig. 15. Despite their very good spatial resolution, their limited spectral resolution (1.36 km s^{-1} channel separation) allows them to detect only two broad peaks besides the Compact Ridge, corresponding to our MF2 and MF4-5 peaks. At the Compact Ridge peak (MF1), again summing up our two velocity components, our column density agrees with their value derived for a temperature of 100 K.

The interferometric map of methyl formate at $2'' \times 1.5''$ resolution integrated over velocities obtained with the Owens Valley

interferometer by [Blake et al. \(1996\)](#) shows a reasonable, general agreement with ours. Hot Core-SW and MF4-5 (IRc6) peaks are displaced from ours by $<1''$, and their Compact Ridge peak lies $1.5''$ North of MF1. The emission around MF4-5 (IRc6) appears more intense and more extended, with peaks displaced by $\sim 1''$ compared to ours.

7.3. Other temperature determinations

7.3.1. From dust infrared emission

Our temperature estimates lie in the range 80–170 K, which is close to the range of (color) dust temperatures found by [Wynn-Williams et al. \(1984\)](#) from their 30 μm and 20 μm measurements, but they are lower than the temperatures they derive at shorter (and more optically thick) wavelengths. However, the temperature variations observed by [Wynn-Williams et al. \(1984\)](#) between the Hot Core, the Compact Ridge, and IRc6 (MF4-5) are not ordered like in our study. This may be the remaining opacity effects in the mid-infrared. In a more recent work [Robberto et al. \(2005\)](#) derive color temperatures in Orion-KL (excepting BN) of 125–140 K from 10 and 20 μm observations, and higher values (200–230 K) from silicate features, using a simple “two-component” model for the IR emission.

7.3.2. From methanol and methyl cyanide high-resolution studies

A comparison of our results with the temperatures derived from previous interferometric works on methanol (CH_3OH) by [Beuther et al. \(2005\)](#) cannot be done toward the Compact Ridge and the Hot Core-SW because, unfortunately but not surprisingly, our two strongest methyl formate peaks correspond to areas where methanol is optically thick. It is only in the direction of MF4-MF5 (IRc6) that we observe some overlap with their temperature map. They find a somewhat higher temperature, around 180–240 K to be compared with our $\sim 110 \text{ K}$. Methanol emission is more extended than methyl formate and does not sample exactly the same gas, and methanol may be formed at least in part in the gas phase (e.g. [Plambeck & Wright 1988](#)); likewise, a methanol maser has been identified by these authors at IRc6.

As N-bearing and O-bearing molecules clearly do not share the same spatial and velocity distribution (see e.g. their position velocity diagram showing the much broader velocity range of CH_3CN emission), no simple comparison can be made of our work with the higher temperature values recently obtained by [Wang et al. \(2010\)](#) using CH_3CN (190–620 K in the Hot Core and 170–280 K in the Compact Ridge).

Our temperatures and column densities derived from the analysis of the MF1 emission peak suggest an external heating towards the Compact Ridge. It is interesting to mention that recently [Zapata et al. \(2011\)](#) have also found some evidence for external heating towards the Hot Core. These two dense regions of the Orion-KL nebula seem to be associated with the dynamical event that occurred 500 years ago.

7.3.3. From single-dish methyl formate and methanol studies

From a single-dish measurement of the optically thin isotopologue $^{13}\text{CH}_3\text{OH}$ [Blake et al. \(1984\)](#) derived a rotational temperature of 120 K averaged over their $30''$ beam. This is close to the 140 K derived for CH_3OH by [Johansson et al. \(1984\)](#) with a similar beam. [Blake et al. \(1987\)](#), also in a $30''$ beam,

⁶ The MF5 emission peak corresponds to the IRc6 position in [Friedel & Snyder \(2008\)](#) and [Beuther et al. \(2005\)](#).

⁷ The Compact Ridge position defined in [Friedel & Snyder \(2008\)](#) is not the same as used in this study. Their IRc5 position is closer to our Compact Ridge position ($1.5''$ away).

have attributed the methanol and methyl formate emissions to the Compact Ridge and derived rotational temperatures of 146 ± 3 K and 90 ± 10 K, respectively, whereas a temperature of 166 ± 70 K was found in the Hot Core from their H₂CO data. Within a ~ 22 – $28''$ beam Menten et al. (1988) have derived from their CH₃OH and ¹³CH₃OH observations rotational temperatures of 109–147 K and 33 K respectively. Their CH₃OH line profiles are interpreted as the superposition of a broad and a narrow component (the former marginally warmer by 10–20 K). This interpretation, aimed both at thermal emission and maser excitation, suggests that infrared radiation from the dust plays an important role in exciting methanol in addition to collisions. From a 325–360 GHz survey made with 20'' resolution, Schilke et al. (1997) found rotational temperatures of 188 ± 3 K (methanol) and 98 ± 3 K (methyl formate). More recently, at 350 μ m and with a 11'' beam Comito et al. (2005) infer 220 K for the Hot Core, and 160 K for the Compact Ridge from CH₃OH lines, and an almost identical value (220 K and 155 K) from H₂CO. A somewhat lower temperature, 61 K, was found in a 40'' beam for methyl formate by Ziurys & McGonagle (1993).

Very recently, Herschel observations of ¹³CH₃OH (and CH₃OH) at 534 GHz and 1061 GHz made by Wang et al. (2011) have determined $T_{\text{rot}} = 105 \pm 2.6$ K (resp. $T_{\text{rot}} = 125 \pm 2.8$ K) in the Compact Ridge, which was isolated from other spatial components in the 43'' and 20'' Herschel beams thanks to its velocity profile. A more elaborated transfer model developed for a spherical source with a temperature gradient provides a very good fit to the methanol population diagram of the Compact Ridge at both frequencies if it is externally heated. This conclusion agrees well with our findings.

8. Discussion on methyl formate distribution and Orion structure

The Orion-KL region is located about 1' from the Trapezium OB stars at the heart of a large stellar cluster still in formation. Many remarkable objects have been identified in this region (see e.g. reviews by Irvine et al. 1987; Genzel & Stutzki 1989; O'Dell et al. 1993; O'Dell 2001; O'Dell & Henney 2008; O'Dell et al. 2009). In this section, we primarily try to correlate the HCOOCH₃ distribution with several optical, NIR, MIR, X, radio continuum, and radio line data, with the help of the ALADIN software⁸ (Bonnarel et al. 2000) and the SIMBAD database⁸. We focus our discussion on the Compact Ridge and Hot Core regions as they contain the main methyl formate peaks in Orion-KL (MF1 and MF2, respectively).

8.1. Stars and YSOs

Orion-KL is a complex region, with a very high density of YSOs (young stellar objects) and recently formed stars.

Putting together the remarkably detailed NIR pictures of Stolovy et al. (1998) and D. Rouan (priv. comm.), together with the X picture (Getman et al. 2005; Grosso et al. 2005) and previous IR work (Greenhill et al. 2004; Hillenbrand & Carpenter 2000; Lonsdale et al. 1982; Muench et al. 2002), and including the IR polarization work of Simpson et al. (2006), we have been able to identify more than 34 probable stars or forming stars in the 0.5' region of methyl formate emission in

Fig. 17. Positions of the IRC sources identified by Shuping et al. (2004) on the methyl formate integrated intensity map (see Fig. 4).

Fig. 4. In this 0.058 pc wide field, this means a projected density of 156 objects arcmin⁻² (1 object every $\sim 5''$) or 10^4 objects pc⁻². For comparison, Lada et al. (2004) determined stellar projected densities for deeply embedded sources reaching up to 3000 star pc⁻² south of Orion-KL (this would mean 10 objects in the same 0.5' region of Fig. 4). For less embedded stars close to the Trapezium, the observed projected density is twice higher, up to 6000 star pc⁻². With such a high density, one should always keep in mind the possibility of chance projection effects in the following spatial comparisons.

On small distance scales (a few '' or 1000–2000 AU) and with the exception of Parenago 1822/LBLS k at the center of the Compact Ridge (see discussion below), little correlation is seen between the methyl formate (MF) peaks and the stellar objects. Almost no association is obvious either with the IRC sources, as seen in Fig. 17, which shows the position of the IRC sources from Shuping et al. (2004) with respect to the methyl formate emission. On larger scales ($\geq 10''$ or 4500 AU), it seems, as discussed below, that the methyl formate distribution is closely linked to the presence of a few remarkable objects, in particular the “low-velocity” SiO outflow whose origin is attributed to radio source I by Goddi et al. (2009) and Plambeck et al. (2009), and linked to the matter (traced in CO and H₂) ejected during the recent (~ 500 yr) stellar collision or close interaction between the B-type star BN, and the I and n objects (at least) as proposed by, e.g., Zapata et al. (2009). Long-range effects of heating, photodissociating photons, or shocks are also possible from BN itself and source n. Our data do not allow us to separate the respective effects of source I from source SMA1, which has recently been identified by Beuther & Nissen (2008) as another candidate source for the high-velocity CO and H₂ outflow.

8.2. HCOOCH₃ and the “low-velocity” SiO outflow

As shown in Fig. 18 there is a striking complementarity of the 87 GHz SiO $v = 0$ $J = 2-1$ line map from Plambeck et al. (2009) with our methyl formate distribution because the SiO fills the hole in the HCOOCH₃ distribution. We consider that this is not fortuitous and that it points to some kind of direct connection between both species. The SiO traces the large “low-velocity”

⁸ Centre de Données Astronomiques de Strasbourg, see: <http://aladin.u-strasbg.fr/aladin.gml> and <http://simbad.u-strasbg.fr/simbad/>.

Fig. 18. HCOOCH_3 contours (in black) overlaid over the $\text{SiO } J = 2-1$ $v = 0$ map (red contours) by Plambeck et al. (2009).

outflow emanating from radio source I. As shown by various proper motion studies (Gómez et al. 2005; Rodríguez et al. 2005; Goddi et al. 2011), source I is moving to the southeast (bottom left).

The HCOOCH_3 distribution near MF2 (Hot Core-SW) may be due, to a large extent, to the recent sidewise “encounter” of this outflow with quiet dense gas resulting in shocks, which in turn disrupt icy grain mantles and release new molecules. The Hot Core region would then be the prominent result of this sidewise encounter. With this picture in mind, one expects a recent major increase in the release of molecules from grains in the Hot Core region and in the eastern side of the large-scale V-shaped region mapped in MF in this work.

The Compact Ridge methyl formate distribution also matches the shape of the SiO outflow. In this area, the interaction is more frontal, the outflowing matter arriving more or less perpendicular at the border of the quiescent gas. The SiO outflow could be older than the stellar collision event. In that case the shock at the Compact Ridge would be older than the collision and only be modified by the recent motion of source I. Alternatively, the outflow could be linked to the stellar collision, or its trajectory might have encountered the Compact Ridge gas because of the recent proper motion of source I. In the first case, the release of molecules from grains would be older than 500 yr, and in the second case it would be more recent. Such a connection between the “low-velocity” outflow and the Compact Ridge was proposed earlier (see e.g. Irvine et al. 1987).

A shock from the I outflow can either release CH_3OH rich ices, followed by gas-phase chemistry leading to HCOOCH_3 formation (Charnley & Rodgers 2005), or directly release HCOOCH_3 formed on the grain (Garrod & Herbst 2006). The detailed chemical modeling is beyond the scope of the present study.

8.3. HCOOCH_3 and IR $11 \mu\text{m}$ map

In Fig. 19 we compare the methyl formate distribution with the $11 \mu\text{m}$ map of Smith et al. (2005). There is a clear trend for the MF emission peaks to lie outside the bright $11 \mu\text{m}$ regions – it is especially true for the eastern branch of the V-shaped MF emission, which encompasses the Hot Core MF2 and goes

Fig. 19. The HCOOCH_3 emission contours from MF7 to MF10, closely following a black zone where $11 \mu\text{m}$ IR emission is lacking (Smith et al. 2005).

from MF7 to MF10. A notable apparent exception to this anti-correlation (but see below) is the main source MF1 located in the Compact Ridge.

It has long been noted that there is a tendency for some molecular emission in Orion-KL, in particular NH_3 , to be anticorrelated with mid-IR emission (e.g. Genzel & Stutzki 1989; Wynn-Williams et al. 1984). Recently, Shuping et al. (2004) has reached a similar conclusion from their high-resolution mid-IR map and the NH_3 high-resolution map of Wilson et al. (2000), and they suggest that the NH_3 emission comes from a foreground layer of interstellar matter, which is cold and dense enough to be seen in the mid-IR as an absorbing dark lane against a brighter background.

We propose that most of the methyl formate emission seen in places of low $11 \mu\text{m}$ emission also originates in this dark foreground material. In the case of MF1 in the Compact Ridge, there are indications that the methyl formate layer is also in the foreground material, but is thin enough to let the IR background radiation to be seen through it (see discussion on excited H_2).

8.4. HCOOCH_3 and $2.12 \mu\text{m}$ H_2 emission

MF1: a most striking spatial correlation is observed between the methyl formate distribution at the MF1 peak and the $2.12 \mu\text{m}$ H_2 emission imaged by Lacombe et al. (2004) with adaptive optics (NACO) at the Very Large Telescope. This is shown in Fig. 20. Additional H_2 pictures can be found in Stolovy et al. (1998) and Nissen et al. (2007).

We first note a global overlap of MF1 with a zone of excited H_2 emission. Going into details, the MF1 methyl formate distribution departs from a simple elliptical shape, showing several extensions: 1) the MF1 peak corresponds to a local maximum of H_2 emission; 2) there is a second peak at a northwest position of the Compact Ridge (labeled NW in Fig. 20) in both tracers; 3) two extensions of the MF map towards the south-southeast and west, respectively, of the Compact Ridge (labeled SSE and SSW in Fig. 20) correspond to two other peaks. These findings strongly support the association between MF and excited H_2 . To the northeast of the Compact Ridge (position labeled NE in Fig. 20), MF overlaps the strong $2 \mu\text{m}$ continuum

Fig. 20. Methyl formate 8.7 km s⁻¹ channel map contours overlaid over Lacombe et al. (2004) 2.12 μm excited H₂ emission showing a good correlation of both tracers toward MF1 (white cross) and around (north-west (NW), south-southwest (SSW) and south-southeast (SSE)). The northeast (NE) region analysis is hampered by the subtraction of strong 2 μm continuum from IRc4 (see Fig. 17) – which results in an artefact (the zone in black). The red circled cross marks the proper motion center where the sources n, i, and BN were located 500 years ago (Gómez et al. 2005, 2008; Rodríguez et al. 2005).

emission, which has been subtracted (see black zone in Fig. 20). This prevents a good comparison of the H₂ emission in this area. However, inspection of the Subaru map (Fig. 21) confirms that there is also 2.12 μm emission there.

The north and south MF extensions have no counterpart at 2.12 μm (only faint 2.12 μm emission is present near N). They seem to be related to a different layer of emission, which appears as a north-south bar in the MF channel maps at velocities around or higher than 9 km s⁻¹. Because such a structure does not show up in any optical or IR map, we consider it likely that the gas is on the far side of OMC-1, probably behind the KL nebula itself.

Other peaks: the methyl formate – excited H₂ association observed in the MF1 area is also observed on a broader scale, especially, clockwise from the west, toward MF19, MF18-SW, MF21, MF27, MF8, MF23 (see Fig. 21). However, some MF peaks have no excited H₂ emission counterpart: for example and most notably, there is no H₂ emission at the MF2 (Hot Core-SW) peak. However, excited H₂ emission is present in its southern part (Figs. 20 and 21). Conversely bright 2.12 μm emission areas (e.g. east of the Hot Core, close to star LBLS t) do not exhibit MF emission.

To better understand the diversity of the observations, the following explanations are worth considering.

Fig. 21. Map of the integrated methyl formate emission (cf. Fig. 4) overlaid over a Subaru Observatory image of H₂ at 2.12 μm emission (© Subaru Telescope, NAOJ. All rights reserved).

- MF is seen associated with a 2.12 μm emission if the shock related to the Orion-KL explosive event passes through interstellar material dense and cold enough so that grains have ice mantles. In that case the correlation observed toward MF1 is explained by the shock-induced release of methyl formate or its progenitor CH₃OH from ice-coated grain mantles.
- The molecular production efficiency related to the shock may also be low in places, or cold grain mantles may be less abundant (e.g. closer to the very luminous Trapezium OB stars located 1' SE of Orion-KL), so that the MF column density is undetectable.
- In some other places (e.g. around LBLS t) the 2.12 μm emission geometry suggests that the emission is linked to the star and thus might be of a different nature.
- MF may also peak in regions where it is released or produced by mechanisms (e.g. thermal heating) different from the shock generated by the explosive event.
- H₂ emission may be hidden in some areas by a high column density of foreground dust.

This possibility is illustrated well by the comparison of the H₂ 2.12 μm map of Lacombe et al. (2004) (Fig. 20) with the Subaru deep exposure (Fig. 21, reproduced in extenso in Shuping et al. 2004). The larger extension of the H₂ emission seen in the Subaru map indicates that a rather “thin” layer prevented some H₂ peaks to be visible in the Lacombe et al. (2004) map. For a few H₂ emission spots in this field Colgan et al. (2007) estimated indeed a foreground absorption corresponding to $A_v = 4-8$. In the direction of the Compact Ridge, the NIR sources IRc4 and IRc5 are interpreted as reflection nebulae seen through holes of foreground matter (Shuping et al. 2004; Simpson et al. 2006). The larger size of these sources (hence of these holes) at 11 μm compared to 2 μm (continuum) is an additional indication of the relative thinness of the foreground matter.

In contrast, the MF2 peak would be a case where strong dust absorption hides all H₂ 2.12 μm emission. Close to MF2, very high opacities are advocated to explain not detecting the bright

Table 9. Coordinates of noticeable objects or places near the main methyl formate peak (MF1).

Object/place	RA (J2000) 05 ^h 35 ^m	Dec (J2000) −05°22′	Precision
HCOOCH ₃ MF1 peak ^a	05 35 14.09	−05 22 36.7	±0.8″
P1822/LBLS k ^b	05 35 14.092	−05 22 36.43	
COUP 600 X source ^c	05 35 14.09	−05 22 36.4	
H ₂ O supermaser ^d	05 35 14.12	−5 22 36.27	
HC 438 ^e	05 35 14.09	−5 22 36.6	
CO Fingers Outflow Center ^f	05 35 14.37	−05 22 27.9	±1.5″
Proper motion center ^g	05 35 14.35	−05 22 27.7	±1″

Notes. ^(a) This study; ^(b) SIMBAD; ^(c) Grosso et al. (2005); ^(d) Matveenko et al. (2000) after Greenhill et al. (2004); ^(e) Eisner et al. (2008); ^(f) Stolovy et al. (1998); Zapata et al. (2009); ^(g) Gómez et al. (2005, 2008); Rodríguez et al. (2005).

source I (e.g. Greenhill et al. 2004). Indeed from our continuum data (Sect. 6) we derive high N_{H_2} column densities (5 and $3.1 \times 10^{24} \text{ cm}^{-2}$) at both MF1 and MF2 peaks, and this corresponds to $A_v \gtrsim 1000$, assuming standard dust opacities. Our interpretation of the contrasted situation at both peaks is that, at the Compact Ridge (MF1), a shock hits the front side of a dense clump of matter, whereas at the Hot Core-SW (MF2), it hits the rear side (with respect to the observer). The presence close to MF2 of a H₂O maser spot (053247.001-052427.81, Gaume et al. 1998), similar to other spots found in the Compact Ridge, strengthens the hypothesis that a shock is present there, too.

The source of excitation of the H₂ molecules is most likely linked to the global explosive event. Most of the H₂ emission can be traced to a common center whose coordinates are given in Table 9 (e.g. Zapata et al. 2009, and refs. therein). Stolovy et al. (1998) analyze in detail two remarkable features which they call the “nested arcs” and the “bullets” (see their Fig. 4c), and suggest that other H₂ features in their map could be similar but are less easily identified due to projection effects. If this is indeed the case, the comparison with these two features favorably seen in a more edge-on configuration sheds some light on the probable geometry of the shocked region at MF1, and indicates how the shock might lead to the release of methyl formate from grain mantles. A detailed modeling at MF1 is, however, required.

8.5. Main methyl formate peak MF1 (Compact Ridge)

In addition to the correlation observed between the low-velocity outflow traced by SiO and the excited H₂ emission at $2.12 \mu\text{m}$ discussed above, some other remarkable objects are observed towards the main MF peak, MF1. The visible star Parenago 1822/LBLS k (Parenago 1954, 1997) is situated right in the middle of the MF1 methyl formate peak. It exhibits 1.3 mm continuum emission, which is analyzed as disk emission by Eisner et al. (2008) under the name HC 438. Getman et al. (2005) derive an age of $22\,000 \text{ yr}$ and a low mass of $0.26 M_\odot$. Another nearby remarkable object is the H₂O “Supermaser” identified and studied by Matveenko et al. (2000), see also Demichev & Matveenko (2009) and Matveyenko et al. (2007). Table 9 gives the *absolute* position of this H₂O source, together with our methyl formate position and positions from other studies of nearby objects. Matveenko et al. (2000) estimate a very low mass of $0.007 M_\odot$ for their H₂O supermaser central source whose position is distinct from P1822/LBLS k. However,

the proximity and youth of these two objects suggest that they might be a binary still in its forming phase.

P1822/LBLS k and associated supermaser could perhaps play a role in the observed distribution of methyl formate. Shocks play a central role in the vicinity of the H₂O supermaser whose excitation and properties are best explained by molecular collisions in shocked dense gas clumps. These shocks may well have released the methyl formate or its precursor from grain mantles; however, the methyl formate clumps cannot always be tightly associated with all the H₂O maser spots because H₂O maser emission traces only the hottest and densest pockets of gas.

We suggest that four phenomena, observed in an area as small as $5''$, may play a role in the release of the methyl formate molecule from ice grain mantles: i) bullets ejected 500 years ago (owing to the BN-I-n encounter); ii) bipolar outflow from source I; iii) action from the star P1822/LBLS k; and iv) shocks linked to the excitation of the H₂O supermaser. From a statistical point of view it seems unlikely that the above suggestions are unrelated; however, the relative importance of these four phenomena in the MF production, their relative timing and their causal relationship deserve further study.

9. Conclusions

We have studied the distribution of the complex O-bearing molecule Methyl Formate (MF) HCOOCH₃ with medium-to-high angular resolution ($\approx 7''$ to $2''$) using interferometric data from the IRAM Plateau de Bure Interferometer. Our main results and conclusions follow:

1. Our data sets include 21 well-detected transitions of MF from $E_{\text{up}} = 25 \text{ K}$ to $E_{\text{up}} = 618 \text{ K}$. A few more lines are present, still usable but partially blended with other lines. Only about 40% of the lines stronger than the weakest detected line appear free of blend. The lines are optically thin ($\tau < 0.1$).
2. We confirm the detection of $v_t = 1$ transitions. In this study, we used $v_t = 0$ and $v_t = 1$ transitions together to derive rotational temperatures.
3. We identify at least 28 MF concentrations. The most intense emissions, MF1 and MF2, arise from the Compact Ridge and the Hot Core-SW, respectively. The emission toward MF1 is much stronger than toward MF2 for low-energy levels, whereas the emission at MF2 becomes stronger at high-energy levels.
4. We determined the MF temperature using rotational diagrams for the five main positions and deduced HCOOCH₃ column densities assuming LTE. Temperatures cover the range 80 to 170 K , and column densities are 1.6×10^{16} to $1.6 \times 10^{17} \text{ cm}^{-2}$.
5. In the course of the MF data reduction, we had to produce and subtract maps of the continuum emission, using line-free channels. We used these continuum maps to identify four major clumps Ca to Cd, for which we derived dust masses in the range 0.01 to $0.05 M_\odot$ using a dust temperature equal to the MF rotational temperature. Assuming a gas-to-dust ratio of 100 the gas masses are in the range 1 to $5 M_\odot$.
6. MF gas velocities lie in the range 7 – 8 km s^{-1} . At some places, two different velocity components are clearly seen and the high velocity component (around 9 – 10 km s^{-1}) has a linear north-south structure. We see no gas emission at the 5 km s^{-1} velocity usually reported for the Hot Core: the gas we observe there is slightly higher in velocity and probably

of the same nature as the gas we observe for the Compact Ridge.

7. We searched for the two isomers of methyl formate but did not detect them. We find an abundance ratio of less than 1/50 for acetic acid CH₃COOH and less than 1/(200–500) for glycolaldehyde CH₂OHCHO.
8. We correlated the MF1/Compact Ridge emission with other gas tracers and with various Orion objects. A very clear association is found with 2.12 μ m excited H₂ maps. This tends to confirm a scenario of MF production involving the release of molecules from ice mantles, either MF itself or a precursor (CH₃OH). Four possible origins were identified for the excited H₂ emission and the MF production: shock from the “low-velocity” outflow from source I, shock from a bullet ejected during the supposed collision-explosion event 500 yr ago (Zapata et al. 2009), action of the young forming star Parenago 1822/LBLS k, or from the nearby source (and possible companion of the star) responsible for the H₂O supermaser (Matveenko et al. 2000).

We cannot conclude yet which of these four likely processes dominates the MF production, but all may have contributed. To further analyze the Compact Ridge history more radio and IR high angular resolution images are needed. In the future, ALMA and adaptive optics on large ground-based telescopes and space telescopes will provide the new data required to progress further in our understanding of the Orion-KL region.

The structure we find in Orion-KL might help for better understanding the correlation previously found between cometary and interstellar ices (Bockelée-Morvan et al. 2000). In this correlation, sources of different a priori natures, “hot cores”, on one hand, and a bipolar flow L1157, on the other, both appear to be a good match of cometary ices. Shocks releasing molecules from icy grain mantles are a major source of molecules in the gas phase in L1157. From the correlation we find between methyl formate and excited H₂ emission, this might also be the case in both Orion-KL and other hot cores.

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Table 10. Transitions of methyl formate observed with the Plateau de Bure Interferometer toward position MF1 in Orion-KL.

No.	Set	Frequency (MHz)	Transition	E_{up} (K)	$S\mu^2$ (D ²)	sigma (K)	v (km s ⁻¹)	$\Delta v_{1/2}$ (km s ⁻¹)	T_B (K)	W (K km s ⁻¹)	$N_{\text{up}}/g_{\text{up}}$ (10 ¹² cm ⁻²)	Source size ('' × '')	PA(°)	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1	1	80531.669(0.030)	9 _{2,8} -9 _{0,9} E, ($v_t = 1$)	216	0.6	0.05	—	—	≤0.15	≤0.6	≤1.04	—	—	not detected
2	1	80565.210(0.010)	10 _{2,8} -9 _{3,7} E	36	1.1	0.05	7.9(0.1)	3.8(0.3)	0.51	2.0(0.1)	1.88	10.0 × 7.0	10	detected
3	1	80572.589(0.010)	10 _{2,8} -9 _{3,7} A	36	1.1	0.05	8.0(0.5)	4.3(1.5)	0.47	2.2(0.5)	2.07	10.0 × 8.0	45	detected
4	2	80604.508(0.030)	12 _{0,3} -13 _{8,5} E, ($v_t = 1$)	288	0.2	0.09	—	—	≤0.31	≤1.3	≤6.73	—	—	blend
5	2	80652.521(0.010)	15 _{4,11} -14 _{5,10} A	83	1.0	0.09	—	—	≤0.74	≤3.0	≤3.10	—	—	blend
6	3	101202.806(0.010)	9 _{1,9} -8 _{0,8} A, ($v_t = 1$)	213	4.2	0.04	7.6(0.1)	3.5(0.2)	1.02	3.8(0.2)	0.75	—	—	partial blend with U-line
7	3	101210.208(0.004)	24 _{3,21} -25 _{2,24} A	187	0.04	0.04	—	—	≤0.12	≤0.4	≤8.68	—	—	not detected
8	3	101279.006(0.010)	9 _{1,9} -8 _{0,8} E, ($v_t = 1$)	212	4.0	0.04	7.8(0.1)	3.4(0.1)	1.18	4.3(0.1)	0.89	5.5 × 3.5	84	detected
9	3	101289.471(0.010)	29 _{9,20} -28 _{10,19} A, ($v_t = 1$)	498	1.8	0.04	—	—	≤0.12	≤0.4	≤0.18	—	—	not detected
10	3	101302.159(0.010)	25 _{6,19} -25 _{5,20} A	219	11.1	0.04	7.6(0.1)	3.9(0.4)	3.11	12.8(1.0)	0.95	5.0 × 3.5	26	detected
11	3	101305.506(0.010)	25 _{6,19} -25 _{5,20} E	219	11.1	0.04	7.8(0.2)	3.7(0.4)	2.65	10.4(1.0)	0.77	5.5 × 3.5	20	detected
12	3	101318.966(0.010)	13 _{3,11} -13 _{2,12} E, ($v_t = 1$)	246	3.2	0.04	7.8(0.1)	3.1(0.3)	0.70	2.3(0.2)	0.59	5.5 × 3.5	5	detected
13	3	101356.788(0.010)	15 _{2,13} -15 _{1,14} A, ($v_t = 1$)	263	3.5	0.04	—	—	≤0.59	≤2.1	≤0.49	—	—	blend
14	3	101370.505(0.010)	13 _{3,11} -13 _{2,12} E	60	3.2	0.04	7.9(0.1)	3.7(0.1)	3.78	14.7(0.1)	3.78	5.0 × 3.5	5	detected
15	3	101414.746(0.010)	13 _{3,11} -13 _{2,12} A	60	3.2	0.04	7.8(0.1)	3.6(0.1)	3.73	14.3(0.1)	3.68	5.0 × 3.5	5	detected
16	3	101418.330(0.001)	5 _{3,3} -5 _{1,4} A, ($v_t = 1$)	203	0.04	0.04	—	—	≤0.12	≤0.4	≤7.37	—	—	not detected
17	3	101477.421(0.010)	18 _{3,15} -18 _{3,16} E	111	1.8	0.04	—	—	≤9.31	≤33.2	≤15.17	—	—	blend with H ₂ CS
18	3	101545.453(0.010)	18 _{3,15} -18 _{3,16} A	111	1.8	0.04	7.8(0.1)	3.6(0.1)	1.80	6.9(0.2)	3.15	5.0 × 3.5	5	detected
19	3	101626.884(0.010)	9 _{1,9} -8 _{0,8} E	25	4.1	0.04	—	—	≤5.96	≤21.2	≤4.25	—	—	blend with HCOOCH ₃ -A
20	3	101628.149(0.010)	9 _{1,9} -8 _{0,8} A	25	4.1	0.04	—	—	≤5.47	≤19.5	≤3.91	—	—	blend with HCOOCH ₃ -E
21	4	105663.117(0.030)	19 _{13,7} -20 _{12,9} E, ($v_t = 1$)	412	0.4	0.02	—	—	≤0.06	≤0.1	≤0.20	—	—	not detected
22	4	105722.672(0.030)	10 _{4,6} -10 _{3,8} E, ($v_t = 1$)	230	0.5	0.02	—	—	≤0.11	≤0.2	≤0.32	—	—	blend
23	5	105810.803(0.030)	14 _{11,4} -15 _{10,6} E	142	0.2	0.03	—	—	≤0.11	≤0.2	≤0.79	—	—	blend
24	5	105815.953(0.030)	3 _{3,1} -2 _{2,0} E	10	0.2	0.03	7.6(0.1)	2.2(0.2)	0.39	0.9(0.1)	3.55	10.5 × 7.5	6	detected
25	5	105832.067(0.030)	14 _{11,3} -15 _{10,5} E	142	0.2	0.03	7.9(0.1)	1.6(0.2)	0.20	0.4(0.1)	1.58	10.5 × 7.5	6	detected
26	6	110153.652(0.010)	10 _{1,10} -9 _{1,9} A, ($v_t = 1$)	218	25.1	0.12	—	—	≤8.08	≤9.7	≤0.29	—	—	blend with NH ₂ D
27	7	203349.158(0.006)	24 _{19,5} -25 _{18,7} E	416	0.2	0.09	—	—	≤1.73	≤2.8	≤5.77	—	—	blend
28	7	203378.812(0.007)	24 _{19,6} -25 _{18,8} E	416	0.2	0.09	—	—	≤5.64	≤9.2	≤18.94	—	—	blend
29	8	203427.575(0.100)	21 _{8,13} -21 _{7,14} A, ($v_t = 1$)	366	6.2	0.09	7.9(0.4)	1.7(0.8)	1.40	2.5(1.0)	0.17	4.5 × 2.5	45	detected
30	8	203435.554(0.100)	19 _{8,11} -19 _{7,12} A	155	5.3	0.09	7.6(0.9)	1.6(0.9)	6.40	10.6(1.6)	0.82	5.0 × 3.5	65	detected
31	8	203471.840(0.05)	19 _{8,11} -19 _{7,12} E	155	4.9	0.09	7.5(0.1)	1.6(0.1)	5.28	9.2(2.0)	0.77	5.0 × 3.5	40	detected
32	9	223435.416(0.001)	11 _{4,8} -10 _{3,7} A, ($v_t = 1$)	237	1.8	0.17	—	—	≤3.66	≤6.7	≤1.38	—	—	blend
33	9	223465.340(0.050)	11 _{4,8} -10 _{3,7} E	50	2.1	0.17	7.6(0.1)	2.0(0.2)	10.74	22.5(1.9)	4.00	3.0 × 2.0	0	detected
34	9	223500.463(0.001)	11 _{4,8} -10 _{3,7} A	50	1.8	0.17	7.4(0.1)	1.8(0.1)	11.49	21.8(1.7)	4.61	3.0 × 1.5	0	detected
35	9	223534.727(0.100)	18 _{5,14} -17 _{5,13} E, ($v_t = 1$)	305	41.6	0.17	7.4(0.1)	1.7(0.1)	10.25	18.5(0.8)	0.17	3.5 × 2.0	0	detected
36	9	223538.511(0.100)	43 _{8,35} -43 _{7,36} E	618	13.9	0.17	—	—	≤0.51	≤0.9	≤0.02	—	—	not detected
37	9	223592.231(0.100)	43 _{8,35} -43 _{7,36} A	618	13.9	0.17	—	—	≤0.91	≤1.7	≤0.05	—	—	blend
38	9	223618.470(0.007)	27 _{9,19} -27 _{8,19} E, ($v_t = 1$)	464	0.4	0.17	—	—	≤0.51	≤0.9	≤0.90	—	—	not detected
39	9	223624.496(0.100)	37 _{8,30} -37 _{7,31} E	463	11.7	0.17	7.7(0.3)	1.8(0.6)	0.68	1.3(0.4)	0.04	—	—	partial blend
40	9	223634.916(0.100)	37 _{8,30} -37 _{7,31} A	463	11.7	0.17	—	—	≤2.06	≤3.8	≤0.12	—	—	blend
41	9	223642.180(0.001)	12 _{5,7} -12 _{3,10} E	63	0.1	0.17	—	—	≤4.08	≤7.4	≤32.97	—	—	blend
42	9	223645.342(0.001)	12 _{5,7} -12 _{3,10} A	63	0.1	0.17	—	—	≤1.66	≤3.0	≤11.23	—	—	blend
43	9	223651.592(0.007)	33 _{9,24} -33 _{8,26} E, ($v_t = 1$)	573	0.7	0.17	—	—	≤1.35	≤2.5	≤1.25	—	—	blend

Table 10. continued.

No.	Set	Frequency (MHz)	Transition	E_{up} (K)	$S\mu^2$ (D ²)	sigma (K)	v (km s ⁻¹)	$\Delta v_{1/2}$ (km s ⁻¹)	T_{B} (K)	W (K km s ⁻¹)	$N_{\text{up}}/g_{\text{up}}$ (10 ¹² cm ⁻²)	Source size ('' × '')	Source size PA(°)	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
44	9	223676.472(0.006)	35 _{7,29} –35 _{5,30} A, ($u_l = 1$)	593	3.0	0.17	–	–	≤2.09	≤3.8	≤0.47	–	–	blend
45	9	223782.081(0.007)	33 _{4,28} –33 _{5,29} E, ($u_l = 1$)	543	7.0	0.17	–	–	≤0.51	≤0.9	≤0.05	–	–	not detected
46	9	223821.523(0.002)	35 _{7,29} –35 _{6,30} E	409	8.2	0.17	–	–	≤2.31	≤4.2	≤0.19	–	–	blend
47	9	223854.201(0.100)	35 _{7,29} –35 _{6,30} A	409	10.1	0.17	–	–	≤4.63	≤8.4	≤0.31	–	–	blend
48	10	225689.371(0.008)	34 _{5,29} –34 _{5,30} A, ($u_l = 1$)	562	3.0	0.13	–	–	≤12.20	≤12.6	≤1.57	–	–	blend
49	10	225696.842(0.100)	20 _{1,19} –19 _{1,18} E, ($u_l = 1$)	307	50.2	0.13	–	–	≤16.8	≤17.4	≤0.13	–	–	blend
50	10	225702.857(0.100)	19 _{2,17} –18 _{2,16} A, ($u_l = 1$)	304	46.8	0.13	–	–	≤20.09	≤20.8	≤0.16	–	–	blend
51	10	225727.506(0.100)	6 _{6,1} –5 _{5,0} A, ($u_l = 1$)	224	3.1	0.13	–	–	≤4.04	≤4.2	≤0.50	–	–	blend
52	10	225727.506(0.100)	6 _{6,0} –5 _{5,1} A, ($u_l = 1$)	224	3.1	0.13	–	–	≤4.04	≤4.2	≤0.50	–	–	blend
53	11	225855.505(0.100)	6 _{6,1} –5 _{5,1} E	36	3.1	0.10	7.6(0.1)	1.2(0.1)	6.84	9.1(0.1)	1.08	5.5 × 4.5	5	detected
54	11	225900.684(0.100)	6 _{6,0} –5 _{5,0} E	36	3.1	0.10	–	–	≤12.74	≤13.2	≤1.57	–	–	blend with HDO
55	11	225928.659(0.100)	6 _{6,0} –5 _{5,1} A	36	3.1	0.10	–	–	≤11.42	≤11.8	≤1.41	–	–	blend
56	11	225928.659(0.100)	6 _{6,1} –5 _{5,0} A	36	3.1	0.10	–	–	≤11.42	≤11.8	≤1.41	–	–	blend
57	12	225999.145(0.100)	30 _{7,23} –29 _{8,22} E	312	2.2	0.11	7.5(0.1)	0.9(0.3)	0.70	0.6(0.2)	0.10	5.0 × 3.5	0	detected
58	12	226061.796(0.100)	20 _{3,17} –19 _{4,16} E, ($u_l = 1$)	321	4.0	0.11	7.6(0.2)	1.0(0.5)	0.72	0.8(0.3)	0.07	5.5 × 3.5	25	detected
59	12	226077.920(0.001)	10 _{3,7} –9 _{1,8} E	39	0.3	0.11	–	–	≤2.62	≤2.7	≤3.53	–	–	blend
60	12	226081.175(0.002)	30 _{7,23} –29 _{8,22} A	312	1.8	0.11	–	–	≤0.71	≤0.7	≤0.14	–	–	blend
61	12	226087.718(0.007)	29 _{4,26} –29 _{3,27} A, ($u_l = 1$)	450	4.3	0.11	–	–	≤0.82	≤0.8	≤0.07	–	–	blend
62	12	226090.301(0.100)	19 _{2,17} –18 _{2,16} E, ($u_l = 1$)	303	47.0	0.11	–	–	≤9.62	≤9.6	≤0.08	–	–	blend
63	12	226112.470(0.007)	29 _{4,26} –29 _{2,27} A, ($u_l = 1$)	450	2.1	0.11	–	–	≤0.33	≤0.3	≤0.05	–	–	not detected
64	12	226125.600(0.001)	10 _{3,7} –9 _{1,8} A	39	0.3	0.11	–	–	≤4.04	≤4.2	≤5.49	–	–	blend

Notes. (1) Observed transitions with $E_{\text{upper}} \lesssim 650$ K. (2) Reference number of the corresponding data set (see Table 1). (3) Frequencies and uncertainties taken from Ilyushin et al. (2009) and from the JPL database (<http://spec.jpl.nasa.gov/>). (4) Transitions in ground state ($u_l = 0$). Transitions in torsional levels ($u_t = 1$) are specified. (5) Energy of the upper level. (6) Line strength calculated by Ilyushin et al. (2009). For the transitions coming from the JPL database, the line strength is calculated from the formulae of Pickett et al. (1998). (7) Noise estimated from spectrum (1σ). (8) Lines with number 30, 31, 33–35, 41, 53, and 57 are decomposed. Only the first component is given here, other components are given in Table 3, except for lines 29, 39, and 58 because of the blend with the second component. (8)–(11) Velocity, linewidth at half intensity, brightness temperature, and integrated intensities. The uncertainties are estimated with the CLASS software. (12) Column densities of the upper state of the transition with respect to the rotational degeneracy ($2J_{\text{up}} + 1$). (13) and (14) Source size estimated at half flux density from detected transitions with spatial resolution allowing isolation of the source. (15) Blended lines are specified.

**Appendix A: Transitions of methyl formate
observed with the Plateau de Bure
Interferometer towards positions MF2 to MF5
in Orion-KL**

The following tables summarize the line parameters for all detected, blended, or not detected transitions of the methyl formate molecule (HCOOCH_3) in all our PdBI data sets towards the emission peaks MF2 to MF5.

Table A.1. Transitions of methyl formate observed with the Plateau de Bure Interferometer toward position MF2 in Orion-KL.

No.	Set	Frequency (MHz)	Transition	E_{up} (K)	$S\mu^2$ (D ²)	sigma (K)	v (km s ⁻¹)	$\Delta v_{1/2}$ (km s ⁻¹)	T_{B} (K)	W (K km s ⁻¹)	$N_{\text{up}}/g_{\text{up}}$ (10 ¹² cm ⁻²)	Source size (" × ")	PA(°)	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1	1	80531.669(0.030)	9 _{2,8} -9 _{0,9} E, ($\nu_t = 1$)	216	0.6	0.03	—	—	≤0.09	≤0.4	≤0.69	—	—	not detected
2	1	80565.210(0.010)	10 _{2,8} -9 _{3,7} E	36	1.1	0.03	7.9(0.3)	4.4(0.5)	0.24	1.1(0.1)	1.04	—	—	detected
3	1	80572.589(0.010)	10 _{2,8} -9 _{3,7} A	36	1.1	0.03	—	—	≤0.30	≤1.3	≤1.22	—	—	blend
4	2	80604.508(0.030)	12 _{9,3} -13 _{8,5} E, ($\nu_t = 1$)	288	0.2	0.10	—	—	≤8.03	≤35.3	≤182.73	—	—	blend
5	2	80652.521(0.010)	15 _{4,11} -14 _{5,10} A	83	1.0	0.10	—	—	≤3.92	≤17.2	≤17.80	—	—	blend
6	3	101202.806(0.010)	9 _{1,9} -8 _{0,8} A, ($\nu_t = 1$)	213	4.2	0.04	—	—	≤0.64	≤2.6	≤0.51	—	—	blend
7	3	101210.208(0.004)	24 _{3,21} -25 _{2,24} A	187	0.04	0.04	—	—	≤0.34	≤1.4	≤30.36	—	—	blend
8	3	101279.006(0.010)	9 _{1,9} -8 _{0,8} E, ($\nu_t = 1$)	212	4.0	0.04	7.6(0.7)	4.1(2.0)	0.64	2.8(1.0)	0.58	4.0 × 2.5	20	detected
9	3	101289.471(0.010)	29 _{9,20} -28 _{10,19} A, ($\nu_t = 1$)	498	1.8	0.04	—	—	≤0.12	≤0.5	≤0.23	—	—	not detected
10	3	101302.159(0.010)	25 _{6,19} -25 _{5,20} A	219	11.1	0.04	7.1(0.4)	4.3(1.0)	2.09	9.6(1.9)	0.71	—	—	partial blend
11	3	101305.506(0.010)	25 _{6,19} -25 _{5,20} E	219	11.1	0.04	7.5(0.8)	4.4(2.2)	1.58	7.3(3.0)	0.54	5.0 × 2.5	20	detected
12	3	101318.966(0.010)	13 _{3,11} -13 _{2,12} E, ($\nu_t = 1$)	246	3.2	0.04	7.7(0.5)	3.8(1.2)	0.50	2.0(0.5)	0.51	5.5 × 2.5	35	detected
13	3	101356.788(0.010)	15 _{2,13} -15 _{1,14} A, ($\nu_t = 1$)	263	3.5	0.04	—	—	≤0.56	≤2.2	≤0.52	—	—	blend
14	3	101370.505(0.010)	13 _{3,11} -13 _{2,12} E	60	3.2	0.04	7.5(0.1)	3.8(0.1)	1.66	6.6(0.2)	1.70	4.5 × 2.5	35	detected
15	3	101414.746(0.010)	13 _{3,11} -13 _{2,12} A	60	3.2	0.04	7.5(0.1)	4.1(0.3)	1.49	6.6(0.4)	1.70	4.5 × 2.5	35	detected
16	3	101418.330(0.001)	5 _{3,3} -5 _{1,4} A, ($\nu_t = 1$)	203	0.04	0.04	—	—	≤0.12	≤0.5	≤9.22	—	—	not detected
17	3	101477.421(0.010)	18 _{3,15} -18 _{3,16} E	111	1.8	0.04	—	—	≤9.17	≤36.7	≤16.77	—	—	blend with H ₂ CS
18	3	101545.453(0.010)	18 _{3,15} -18 _{3,16} A	111	1.8	0.04	7.6(0.3)	3.5(0.6)	1.03	3.8(0.6)	1.73	4.5 × 2.5	35	detected
19	3	101626.884(0.010)	9 _{1,9} -8 _{0,8} E	25	4.1	0.04	—	—	≤2.80	≤11.2	≤2.24	—	—	blend with HCOOCH ₃ -A
20	3	101628.149(0.010)	9 _{1,9} -8 _{0,8} A	25	4.1	0.04	—	—	≤2.97	≤11.9	≤2.38	—	—	blend with HCOOCH ₃ -E
21	4	105663.117(0.030)	19 _{13,7} -20 _{12,9} E, ($\nu_t = 1$)	412	0.4	0.02	—	—	≤0.19	≤0.6	≤1.18	—	—	blend
22	4	105722.672(0.030)	10 _{4,6} -10 _{3,8} E, ($\nu_t = 1$)	230	0.5	0.02	—	—	≤0.06	≤0.2	≤0.32	—	—	not detected
23	5	105810.803(0.030)	14 _{11,4} -15 _{10,6} E	142	0.2	0.02	—	—	≤0.09	≤0.3	≤1.18	—	—	blend
24	5	105815.953(0.030)	3 _{3,1} -2 _{2,0} E	10	0.2	0.02	7.7(0.2)	3.0(0.9)	0.17	0.5(0.1)	1.97	—	—	detected
25	5	105832.067(0.030)	14 _{11,3} -15 _{10,5} E	142	0.2	0.02	—	—	≤0.23	≤0.7	≤2.76	—	—	blend
26	6	110153.652(0.010)	10 _{1,10} -9 _{1,9} A, ($\nu_t = 1$)	218	25.1	0.10	—	—	≤8.63	≤9.5	≤0.29	—	—	blend with NH ₂ D
27	7	203349.158(0.006)	24 _{19,5} -25 _{18,7} E	416	0.2	0.07	—	—	≤3.35	≤8.3	≤17.09	—	—	blend
28	7	203378.812(0.007)	24 _{19,6} -25 _{18,8} E	416	0.2	0.07	—	—	≤20.42	≤50.4	≤103.77	—	—	blend
29	8	203427.575(0.100)	21 _{8,13} -21 _{7,14} A, ($\nu_t = 1$)	366	6.2	0.07	7.8(0.4)	2.3(1.0)	1.14	2.7(1.1)	0.18	6.5 × 3.0	35	detected
30	8	203435.554(0.100)	19 _{8,11} -19 _{7,12} A	155	5.3	0.07	7.8(0.2)	2.6(0.6)	4.24	11.8(2.0)	0.91	6.0 × 2.5	25	detected
31	8	203471.840(0.050)	19 _{8,11} -19 _{7,12} E	155	4.9	0.07	7.6(0.5)	2.5(1.3)	3.22	8.5(3.4)	0.71	6.0 × 2.5	25	detected
32	9	223435.416(0.001)	11 _{4,8} -10 _{3,7} A, ($\nu_t = 1$)	237	1.8	0.25	—	—	≤5.75	≤13.9	≤2.86	—	—	blend
33	9	223465.340(0.050)	11 _{4,8} -10 _{3,7} E	50	2.1	0.25	7.8(0.1)	2.2(0.2)	5.62	12.9(1.3)	2.29	2.5 × 1.2	10	detected
34	9	223500.463(0.001)	11 _{4,8} -10 _{3,7} A	50	1.8	0.25	7.5(0.2)	2.3(0.5)	5.71	13.7(2.8)	2.90	2.5 × 1.2	10	detected
35	9	223534.727(0.100)	18 _{5,14} -17 _{5,13} E, ($\nu_t = 1$)	305	41.6	0.25	7.5(0.1)	2.6(0.3)	12.67	35.5(3.5)	0.32	—	—	partial blend
36	9	223538.511(0.100)	43 _{8,35} -43 _{7,36} E	618	13.9	0.25	—	—	≤1.23	≤3.0	≤0.08	—	—	blend
37	9	223592.231(0.100)	43 _{8,35} -43 _{7,36} A	618	13.9	0.25	7.8(0.9)	2.2(1.8)	1.22	2.8(2.2)	0.08	2.0 × 1.2	20	detected
38	9	223618.470(0.007)	27 _{9,19} -27 _{8,19} E, ($\nu_t = 1$)	464	0.4	0.25	—	—	≤0.75	≤1.8	≤1.80	—	—	not detected
39	9	223624.496(0.100)	37 _{8,30} -37 _{7,31} E	463	11.7	0.25	—	—	≤0.92	≤2.2	≤0.07	—	—	blend
40	9	223634.916(0.100)	37 _{8,30} -37 _{7,31} A	463	11.7	0.25	—	—	≤1.83	≤4.2	≤0.13	—	—	blend
41	9	223642.180(0.001)	12 _{5,7} -12 _{3,10} E	63	0.1	0.25	—	—	≤3.58	≤8.7	≤38.77	—	—	blend
42	9	223645.342(0.001)	12 _{5,7} -12 _{3,10} A	63	0.1	0.25	—	—	≤0.83	≤2.0	≤7.49	—	—	blend
43	9	223651.592(0.007)	33 _{9,24} -33 _{8,26} E, ($\nu_t = 1$)	573	0.7	0.25	—	—	≤1.88	≤4.5	≤2.25	—	—	blend
44	9	223676.472(0.006)	35 _{7,29} -35 _{5,30} A, ($\nu_t = 1$)	593	3.0	0.25	—	—	≤3.42	≤8.3	≤1.02	—	—	blend

Table A.1. continued.

No.	Set	Frequency (MHz)	Transition	E_{up} (K)	$S\mu^2$ (D ²)	sigma (K)	v (km s ⁻¹)	$\Delta v_{1/2}$ (km s ⁻¹)	T_{B} (K)	W (K km s ⁻¹)	$N_{\text{up}}/g_{\text{up}}$ (10 ¹² cm ⁻²)	Source size ('' × '')	Source size PA(°)	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
45	9	223782.081(0.007)	33 _{6,28} -33 _{5,29} E, ($\nu_t = 1$)	543	7.0	0.25	—	—	≤0.75	≤1.8	≤0.10	—	—	not detected
46	9	223821.523(0.002)	35 _{7,29} -35 _{6,30} E	409	8.2	0.25	—	—	≤2.06	≤5.0	≤0.23	—	—	blend
47	9	223854.201(0.100)	35 _{7,29} -35 _{6,30} A	409	10.1	0.25	—	—	≤2.33	≤5.6	≤0.21	—	—	blend
48	10	225689.371(0.008)	34 _{5,29} -34 _{5,30} A, ($\nu_t = 1$)	562	3.0	0.10	—	—	≤17.26	≤19.0	≤2.37	—	—	blend
49	10	225696.842(0.100)	20 _{1,19} -19 _{1,18} E, ($\nu_t = 1$)	307	50.2	0.10	—	—	≤24.50	≤27.0	≤0.20	—	—	blend
50	10	225702.857(0.100)	19 _{2,17} -18 _{2,16} A, ($\nu_t = 1$)	304	46.8	0.10	—	—	≤43.23	≤47.6	≤0.38	—	—	blend
51	10	225727.506(0.100)	6 _{6,1} -5 _{5,0} A, ($\nu_t = 1$)	224	3.1	0.10	—	—	≤4.61	≤5.1	≤0.61	—	—	blend
52	10	225727.506(0.100)	6 _{6,0} -5 _{5,1} A, ($\nu_t = 1$)	224	3.1	0.10	—	—	≤4.61	≤5.1	≤0.61	—	—	blend
53	11	225855.505(0.100)	6 _{6,1} -5 _{5,1} E	36	3.1	0.11	—	—	≤3.68	≤4.0	≤0.48	—	—	blend
54	11	225900.684(0.100)	6 _{6,0} -5 _{5,0} E	36	3.1	0.11	—	—	≤19.23	≤21.2	≤2.53	—	—	blend with HDO
55	11	225928.659(0.100)	6 _{6,0} -5 _{5,1} A	36	3.1	0.11	—	—	≤5.80	≤6.4	≤0.76	—	—	blend
56	11	225928.659(0.100)	6 _{6,1} -5 _{5,0} A	36	3.1	0.11	—	—	≤5.80	≤6.4	≤0.76	—	—	blend
57	12	225999.145(0.100)	30 _{7,23} -29 _{8,22} E	312	2.2	0.10	—	—	≤0.30	≤0.3	≤0.05	—	—	not detected
58	12	226061.796(0.100)	20 _{3,17} -19 _{4,16} E, ($\nu_t = 1$)	321	4.0	0.10	7.8(0.3)	1.1(0.6)	0.42	0.5(0.2)	0.05	—	—	partial blend
59	12	226077.920(0.001)	10 _{3,7} -9 _{1,8} E	39	0.3	0.10	—	—	≤2.52	≤2.8	≤3.66	—	—	blend
60	12	226081.175(0.002)	30 _{7,23} -29 _{8,22} A	312	1.8	0.10	—	—	≤0.42	≤0.5	≤0.10	—	—	blend
61	12	226087.718(0.007)	29 _{4,26} -29 _{3,27} A, ($\nu_t = 1$)	450	4.3	0.10	—	—	≤0.73	≤0.8	≤0.07	—	—	blend
62	12	226090.301(0.100)	19 _{2,17} -18 _{2,16} E, ($\nu_t = 1$)	303	47.0	0.10	—	—	≤7.67	≤8.4	≤0.07	—	—	blend
63	12	226112.470(0.007)	29 _{4,26} -29 _{2,27} A, ($\nu_t = 1$)	450	2.1	0.10	—	—	≤0.53	≤0.6	≤0.11	—	—	blend
64	12	226125.600(0.001)	10 _{3,7} -9 _{1,8} A	39	0.3	0.10	—	—	≤3.22	≤3.5	≤4.58	—	—	blend

Notes. (1) Observed transitions with $E_{\text{upper}} \lesssim 650$ K. (2) Reference number of the corresponding data set (see Table 1). (3) Frequencies and uncertainties taken from Ilyushin et al. (2009) and from the JPL database (<http://spec.jpl.nasa.gov/>). (4) Transitions in ground state ($\nu_t = 0$). Transitions in torsional levels ($\nu_t = 1$) are specified. (5) Energy of the upper level. (6) Line strength calculated by Ilyushin et al. (2009). For the transitions coming from the JPL database, the line strength is calculated from the formulae of Pickett et al. (1998). (7) Noise estimated from the spectrum (1 σ). (8)–(11) Velocity, linewidth at half intensity, brightness temperature, and integrated intensities. The uncertainties are estimated with the CLASS software. (12) Column densities of the upper state of the transition with respect to the rotational degeneracy ($2J_{\text{up}} + 1$). (13) and (14) Source size estimated at half flux density from detected transitions with spatial resolution allowing isolation of the source. (15) Blended lines are specified.

Table A.2. Transitions of methyl formate observed with the Plateau de Bure Interferometer toward position MF3 in Orion-KL.

No.	Set	Frequency (MHz)	Transition	E_{up} (K)	$S\mu^2$ (D ²)	sigma (K)	v (km s ⁻¹)	$\Delta v_{1/2}$ (km s ⁻¹)	T_{B} (K)	W (K km s ⁻¹)	$N_{\text{up}}/g_{\text{up}}$ (10 ¹² cm ⁻²)	Source size (" × ")	PA(°)	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1	1	80531.669(0.030)	9 _{2,8} -9 _{0,9} E, ($u_l = 1$)	216	0.6	0.02	—	—	≤0.06	≤0.2	≤0.35	—	—	not detected
2	1	80565.210(0.010)	10 _{2,8} -9 _{3,7} E	36	1.1	0.02	7.8(0.1)	3.8(0.2)	0.43	1.8(0.1)	1.69	10.0 × 7.0	10	detected
3	1	80572.589(0.010)	10 _{2,8} -9 _{3,7} A	36	1.1	0.02	—	—	≤0.39	≤1.5	≤1.41	—	—	blend
4	2	80604.508(0.030)	12 _{9,3} -13 _{8,5} E, ($u_l = 1$)	288	0.2	0.06	—	—	≤3.20	≤12.2	≤63.15	—	—	blend
5	2	80652.521(0.010)	15 _{4,11} -14 _{5,10} A	83	1.0	0.06	—	—	≤1.94	≤7.4	≤7.66	—	—	blend
6	3	101202.806(0.010)	9 _{1,9} -8 _{0,8} A, ($u_l = 1$)	213	4.2	0.04	8.0(0.1)	4.0(0.2)	0.51	2.2(0.1)	0.43	—	—	partial blend
7	3	101201.208(0.004)	24 _{3,21} -25 _{2,24} A	187	0.04	0.04	—	—	≤0.12	≤0.5	≤10.84	—	—	not detected
8	3	101279.006(0.010)	9 _{1,9} -8 _{0,8} E, ($u_l = 1$)	212	4.0	0.04	7.5(0.4)	3.5(0.9)	0.55	2.0(0.4)	0.41	—	—	detected
9	3	101289.471(0.010)	29 _{9,20} -28 _{10,19} A, ($u_l = 1$)	498	1.8	0.04	—	—	≤0.12	≤0.5	≤0.23	—	—	not detected
10	3	101302.159(0.010)	25 _{6,19} -25 _{5,20} A	219	11.1	0.04	7.4(0.4)	4.1(1.2)	1.76	7.6(1.8)	0.56	—	—	partial blend
11	3	101305.506(0.010)	25 _{6,19} -25 _{5,20} E	219	11.1	0.04	7.8(0.2)	4.0(0.6)	1.33	5.7(0.6)	0.42	—	—	detected
12	3	101318.966(0.010)	13 _{3,11} -13 _{2,12} E, ($u_l = 1$)	246	3.2	0.04	7.5(0.3)	3.2(0.8)	0.28	1.0(0.2)	0.26	—	—	detected
13	3	101356.788(0.010)	15 _{2,13} -15 _{1,14} A, ($u_l = 1$)	263	3.5	0.04	—	—	≤0.30	≤1.1	≤0.26	—	—	blend
14	3	101370.505(0.010)	13 _{3,11} -13 _{2,12} E	60	3.2	0.04	7.7(0.1)	3.8(0.1)	1.77	7.2(0.1)	1.85	—	—	detected
15	3	101414.746(0.010)	13 _{3,11} -13 _{2,12} A	60	3.2	0.04	7.7(0.1)	3.7(0.1)	1.83	7.2(0.2)	1.85	—	—	detected
16	3	101418.330(0.001)	53 _{3,3} -51 _{4,4} A, ($u_l = 1$)	203	0.04	0.04	—	—	≤0.12	≤0.5	≤9.22	—	—	not detected
17	3	101477.421(0.010)	18 _{3,15} -18 _{3,16} E	111	1.8	0.04	—	—	≤10.05	≤37.8	≤17.27	—	—	blend with H ₂ CS
18	3	101545.453(0.010)	18 _{3,15} -18 _{3,16} A	111	1.8	0.04	7.9(0.1)	3.8(0.2)	0.83	3.4(0.1)	1.55	—	—	detected
19	3	101626.884(0.010)	9 _{1,9} -8 _{0,8} E	25	4.1	0.04	—	—	≤3.21	≤12.1	≤2.42	—	—	blend with HCOOCH ₃ -A
20	3	101628.149(0.010)	9 _{1,9} -8 _{0,8} A	25	4.1	0.04	—	—	≤3.23	≤12.2	≤2.44	—	—	blend with HCOOCH ₃ -E
21	4	105663.117(0.030)	19 _{13,7} -20 _{12,9} E, ($u_l = 1$)	412	0.4	0.02	7.6(0.3)	2.1(0.8)	0.09	0.2(0.1)	0.39	11 × 8.5	6	detected
22	4	105722.672(0.030)	10 _{4,6} -10 _{3,8} E, ($u_l = 1$)	230	0.5	0.02	—	—	≤0.11	≤0.2	≤0.32	—	—	blend
23	5	105810.803(0.030)	14 _{11,4} -15 _{10,6} E	142	0.2	0.02	—	—	≤0.12	≤0.2	≤0.79	—	—	blend
24	5	105815.953(0.030)	33 _{1,1} -22 ₀ E	10	0.2	0.02	7.6(0.1)	2.1(0.3)	0.35	0.8(0.1)	3.15	10.5 × 8.5	6	detected
25	5	105832.067(0.030)	14 _{11,3} -15 _{10,5} E	142	0.2	0.02	7.7(0.1)	1.5(0.2)	0.17	0.3(0.1)	1.18	10.0 × 7.5	6	detected
26	6	110153.652(0.010)	10 _{1,10} -9 _{1,9} A, ($u_l = 1$)	218	25.1	0.12	—	—	≤6.40	≤12.2	≤0.37	—	—	blend with NH ₂ D
27	7	203349.158(0.006)	24 _{19,5} -25 _{18,7} E	416	0.2	0.20	—	—	≤0.60	≤1.0	≤2.06	—	—	not detected
28	7	203378.812(0.007)	24 _{19,6} -25 _{18,8} E	416	0.2	0.20	—	—	≤2.94	≤5.0	≤10.29	—	—	blend
29	8	203427.575(0.100)	21 _{8,13} -21 _{7,14} A, ($u_l = 1$)	366	6.2	0.20	—	—	≤0.60	≤1.0	≤0.07	—	—	not detected
30	8	203435.554(0.100)	19 _{8,11} -19 _{7,12} A	155	5.3	0.20	7.7(0.1)	1.7(0.1)	3.33	6.1(0.3)	0.47	—	—	detected
31	8	203471.840(0.050)	19 _{8,11} -19 _{7,12} E	155	4.9	0.20	7.6(0.1)	1.7(0.3)	2.73	4.8(0.8)	0.40	—	—	detected
32	9	223435.416(0.001)	11 _{4,8} -10 _{3,7} A, ($u_l = 1$)	237	1.8	0.30	—	—	≤0.90	≤1.4	≤0.29	—	—	not detected
33	9	223465.340(0.050)	11 _{4,8} -10 _{3,7} E	50	2.1	0.30	7.7(0.1)	1.7(0.3)	3.24	5.8(1.2)	1.03	—	—	partial blend
34	9	223500.463(0.001)	11 _{4,8} -10 _{3,7} A	50	1.8	0.30	7.7(0.1)	1.2(0.1)	4.02	5.2(0.3)	1.10	3.0 × 1.5	0	detected
35	9	223534.727(0.100)	18 _{5,14} -17 _{5,13} E, ($u_l = 1$)	305	41.6	0.30	7.7(0.1)	1.6(0.1)	3.49	6.0(0.4)	0.05	2.5 × 1.5	0	detected
36	9	223538.511(0.100)	43 _{8,35} -43 _{7,36} E	618	13.9	0.30	—	—	≤0.90	≤1.4	≤0.04	—	—	not detected
37	9	223592.231(0.100)	43 _{8,35} -43 _{7,36} A	618	13.9	0.30	—	—	≤0.90	≤1.4	≤0.04	—	—	not detected
38	9	223618.470(0.007)	27 _{9,19} -27 _{8,19} E, ($u_l = 1$)	464	0.4	0.30	—	—	≤0.90	≤1.4	≤1.40	—	—	not detected
39	9	223624.496(0.100)	37 _{8,30} -37 _{7,31} E	463	11.7	0.30	—	—	≤0.90	≤1.4	≤0.04	—	—	not detected
40	9	223634.916(0.100)	37 _{8,30} -37 _{7,31} A	463	11.7	0.30	—	—	≤0.90	≤1.4	≤0.04	—	—	not detected
41	9	223642.180(0.001)	12 _{5,7} -12 _{3,10} E	63	0.1	0.30	—	—	≤1.13	≤1.7	≤7.57	—	—	blend
42	9	223645.342(0.001)	12 _{5,7} -12 _{3,10} A	63	0.1	0.30	—	—	≤0.90	≤1.4	≤5.24	—	—	not detected
43	9	223651.592(0.007)	33 _{9,24} -33 _{8,26} E, ($u_l = 1$)	573	0.7	0.30	—	—	≤0.90	≤1.4	≤0.70	—	—	not detected
44	9	223676.472(0.006)	35 _{7,29} -35 _{5,30} A, ($u_l = 1$)	593	3.0	0.30	—	—	≤0.90	≤1.4	≤0.17	—	—	not detected

Table A.2. continued.

No.	Set	Frequency (MHz)	Transition	E_{up} (K)	$S\mu^2$ (D ²)	sigma (K)	v (km s ⁻¹)	$\Delta v_{1/2}$ (km s ⁻¹)	T_{B} (K)	W (K km s ⁻¹)	$N_{\text{up}}/g_{\text{up}}$ (10 ¹² cm ⁻²)	Source size ('' × '')	PA(°)	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
45	9	223782.081(0.007)	33 _{6,28} –33 _{5,29} E, ($u_l = 1$)	543	7.0	0.30	–	–	≤0.90	≤1.4	≤0.08	–	–	not detected
46	9	223821.523(0.002)	35 _{7,29} –35 _{6,30} E	409	8.2	0.30	–	–	≤0.90	≤1.4	≤0.06	–	–	not detected
47	9	223854.201(0.100)	35 _{7,29} –35 _{6,30} A	409	10.1	0.30	–	–	≤0.90	≤1.4	≤0.05	–	–	not detected
48	10	225689.371(0.008)	34 _{5,29} –34 _{5,30} A, ($u_l = 1$)	562	3.0	0.14	–	–	≤13.06	≤22.2	≤2.77	–	–	blend
49	10	225696.842(0.100)	20 _{1,19} –19 _{1,18} E, ($u_l = 1$)	307	50.2	0.14	–	–	≤22.85	≤38.8	≤0.29	–	–	blend
50	10	225702.857(0.100)	19 _{2,17} –18 _{2,16} A, ($u_l = 1$)	304	46.8	0.14	–	–	≤25.75	≤43.8	≤0.35	–	–	blend
51	10	225727.506(0.100)	6 _{6,1} –5 _{5,0} A, ($u_l = 1$)	224	3.1	0.14	–	–	≤3.20	≤5.4	≤0.64	–	–	blend
52	10	225727.506(0.100)	6 _{6,0} –5 _{5,1} A, ($u_l = 1$)	224	3.1	0.14	–	–	≤3.20	≤5.4	≤0.64	–	–	blend
53	11	225855.505(0.100)	6 _{6,1} –5 _{5,1} E	36	3.1	0.09	–	–	≤5.27	≤9.0	≤1.07	–	–	blend
54	11	225900.684(0.100)	6 _{6,0} –5 _{5,0} E	36	3.1	0.09	–	–	≤11.08	≤18.8	≤2.24	–	–	blend with HDO
55	11	225928.659(0.100)	6 _{6,0} –5 _{5,1} A	36	3.1	0.09	–	–	≤7.14	≤12.1	≤1.44	–	–	blend
56	11	225928.659(0.100)	6 _{6,1} –5 _{5,0} A	36	3.1	0.09	–	–	≤7.14	≤12.1	≤1.44	–	–	blend
57	12	225999.145(0.100)	30 _{7,23} –29 _{8,22} E	312	2.2	0.12	–	–	≤0.36	≤0.6	≤0.10	–	–	not detected
58	12	226061.796(0.100)	20 _{3,17} –19 _{4,16} E, ($u_l = 1$)	321	4.0	0.12	–	–	≤0.46	≤0.8	≤0.07	–	–	blend
59	12	226077.920(0.001)	10 _{3,7} –9 _{1,8} E	39	0.3	0.12	–	–	≤2.48	≤4.2	≤5.50	–	–	blend
60	12	226081.175(0.002)	30 _{7,23} –29 _{8,22} A	312	1.8	0.12	–	–	≤0.36	≤0.6	≤0.12	–	–	not detected
61	12	226087.718(0.007)	29 _{4,26} –29 _{3,27} A, ($u_l = 1$)	450	4.3	0.12	–	–	≤0.46	≤0.8	≤0.07	–	–	blend
62	12	226090.301(0.100)	19 _{2,17} –18 _{2,16} E, ($u_l = 1$)	303	47.0	0.12	–	–	≤6.10	≤10.4	≤0.08	–	–	blend
63	12	226112.470(0.007)	29 _{4,26} –29 _{2,27} A, ($u_l = 1$)	450	2.1	0.12	–	–	≤0.36	≤0.6	≤0.11	–	–	not detected
64	12	226125.600(0.001)	10 _{3,7} –9 _{1,8} A	39	0.3	0.12	–	–	≤1.83	≤3.1	≤4.05	–	–	blend

Notes. (1) Observed transitions with $E_{\text{upper}} \lesssim 650$ K. (2) Reference number of the corresponding data set (see Table 1). (3) Frequencies and uncertainties taken from Ilyushin et al. (2009) and from the JPL database (<http://spec.jpl.nasa.gov/>). (4) Transitions in ground state ($u_l = 0$). Transitions in torsional levels ($u_l = 1$) are specified. (5) Energy of the upper level. (6) Line strength calculated by Ilyushin et al. (2009). For the transitions coming from the JPL database, the line strength is calculated from the formulae of Pickett et al. (1998). (7) Noise estimated from spectrum (1σ). (8)–(11) Velocity, linewidth at half intensity, brightness temperature, and integrated intensities. The uncertainties are estimated with the CLASS software. (12) Column densities of the upper state of the transition with respect to the rotational degeneracy ($2J_{\text{up}} + 1$). (13) and (14) Source size estimated at half flux density from detected transitions with spatial resolution allowing isolation of the source. (15) Blended lines are specified.

Table A.3. Transitions of methyl formate observed with the Plateau de Bure Interferometer toward position MF4 in Orion-KL

No.	Set	Frequency (MHz)	Transition	E_{up} (K)	$S\mu^2$ (D ²)	sigma (K)	v (km s ⁻¹)	$\Delta v_{1/2}$ (km s ⁻¹)	T_{B} (K)	W (K km s ⁻¹)	$N_{\text{up}}/g_{\text{up}}$ (10 ¹² cm ⁻²)	Source size (" × ")	PA(°)	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1	1	80531.669(0.030)	9 _{2,8} -9 _{0,9} E, ($\nu_1 = 1$)	216	0.6	0.02	—	—	≤0.06	≤0.2	≤0.35	—	—	not detected
2	1	80565.210(0.010)	10 _{2,8} -9 _{3,7} E	36	1.1	0.02	8.1(0.2)	4.0(0.4)	0.28	1.2(0.1)	1.13	—	—	detected
3	1	80572.589(0.010)	10 _{2,8} -9 _{3,7} A	36	1.1	0.02	—	—	≤0.33	≤1.3	≤1.22	—	—	blend
4	2	80604.508(0.030)	12 _{9,3} -13 _{8,5} E, ($\nu_1 = 1$)	288	0.2	0.12	—	—	≤6.26	≤25.0	≤129.41	—	—	blend
5	2	80652.521(0.010)	15 _{4,11} -14 _{5,10} A	83	1.0	0.12	—	—	≤2.33	≤9.3	≤9.62	—	—	blend
6	3	101202.806(0.010)	9 _{1,9} -8 _{0,8} A, ($\nu_1 = 1$)	213	4.2	0.03	—	—	≤0.42	≤1.8	≤0.35	—	—	blend
7	3	101210.208(0.004)	24 _{3,21} -25 _{2,24} A	187	0.04	0.03	—	—	≤0.37	≤1.6	≤34.70	—	—	blend
8	3	101279.006(0.010)	9 _{1,9} -8 _{0,8} E, ($\nu_1 = 1$)	212	4.0	0.03	—	—	≤0.42	≤1.8	≤0.37	—	—	blend
9	3	101289.471(0.010)	29 _{9,20} -28 _{10,19} A, ($\nu_1 = 1$)	498	1.8	0.03	—	—	≤0.09	≤0.4	≤0.18	—	—	not detected
10	3	101302.159(0.010)	25 _{6,19} -25 _{5,20} A	219	11.1	0.03	—	—	1.07	4.9(0.3)	0.36	—	—	partial blend
11	3	101305.506(0.010)	25 _{6,19} -25 _{5,20} E	219	11.1	0.03	—	—	1.04	4.9(0.6)	0.36	5.0 × 2.7	0	detected
12	3	101318.966(0.010)	13 _{3,11} -13 _{2,12} E, ($\nu_1 = 1$)	246	3.2	0.03	8.4(0.3)	3.9(0.6)	0.23	0.9(0.1)	0.23	4.5 × 2.7	20	detected
13	3	101356.788(0.010)	15 _{2,13} -15 _{1,14} A, ($\nu_1 = 1$)	263	3.5	0.03	—	—	≤0.29	≤1.2	≤0.28	—	—	blend
14	3	101370.505(0.010)	13 _{3,11} -13 _{2,12} E	60	3.2	0.03	7.9(0.1)	4.0(0.1)	1.27	5.4(0.1)	1.39	—	—	partial blend
15	3	101414.746(0.010)	13 _{3,11} -13 _{2,12} A	60	3.2	0.03	8.2(0.1)	4.6(0.1)	1.36	6.6(0.2)	1.70	5.5 × 3.0	0	detected
16	3	101418.330(0.001)	5 _{3,3} -5 _{1,4} A, ($\nu_1 = 1$)	203	0.04	0.03	—	—	≤0.09	≤0.4	≤7.37	—	—	not detected
17	3	101477.421(0.010)	18 _{3,15} -18 _{3,16} E	111	1.8	0.03	—	—	≤7.79	≤32.8	≤14.99	—	—	blend with H ₂ CS
18	3	101545.453(0.010)	18 _{3,15} -18 _{3,16} A	111	1.8	0.03	8.7(0.3)	4.0(0.6)	0.57	2.4(0.3)	1.10	5.5 × 2.7	0	detected
19	3	101626.884(0.010)	9 _{1,9} -8 _{0,8} E	25	4.1	0.03	—	—	≤2.88	≤12.1	≤2.42	—	—	blend with HCOOCH ₃ -A
20	3	101628.149(0.010)	9 _{1,9} -8 _{0,8} A	25	4.1	0.03	—	—	≤2.22	≤9.4	≤1.88	—	—	blend with HCOOCH ₃ -E
21	4	105663.117(0.030)	19 _{13,7} -20 _{12,9} E, ($\nu_1 = 1$)	412	0.4	0.02	—	—	≤0.10	≤0.3	≤0.59	—	—	blend
22	4	105722.672(0.030)	10 _{4,6} -10 _{3,8} E, ($\nu_1 = 1$)	230	0.5	0.02	—	—	≤0.06	≤0.2	≤0.32	—	—	not detected
23	5	105810.803(0.030)	14 _{11,4} -15 _{10,6} E	142	0.2	0.02	—	—	≤0.06	≤0.2	≤0.79	—	—	not detected
24	5	105815.953(0.030)	3 _{3,1} -2 _{2,0} E	10	0.2	0.02	7.9(0.1)	2.5(0.3)	0.15	0.4(0.1)	1.58	—	—	partial blend
25	5	105832.067(0.030)	14 _{11,3} -15 _{10,5} E	142	0.2	0.02	7.6(0.2)	2.5(0.4)	0.14	0.4(0.1)	1.58	—	—	detected
26	6	110153.652(0.010)	10 _{1,10} -9 _{1,9} A, ($\nu_1 = 1$)	218	25.1	0.11	—	—	≤3.32	≤6.6	≤0.20	—	—	blend with NH ₂ D
27	7	203349.158(0.006)	24 _{19,5} -25 _{18,7} E	416	0.2	0.09	—	—	≤1.15	≤2.3	≤4.74	—	—	blend
28	7	203378.812(0.007)	24 _{19,5} -25 _{18,8} E	416	0.2	0.09	—	—	≤16.84	≤33.7	≤69.38	—	—	blend
29	8	203427.575(0.100)	21 _{8,13} -21 _{7,14} A, ($\nu_1 = 1$)	366	6.2	0.09	—	—	≤0.27	≤0.5	≤0.03	—	—	not detected
30	8	203435.554(0.100)	19 _{8,11} -19 _{7,12} E	155	5.3	0.09	7.8(0.1)	2.0(0.3)	2.13	4.6(0.5)	0.36	—	—	partial blend
31	8	203471.840(0.050)	19 _{8,11} -19 _{7,12} E	155	4.9	0.09	—	—	≤1.09	≤2.2	≤0.18	—	—	blend
32	9	223435.416(0.001)	11 _{4,8} -10 _{3,7} A, ($\nu_1 = 1$)	237	1.8	0.20	—	—	≤0.60	≤1.2	≤0.25	—	—	not detected
33	9	223465.340(0.050)	11 _{4,8} -10 _{3,7} E	50	2.1	0.20	—	—	3.83	7.7(2.5)	1.37	2.0 × 1.5	60	detected
34	9	223500.463(0.001)	11 _{4,8} -10 _{3,7} A	50	1.8	0.20	8.0(0.1)	1.9(0.3)	1.90	4.4(0.4)	0.93	2.0 × 1.5	60	detected
35	9	223534.727(0.100)	18 _{5,14} -17 _{5,13} E, ($\nu_1 = 1$)	305	41.6	0.20	8.7(0.3)	3.0(0.4)	1.78	5.8(0.8)	0.05	3.0 × 1.5	60	detected
36	9	223538.511(0.100)	43 _{8,35} -43 _{7,36} E	618	13.9	0.20	—	—	≤0.60	≤1.2	≤0.03	—	—	not detected
37	9	223592.231(0.100)	43 _{8,35} -43 _{7,36} A	618	13.9	0.20	—	—	≤0.60	≤1.2	≤0.03	—	—	not detected
38	9	223618.470(0.007)	27 _{9,19} -27 _{8,19} E, ($\nu_1 = 1$)	464	0.4	0.20	—	—	≤0.60	≤1.2	≤1.20	—	—	not detected
39	9	223624.496(0.100)	37 _{8,30} -37 _{7,31} E	463	11.7	0.20	—	—	≤0.60	≤1.2	≤0.04	—	—	not detected
40	9	223634.916(0.100)	37 _{8,30} -37 _{7,31} A	463	11.7	0.20	—	—	≤0.60	≤1.2	≤0.04	—	—	not detected
41	9	223642.180(0.001)	12 _{5,7} -12 _{3,10} E	63	0.1	0.20	—	—	≤0.60	≤1.2	≤5.35	—	—	not detected
42	9	223645.342(0.001)	12 _{5,7} -12 _{3,10} A	63	0.1	0.20	—	—	≤0.60	≤1.2	≤4.49	—	—	not detected
43	9	223651.592(0.007)	33 _{9,24} -33 _{8,26} E, ($\nu_1 = 1$)	573	0.7	0.20	—	—	≤0.60	≤1.2	≤0.60	—	—	not detected
44	9	223676.472(0.006)	35 _{7,29} -35 _{5,30} A, ($\nu_1 = 1$)	593	3.0	0.20	—	—	≤2.20	≤4.5	≤0.55	—	—	blend

Table A.3. continued.

No.	Set	Frequency (MHz)	Transition	E_{up} (K)	$S\mu^2$ (D ²)	sigma (K)	v (km s ⁻¹)	$\Delta v_{1/2}$ (km s ⁻¹)	T_{B} (K)	W (K km s ⁻¹)	$N_{\text{up}}/g_{\text{up}}$ (10 ¹² cm ⁻²)	Source size ($'' \times ''$)	Source size PA(°)	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
45	9	223782.081(0.007)	33 _{6,28} -33 _{5,29} E, ($u_l = 1$)	543	7.0	0.20	-	-	≤0.60	≤1.2	≤0.06	-	-	not detected
46	9	223821.523(0.002)	35 _{7,29} -35 _{6,30} E	409	8.2	0.20	-	-	≤0.60	≤1.2	≤0.05	-	-	not detected
47	9	223854.201(0.100)	35 _{7,29} -35 _{6,30} A	409	10.1	0.20	-	-	≤0.60	≤1.2	≤0.04	-	-	not detected
48	10	225689.371(0.008)	34 _{5,29} -34 _{5,30} A, ($u_l = 1$)	562	3.0	0.12	-	-	≤20.83	≤41.7	≤5.19	-	-	blend
49	10	225696.842(0.100)	20 _{1,19} -19 _{1,18} E, ($u_l = 1$)	307	50.2	0.12	-	-	≤10.57	≤21.1	≤0.16	-	-	strongly blend
50	10	225702.857(0.100)	19 _{2,17} -18 _{2,16} A, ($u_l = 1$)	304	46.8	0.12	-	-	≤14.30	≤28.6	≤0.23	-	-	blend
51	10	225727.506(0.100)	6 _{6,1} -5 _{5,0} A, ($u_l = 1$)	224	3.1	0.12	-	-	≤0.71	≤1.4	≤0.17	-	-	blend
52	10	225727.506(0.100)	6 _{6,0} -5 _{5,1} A, ($u_l = 1$)	224	3.1	0.12	-	-	≤0.71	≤1.4	≤0.17	-	-	blend
53	11	225855.505(0.100)	6 _{6,1} -5 _{5,1} E	36	3.1	0.07	-	-	≤1.02	≤2.0	≤0.24	-	-	blend
54	11	225900.684(0.100)	6 _{6,0} -5 _{5,0} E	36	3.1	0.07	-	-	≤5.59	≤11.2	≤1.33	-	-	blend with HDO
55	11	225928.659(0.100)	6 _{6,0} -5 _{5,1} A	36	3.1	0.07	-	-	≤1.74	≤3.5	≤0.42	-	-	blend
56	11	225928.659(0.100)	6 _{6,1} -5 _{5,0} A	36	3.1	0.07	-	-	≤1.74	≤3.5	≤0.42	-	-	blend
57	12	225999.145(0.100)	30 _{7,23} -29 _{8,22} E	312	2.2	0.09	-	-	≤0.27	≤0.5	≤0.08	-	-	not detected
58	12	226061.796(0.100)	20 _{3,17} -19 _{4,16} E, ($u_l = 1$)	321	4.0	0.09	-	-	≤0.27	≤0.5	≤0.05	-	-	not detected
59	12	226077.920(0.001)	10 _{3,7} -9 _{1,8} E	39	0.3	0.09	-	-	≤0.27	≤0.5	≤0.65	-	-	not detected
60	12	226081.175(0.002)	30 _{7,23} -29 _{8,22} A	312	1.8	0.09	-	-	≤0.27	≤0.5	≤0.10	-	-	not detected
61	12	226087.718(0.007)	29 _{4,26} -29 _{3,27} A, ($u_l = 1$)	450	4.3	0.09	-	-	≤0.84	≤1.7	≤0.15	-	-	blend
62	12	226090.301(0.100)	19 _{2,17} -18 _{2,16} E, ($u_l = 1$)	303	47.0	0.09	-	-	≤2.57	≤5.1	≤0.04	-	-	blend
63	12	226112.470(0.007)	29 _{4,26} -29 _{2,27} A, ($u_l = 1$)	450	2.1	0.09	-	-	≤0.27	≤0.5	≤0.09	-	-	not detected
64	12	226125.600(0.001)	10 _{3,7} -9 _{1,8} A	39	0.3	0.09	-	-	≤0.32	≤0.6	≤0.78	-	-	blend

Notes. (1) Observed transitions with $E_{\text{upper}} \lesssim 650$ K. (2) Reference number of the corresponding data set (see Table 1). (3) Frequencies and uncertainties taken from Ilyushin et al. (2009) and from the JPL database (<http://spec.jpl.nasa.gov/>). (4) Transitions in ground state ($u_l = 0$). Transitions in torsional levels ($u_t = 1$) are specified. (5) Energy of the upper level. (6) Line strength calculated by Ilyushin et al. (2009). For the transitions coming from the JPL database, the line strength is calculated from the formulae of Pickett et al. (1998). (7) Noise estimated from spectrum (1 σ). (8) Lines with number 33 and 34 are decomposed. Only the first component is given here, other components are given in Table 4, except for line 30 because of the blend with the second component. (9)–(11) Velocity, linewidth at half intensity, brightness temperature, and integrated intensities. The uncertainties are estimated with the CLASS software. (12) Column densities of the upper state of the transition with respect to the rotational degeneracy ($2J_{\text{up}} + 1$). (13) and (14) Source size estimated at half flux density from detected transitions with spatial resolution allowing isolation of the source. (15) Blended lines are specified.

Table A.4. Transitions of methyl formate observed with the Plateau de Bure Interferometer toward position MF5 in Orion-KL.

No.	Set	Frequency (MHz)	Transition	E_{up} (K)	$S\mu^2$ (D ²)	sigma (K)	v (km s ⁻¹)	$\Delta v_{1/2}$ (km s ⁻¹)	T_{B} (K)	W (K km s ⁻¹)	$N_{\text{up}}/g_{\text{up}}$ (10 ¹² cm ⁻²)	Source size ('' × '')	PA(°)	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
1	1	80531.669(0.030)	9 _{2,8} -9 _{0,9} E, ($\nu_1 = 1$)	216	0.6	0.03	—	—	≤0.09	≤0.4	≤0.69	—	—	not detected
2	1	80565.210(0.010)	10 _{2,8} -9 _{3,7} E	36	1.1	0.03	—	—	≤0.21	≤0.8	≤0.75	—	—	blend
3	1	80572.589(0.010)	10 _{2,8} -9 _{3,7} A	36	1.1	0.03	—	—	≤0.28	≤1.1	≤1.04	—	—	blend
4	2	80604.508(0.030)	12 _{9,3} -13 _{8,5} E, ($\nu_1 = 1$)	288	0.2	0.11	—	—	≤5.48	≤21.9	≤113.37	—	—	blend
5	2	80652.521(0.010)	15 _{4,11} -14 _{5,10} A	83	1.0	0.11	—	—	≤1.96	≤7.8	≤8.07	—	—	blend
6	3	101202.806(0.010)	9 _{1,9} -8 _{0,8} A, ($\nu_1 = 1$)	213	4.2	0.04	7.7(0.2)	4.5(0.4)	0.43	2.1(0.2)	0.41	—	—	partial blend
7	3	101210.208(0.004)	24 _{3,21} -25 _{2,24} A	187	0.04	0.04	—	—	≤0.41	≤1.9	≤41.21	—	—	blend
8	3	101279.006(0.010)	9 _{1,9} -8 _{0,8} E, ($\nu_1 = 1$)	212	4.0	0.04	7.5(0.5)	4.6(1.2)	0.49	2.4(0.5)	0.49	5.0 × 2.7	0	detected
9	3	101289.471(0.010)	29 _{9,20} -28 _{10,19} A, ($\nu_1 = 1$)	498	1.8	0.04	—	—	≤0.12	≤0.5	≤0.23	—	—	not detected
10	3	101302.159(0.010)	25 _{6,19} -25 _{5,20} A	219	11.1	0.04	7.7(0.5)	5.5(1.4)	1.16	6.8(1.1)	0.50	—	—	partial blend
11	3	101305.506(0.010)	25 _{6,19} -25 _{5,20} E	219	11.1	0.04	7.7(0.3)	4.2(0.6)	1.11	5.0(0.6)	0.37	5.0 × 2.7	0	detected
12	3	101318.966(0.010)	13 _{3,11} -13 _{2,12} E, ($\nu_1 = 1$)	246	3.2	0.04	7.7(0.2)	4.5(0.5)	0.30	1.4(0.1)	0.36	4.5 × 2.7	20	detected
13	3	101356.788(0.010)	15 _{2,13} -15 _{1,14} A, ($\nu_1 = 1$)	263	3.5	0.04	—	—	≤0.19	≤0.9	≤0.21	—	—	blend
14	3	101370.505(0.010)	13 _{3,11} -13 _{2,12} E	60	3.2	0.04	7.9(0.1)	4.7(0.1)	1.42	7.1(0.1)	1.83	5.0 × 2.7	0	detected
15	3	101414.746(0.010)	13 _{3,11} -13 _{2,12} A	60	3.2	0.04	7.8(0.1)	4.8(0.1)	1.42	7.2(0.1)	1.85	5.5 × 3.0	0	detected
16	3	101418.330(0.001)	5 _{3,3} -5 _{1,4} A, ($\nu_1 = 1$)	203	0.04	0.04	—	—	≤0.12	≤0.5	≤9.22	—	—	not detected
17	3	101477.421(0.010)	18 _{3,15} -18 _{3,16} E	111	1.8	0.04	—	—	≤7.56	≤34.4	≤15.72	—	—	blend with H ₂ CS
18	3	101545.453(0.010)	18 _{3,15} -18 _{3,16} A	111	1.8	0.04	—	—	≤0.58	≤2.6	≤1.19	—	—	blend
19	3	101626.884(0.010)	9 _{1,9} -8 _{0,8} E	25	4.1	0.04	—	—	≤2.89	≤13.1	≤2.62	—	—	blend with HCOOCH ₃ -A
20	3	101628.149(0.010)	9 _{1,9} -8 _{0,8} A	25	4.1	0.04	—	—	≤2.42	≤11.0	≤2.20	—	—	blend with HCOOCH ₃ -E
21	4	105663.117(0.030)	19 _{13,7} -20 _{12,9} E, ($\nu_1 = 1$)	412	0.4	0.02	—	—	≤0.08	≤0.2	≤0.39	—	—	blend
22	4	105722.672(0.030)	10 _{4,6} -10 _{3,8} E, ($\nu_1 = 1$)	230	0.5	0.02	—	—	≤0.06	≤0.1	≤0.16	—	—	not detected
23	5	105810.803(0.030)	14 _{11,4} -15 _{10,6} E	142	0.2	0.02	—	—	≤0.06	≤0.1	≤0.39	—	—	not detected
24	5	105815.953(0.030)	3 _{3,1} -2 _{2,0} E	10	0.2	0.02	7.9(0.4)	2.6(0.3)	0.13	0.3(0.1)	1.18	—	—	partial blend
25	5	105832.067(0.030)	14 _{11,3} -15 _{10,5} E	142	0.2	0.02	7.5(0.2)	2.1(0.3)	0.12	0.3(0.1)	1.18	—	—	detected
26	6	110153.652(0.010)	10 _{1,10} -9 _{1,9} A, ($\nu_1 = 1$)	218	25.1	0.10	—	—	≤2.75	≤7.2	≤0.22	—	—	blend with NH ₂ D
27	7	203349.158(0.006)	24 _{19,5} -25 _{18,7} E	416	0.2	0.16	—	—	≤1.44	≤2.9	≤5.97	—	—	blend
28	7	203378.812(0.007)	24 _{19,6} -25 _{18,8} E	416	0.2	0.16	—	—	≤4.30	≤8.6	≤17.71	—	—	blend
29	8	203427.575(0.100)	21 _{8,13} -21 _{7,14} A, ($\nu_1 = 1$)	366	6.2	0.16	—	—	≤0.48	≤1.0	≤0.07	—	—	not detected
30	8	203435.554(0.100)	19 _{8,11} -19 _{7,12} A	155	5.3	0.16	—	—	≤1.85	≤3.7	≤0.29	—	—	blend
31	8	203471.840(0.050)	19 _{8,11} -19 _{7,12} E	155	4.9	0.16	—	—	≤1.25	≤2.5	≤0.21	—	—	blend
32	9	223435.416(0.001)	11 _{4,8} -10 _{3,7} A, ($\nu_1 = 1$)	237	1.8	0.27	—	—	≤0.81	≤1.7	≤0.35	—	—	not detected
33	9	223465.340(0.050)	11 _{4,8} -10 _{3,7} E	50	2.1	0.27	7.8(0.1)	4.3(0.3)	2.2	10.1(0.6)	1.79	2.0 × 1.5	60	detected
34	9	223500.463(0.001)	11 _{4,8} -10 _{3,7} A	50	1.8	0.27	7.6(0.1)	4.2(0.2)	2.4	10.7(0.5)	2.26	2.0 × 1.5	60	detected
35	9	223534.727(0.100)	18 _{5,14} -17 _{5,13} E, ($\nu_1 = 1$)	305	41.6	0.27	8.1(0.1)	5.7(0.3)	2.5	15.1(0.8)	0.14	3.0 × 1.5	70	detected
36	9	223538.511(0.100)	43 _{8,35} -43 _{7,36} E	618	13.9	0.27	—	—	≤0.81	≤1.7	≤0.05	—	—	not detected
37	9	223592.231(0.100)	43 _{8,35} -43 _{7,36} A	618	13.9	0.27	—	—	≤0.81	≤1.7	≤0.05	—	—	not detected
38	9	223618.470(0.007)	27 _{9,19} -27 _{8,19} E, ($\nu_1 = 1$)	464	0.4	0.27	—	—	≤0.81	≤1.7	≤1.70	—	—	not detected
39	9	223624.496(0.100)	37 _{8,30} -37 _{7,31} E	463	11.7	0.27	—	—	≤0.81	≤1.7	≤0.05	—	—	not detected
40	9	223634.916(0.100)	37 _{8,30} -37 _{7,31} A	463	11.7	0.27	—	—	≤0.81	≤1.7	≤0.05	—	—	not detected
41	9	223642.180(0.001)	12 _{5,7} -12 _{3,10} E	63	0.1	0.27	—	—	≤0.81	≤1.7	≤7.57	—	—	not detected
42	9	223645.342(0.001)	12 _{5,7} -12 _{3,10} A	63	0.1	0.27	—	—	≤0.81	≤1.7	≤6.37	—	—	not detected
43	9	223651.592(0.007)	33 _{9,24} -33 _{8,26} E, ($\nu_1 = 1$)	573	0.7	0.27	—	—	≤0.81	≤1.7	≤0.85	—	—	not detected
44	9	223676.472(0.006)	35 _{7,29} -35 _{5,30} A, ($\nu_1 = 1$)	593	3.0	0.27	—	—	≤0.81	≤1.7	≤0.21	—	—	not detected

Table A.4. continued.

No.	Set	Frequency (MHz)	Transition	E_{up} (K)	$S\mu^2$ (D ²)	sigma (K)	v (km s ⁻¹)	$\Delta v_{1/2}$ (km s ⁻¹)	T_{B} (K)	W (K km s ⁻¹)	$N_{\text{up}}/g_{\text{up}}$ (10 ¹² cm ⁻²)	Source size (" × ")	Source size PA(°)	Comments
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)	(10)	(11)	(12)	(13)	(14)	(15)
45	9	223782.081(0.007)	33 _{6,28} –33 _{5,29} E, ($v_t = 1$)	543	7.0	0.27	–	–	≤0.81	≤1.7	≤0.09	–	–	not detected
46	9	223821.523(0.002)	35 _{7,29} –35 _{6,30} E	409	8.2	0.27	–	–	≤0.81	≤1.7	≤0.08	–	–	not detected
47	9	223854.201(0.100)	35 _{7,29} –35 _{6,30} A	409	10.1	0.27	–	–	≤0.81	≤1.7	≤0.06	–	–	not detected
48	10	225689.371(0.008)	34 _{5,29} –34 _{5,30} A, ($v_t = 1$)	562	3.0	0.13	–	–	≤15.43	≤30.9	≤3.85	–	–	blend
49	10	225696.842(0.100)	20 _{1,19} –19 _{1,18} E, ($v_t = 1$)	307	50.2	0.13	–	–	≤13.25	≤26.5	≤0.20	–	–	blend
50	10	225702.857(0.100)	19 _{2,17} –18 _{2,16} A, ($v_t = 1$)	304	46.8	0.13	–	–	≤7.71	≤15.4	≤0.12	–	–	blend
51	10	225727.506(0.100)	6 _{6,1} –5 _{5,0} A, ($v_t = 1$)	224	3.1	0.13	–	–	≤0.90	≤1.8	≤0.21	–	–	blend
52	10	225727.506(0.100)	6 _{6,0} –5 _{5,1} A, ($v_t = 1$)	224	3.1	0.13	–	–	≤0.90	≤1.8	≤0.21	–	–	blend
53	11	225855.505(0.100)	6 _{6,1} –5 _{5,1} E	36	3.1	0.08	–	–	≤1.20	≤2.4	≤0.29	–	–	blend
54	11	225900.684(0.100)	6 _{6,0} –5 _{5,0} E	36	3.1	0.08	–	–	≤3.16	≤6.3	≤0.75	–	–	blend with HDO
55	11	225928.659(0.100)	6 _{6,0} –5 _{5,1} A	36	3.1	0.08	–	–	≤1.53	≤3.1	≤0.37	–	–	blend
56	11	225928.659(0.100)	6 _{6,1} –5 _{5,0} A	36	3.1	0.08	–	–	≤1.53	≤3.1	≤0.37	–	–	blend
57	12	225999.145(0.100)	30 _{7,23} –29 _{8,22} E	312	2.2	0.10	–	–	≤0.30	≤0.6	≤0.10	–	–	not detected
58	12	226061.796(0.100)	20 _{3,17} –19 _{4,16} E, ($v_t = 1$)	321	4.0	0.10	–	–	≤0.30	≤0.6	≤0.06	–	–	not detected
59	12	226077.920(0.001)	10 _{3,7} –9 _{1,8} E	39	0.3	0.10	–	–	≤0.30	≤0.6	≤0.79	–	–	not detected
60	12	226081.175(0.002)	30 _{7,23} –29 _{8,22} A	312	1.8	0.10	–	–	≤0.30	≤0.6	≤0.12	–	–	not detected
61	12	226087.718(0.007)	29 _{4,26} –29 _{3,27} A, ($v_t = 1$)	450	4.3	0.10	–	–	≤0.79	≤1.6	≤0.14	–	–	blend
62	12	226090.301(0.100)	19 _{2,17} –18 _{2,16} E, ($v_t = 1$)	303	47.0	0.10	–	–	≤1.00	≤2.0	≤0.02	–	–	blend
63	12	226112.470(0.007)	29 _{4,26} –29 _{3,27} A, ($v_t = 1$)	450	2.1	0.10	–	–	≤0.30	≤0.6	≤0.11	–	–	not detected
64	12	226125.600(0.001)	10 _{3,7} –9 _{1,8} A	39	0.3	0.10	–	–	≤0.59	≤1.2	≤1.57	–	–	blend

Notes. (1) Observed transitions with $E_{\text{upper}} \leq 650$ K. (2) Reference number of the corresponding data set (see Table 1). (3) Frequencies and uncertainties taken from Ilyushin et al. (2009) and from the JPL database (<http://spec.jpl.nasa.gov/>). (4) Transitions in ground state ($v_t = 0$). Transitions in torsional levels ($v_t = 1$) are specified. (5) Energy of the upper level. (6) Line strength calculated by Ilyushin et al. (2009). For the transitions coming from the JPL database, the line strength is calculated from the formulae of Pickett et al. (1998). (7) Noise estimated from spectrum (1σ). (8)–(11) Velocity, linewidth at half intensity, brightness temperature, and integrated intensities. The uncertainties are estimated with the CLASS software. (12) Column densities of the upper state of the transition with respect to the rotational degeneracy ($2J_{\text{up}} + 1$). (13) and (14) Source size estimated at half flux density from detected transitions with spatial resolution allowing isolation of the source. (15) Blended lines are specified.