Tentative detection of ethylene glycol toward W51/e2 and G34.3+0.2^{★,★★,★★★}

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ABSTRACT

Context. With only a few low- and high-mass star-formation regions studied in detail so far, it is unclear what role the environment plays in complex molecule formation. In this light, a comparison of relative abundances of related species between sources might be useful for explaining any observed differences.

Aims. We seek to measure the relative abundance between three important complex organic molecules, ethylene glycol ((CH₂OH)₂), glycolaldehyde (CH₂OHCHO) and methyl formate (HCOOCH₃), toward high-mass protostars and thereby provide additional constraints on their formation pathways.

Methods. We use IRAM 30 m single-dish observations of the three species toward two high-mass star-forming regions – W51/e2 and G34.3+0.2 – and report a tentative detection of (CH₂OH)₂ toward both sources.

Results. Assuming that (CH₂OH)₂, CH₂OHCHO, and HCOOCH₃ spatially coexist, relative abundance ratios, HCOOCH₃/(CH₂OH)₂, of 31 and 35 are derived for G34.3+0.2 and W51/e2, respectively. CH₂OHCHO is not detected, but the data provide lower limits to the HCOOCH₃/CH₂OHCHO abundance ratios of ≥ 193 for G34.3+0.2 and ≥ 550 for W51/e2. A comparison of these results to measurements from various sources in the literature indicates that the source luminosities may be correlated with the HCOOCH₃/(CH₂OH)₂ and HCOOCH₃/CH₂OHCHO ratios. This apparent correlation may be a consequence of the relative time scales each source spend at different temperature ranges in their evolution. Furthermore, we obtain lower limits to the ratio of (CH₂OH)₂/CH₂OHCHO for G34.3+0.2 (≥ 6) and W51/e2 (≥ 16). This result confirms that a high (CH₂OH)₂/CH₂OHCHO abundance ratio is not a specific property of comets, as previously speculated.

Key words. ISM: molecules – ISM: abundances – ISM: individual objects: W51/e2 – methods: observational – astrochemistry – ISM: individual objects: G34.3+0.2

1. Introduction

How complex organic – and potentially prebiotic – molecules are formed in regions of low- and high-mass star formation remains a central question in astrochemistry. To date there has been no consensus about how complex organic molecules (COMs hereafter) form in dense regions of the interstellar medium, despite the increasing number of detections (e.g., Herbst & van Dishoeck 2009). One promising suggestion was that warm gas phase chemistry, following evaporation of simple ices, could be a primary formation pathway (e.g., Millar et al. 1991; Charnley et al. 1992). However, more recent laboratory experiments and chemical modeling has shown that this mechanism is not effective enough to account for the observed abundances (e.g., Geppert et al. 2006). An alternative formation mechanism involves UV induced radicals. Garrod et al. (2008) propose that, during the warm up phase, radicals can migrate on the grains surfaces and form complex species that

are then released into the gas phase at higher temperatures. The initial ice composition and the amount of UV radiation have also proved to play an important part in the formation process (Öberg et al. 2009). To determine the formation pathway of COMs, it is useful to determine abundance ratios between different related species because these ratios, in comparison with the predicted abundance ratios from chemical models, can provide constraints on the formation processes. Indeed, variations in the abundance profiles can reflect the physical and chemical conditions that are occurring. It is therefore important to observe these species in different environments.

Some of the simplest species in this context include the oxygen-bearing COMs associated to glycolaldehyde, CH₂OHCHO, including its isomer methyl formate (HCOOCH₃ or CH₃OCHO) and the reduced alcohol version of CH₂OHCHO, ethylene glycol, (CH₂OH)₂ (also commonly known as anti-freeze). By constraining the relative abundances of these species in different environments the hope is to be able to explore, for instance, the importance of initial chemical conditions, temperature and irradiation in the formation for comparison, such as for laboratory experiments (e.g., Öberg et al. 2009) and as input for sophisticated chemical models (e.g., Garrod et al. 2008). For example, in their laboratory experiments Öberg et al. (2009) show that the relative abundances of HCOOCH₃ to CH₂OHCHO and

* Based on observations carried out with the IRAM 30 m telescope.

** The reduced spectra (FITS files) are 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/582/A64>

*** Appendices are available in electronic form at <http://www.aanda.org>

(CH₂OH)₂ strongly depend on both the ice temperature and exact ice composition in terms of the relative amounts of CO and CH₃OH.

So far, (CH₂OH)₂ has been detected toward high-mass sources such as the Galactic center source Sgr B2(N) by Hollis et al. (2002), marginally toward W51 e1/e2 by Kalenskii & Johansson (2010), and recently also toward the Orion Kleinmann-Low (KL) nebula by Brouillet et al. (2015). (CH₂OH)₂ has also been observed toward the low-mass Class 0 protostars IRAS 16293–2422 (Jørgensen et al. 2012, and in prep.) and NGC 1333 IRAS 2A (Maury et al. 2014; Coutens et al. 2015) as well as toward the intermediate-mass protostar NGC 7129 FIRS2 (Fuente et al. 2014). CH₂OHCHO has been detected toward Sgr B2(N) (Hollis et al. 2000, 2001, 2004; Halfen et al. 2006; Requena-Torres et al. 2008), the high-mass hot molecular core G31.41+0.31 (Beltrán et al. 2009), in IRAS 16293–2422 by Jørgensen et al. (2012) and recently also in NGC 7129 FIRS2 (Fuente et al. 2014), NGC 1333 IRAS 2A (Coutens et al. 2015; Taquet et al. 2015) and NGC 1333 IRAS 4A (Taquet et al. 2015). HCOOCH₃ is the most abundant isomer of CH₂OHCHO, and it has previously been observed in numerous hot cores and corinos (e.g., Blake et al. 1987; Bisschop et al. 2007; Demyk et al. 2008; Favre et al. 2014, 2011). There are some notable differences in terms of the abundance ratios. For example, Coutens et al. (2015) find a (CH₂OH)₂/CH₂OHCHO ratio of ~ 5 in NGC 1333 IRAS 2A, while Jørgensen et al. (2012 and in prep.) find a lower value of ~ 1 in IRAS 16293–2422. These changes hint that it might be useful to explore these ratios in different sources sampling similar physical conditions.

This paper presents IRAM 30 m observations of (CH₂OH)₂ and CH₂OHCHO toward the high-mass protostars W51/e2 (distance = 5.4 kpc, Sato et al. 2010) and G34.3+0.2 (distance = 3.8 kpc, Kurtz et al. 2000). The aim of this study is to determine the relative abundance of (CH₂OH)₂ and CH₂OHCHO to HCOOCH₃ and compare to other sources from the literature. Overall our aim is to investigate the use of abundance ratios of species that are believed to be chemically related to explore the origin of complex molecules in the dense interstellar medium. In Sect. 2, the IRAM 30 m observations are presented. Data modeling, results and analysis are presented in Sect. 3 and discussed in Sect. 4.

2. Observations

The observations were performed with the IRAM 30 m telescope at Pico Veleta, Spain on December 13 and 14, 2012 for W51/e2 and G34.3+0.2, respectively. The coordinates of the phase tracking center used for the two sources were $\alpha_{J2000} = 19^{\text{h}}23^{\text{m}}43^{\text{s}}.9$, $\delta_{J2000} = 14^{\circ}30'34''.8$ for W51/e2 and $\alpha_{J2000} = 18^{\text{h}}53^{\text{m}}18^{\text{s}}.6$, $\delta_{J2000} = 01^{\circ}14'58''.0$ for G34.3+0.2. The observations were performed in position-switching mode using $[-600'', 0'']$ as reference for the OFF positions. The spectral setup was chosen to target (CH₂OH)₂ and CH₂OHCHO in the observations. The EMIR receiver was used in dual-band polarisation (E090/E230) in connection with i) the 200 kHz Fourier transform spectrometer (FTS) backend in the frequency ranges 99.70–106.3 GHz and 238.2–246.0 GHz for the E090 and E230 bands, respectively; ii) the WILMA backend in the frequency ranges 99.88–103.6 GHz and 238.4–242.1 GHz for the E090 and E230 bands, respectively. Data was reduced with the Continuum and Line Analysis Single-dish Software¹ (CLASS). The resulting FTS spectra were smoothed to a spectral resolution of 1.15 km s⁻¹

for the E090 band and 1.22 km s⁻¹ for the E230 band, while the WILMA spectra were smoothed to 5.88 km s⁻¹ and 2.49 km s⁻¹ for the E090 and E230 bands, respectively. Spectra resulting from the FTS backend presented a standing wave pattern, and the WILMA observations were therefore used as a sanity check for the FTS data and for confirmation of the detections made in the FTS observations for the lines where the frequency of the two sets of observations match. The standing wave present in the FTS observations was removed using a fast Fourier transform in the data reduction.

Throughout this paper, the intensity is given as the main beam brightness temperature (T_{mb}), which is defined as

$$T_{\text{mb}} = T_{\text{a}} \times \frac{F_{\text{eff}}}{B_{\text{eff}}},$$

where T_{a} is the antenna temperature, F_{eff} the forward efficiency and B_{eff} the beam efficiency. The values used were $F_{\text{eff}} = 0.94$ and 0.92 and $B_{\text{eff}} = 0.78$ and 0.58 for 1 mm and 3 mm respectively. The half-power beam sizes are $\sim 10''$ and $\sim 24''$ for the observations at 1 mm and 3 mm, respectively.

3. Analysis and results

Spectra from both sources show a rich forest of lines characteristic of high-mass sources. A total of 21 and 19 lines have peak temperatures above 5 K for W51/e2 and G34.3+0.2, respectively. The strongest lines in both spectra are the CS 5–4 transition at 244 935 MHz. It is important to know that there is still a remnant oscillation in the baseline even after the removal of the standing wave in the spectra. This increases the rms noise of the spectra, which complicates the analysis of faint lines. Therefore, in addition to the global baseline subtraction, an additional local zero-, or first-order baseline subtraction was therefore performed before making a Gaussian fit of the (CH₂OH)₂ lines. This additional baseline subtraction is applied in a range of ± 100 km s⁻¹ for each line. As for the data reduction, CLASS was used for the additional baseline subtraction, as well as for Gaussian profile fits to the detected lines. The resulting rms of the local baseline is ~ 60 mK for the 1 mm observations and ~ 7 mK for the 3 mm observations.

To ensure proper line identification, we checked the line observations against entries in the Splatalogue database for astronomical spectroscopy². In addition, we made a reference model where we produced synthetic spectra for the line emission of common species (CH₃OCH₃, HCOOH, CH₃CHO, CH₃OH, C₂H₅OH and CH₃CN) in order to visually exclude lines that are blended with any of these molecules. Table 1 lists spectroscopic parameters for the (CH₂OH)₂ transitions that can be excited in the observed frequency range. Transitions with $\log(A_{\text{ul}}) < -5$ for the 3 mm observations and $\log(A_{\text{ul}}) < -4$ and $E_{\text{up}} > 300$ K for the 1 mm observations have been excluded from the table, because these transitions are predicted from the synthetic spectra to have peak intensities ≤ 0.02 K, i.e., are not detectable.

The spectroscopic data for (CH₂OH)₂ come from Christen & Müller (2003) and Christen et al. (1995) and are available from the CDMS database³ (Müller et al. 2001, 2005), while the spectroscopic data for HCOOCH₃ and CH₂OHCHO are from Ilyushin et al. (2009) and Carroll et al. (2010) respectively, available from the JPL database⁴ (Pickett et al. 1998). For the analysis, the (CH₂OH)₂ lines that are reasonably well separated and

¹ <http://www.iram.fr/IRAMFR/GILDAS>

² <http://www.splatalogue.net>

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

⁴ <http://spec.jpl.nasa.gov/home.html>

Table 1. Transitions of $(\text{CH}_2\text{OH})_2$ in the observed frequency range.

Transition	Frequency [MHz]	E_{up} [K]	$\log_{10}(A_{\text{ul}})$ [s ⁻¹]	Rotational diagram	
3 mm observations					
9 _{1,8} $v = 1$ –8 _{1,7} $v = 0$	100 333.6424	23.6	–4.6773	W51/e2	
9 _{3,6} $v = 1$ –8 _{3,5} $v = 0$	100 490.6121	27.0	–4.6800		
11 _{1,10} $v = 1$ –10 _{2,9} $v = 1$	102 064.0770	33.9	–4.6692		
10 _{1,10} $v = 1$ –9 _{1,9} $v = 0$	102 291.5860	26.2	–4.5798		
9 _{2,7} $v = 1$ –8 _{2,6} $v = 0$	102 539.4267	25.0	–4.6355		
10 _{0,10} $v = 1$ –9 _{0,9} $v = 0$	102 689.8384	26.1	–4.4419		
11 _{9,2} $v = 0$ –10 _{9,1} $v = 1$	105 574.9490	72.2	–4.9342		
11 _{8,4/3} $v = 0$ –10 _{8,3/2} $v = 1$	105 644.1940	63.9	–4.5179		
11 _{1,10} $v = 0$ –10 _{1,9} $v = 1$	105 701.0020	33.6	–4.3644		
11 _{7,5/4} $v = 0$ –10 _{7,4/3} $v = 1$	105 735.3520	56.5	–4.4051		
11 _{3,9} $v = 0$ –10 _{3,8} $v = 1$	105 834.6960	36.9	–4.5676		
11 _{6,6/5} $v = 0$ –10 _{6,5/4} $v = 1$	105 866.9546	50.1	–4.3228		
11 _{5,7} $v = 0$ –10 _{5,6} $v = 1$	106 072.0524	44.7	–4.6197		
11 _{5,6} $v = 0$ –10 _{5,5} $v = 1$	106 088.9178	44.8	–4.5104		
1 mm observations					
24 _{17,8/7} $v = 0$ –23 _{17,7/6} $v = 1$	238 828.3252	289.3	–3.4806	W51/e2	
24 _{16,9/8} $v = 0$ –23 _{16,8/7} $v = 1$	238 904.3833	273.1	–3.4330		
24 _{15,10/9} $v = 0$ –23 _{15,9/8} $v = 1$	238 993.6343	257.9	–3.3925		
30 _{12,19/18} $v = 1$ –30 _{11,19/20} $v = 0$	238 994.0910	299.7	–4.8643		
22 _{5,17} $v = 1$ –21 _{5,16} $v = 0$	238 994.7545	138.6	–3.5149		
24 _{13,12/11} $v = 0$ –23 _{13,11/10} $v = 1$	239 231.3329	230.4	–3.3269		
24 _{12,13/12} $v = 0$ –23 _{12,12/11} $v = 1$	239 395.0677	218.2	–3.3002		
24 _{11,14/13} $v = 0$ –23 _{11,13/12} $v = 1$	239 605.3330	206.9	–3.2765		
25 _{3,23} $v = 0$ –24 _{3,22} $v = 1$	239 792.7984	161.6	–3.4697		
24 _{10,15/14} $v = 0$ –23 _{10,14/13} $v = 1$	239 883.5631	196.7	–3.2555		
25 _{2,23} $v = 0$ –24 _{2,22} $v = 1$	239 957.1582	161.6	–3.4917		
23 _{4,20} $v = 1$ –22 _{4,19} $v = 0$	239 980.0390	144.1	–3.4495		
24 _{3,21} $v = 0$ –23 _{3,20} $v = 1$	240 147.9627	155.2	–3.4704		
24 _{9,16/15} $v = 0$ –23 _{9,15/14} $v = 1$	240 265.7687	187.4	–3.2365		
22 _{4,19} $v = 0$ –21 _{3,18} $v = 0$	240 608.1463	132.6	–3.9839		
25 _{1,0,25} $v = 1$ –24 _{1,0,24} $v = 0$	240 778.3210	148.0	–3.1643	W51/e2 and G34.3+0.2	
24 _{8,17} $v = 0$ –23 _{8,16} $v = 1$	240 807.8795	179.2	–3.5201		
24 _{8,16} $v = 0$ –23 _{8,15} $v = 1$	240 828.8863	179.2	–3.5199		
22 _{4,18} $v = 1$ –21 _{4,17} $v = 0$	240 875.3680	135.5	–3.4905		
59 _{10,50} $v = 1$ –59 _{9,51} $v = 1$	240 888.3533	925.5	–4.4992		
24 _{5,20} $v = 0$ –23 _{5,19} $v = 1$	241 291.2695	160.7	–3.5046		
24 _{7,18} $v = 0$ –23 _{7,17} $v = 1$	241 545.2626	172.1	–3.5045		
24 _{7,17} $v = 0$ –23 _{7,16} $v = 1$	241 817.6908	172.1	–3.5026		
24 _{6,19} $v = 0$ –23 _{6,18} $v = 1$	241 860.7330	166.0	–3.5459		
23 _{15,9/8} $v = 1$ –22 _{15,8/7} $v = 0$	242 244.6928	246.4	–3.4004		
23 _{14,10/9} $v = 1$ –22 _{14,9/8} $v = 0$	242 246.3392	232.2	–3.3608		
23 _{16,8/7} $v = 1$ –22 _{16,7/6} $v = 0$	242 267.1576	261.6	–3.4470		
23 _{13,11/10} $v = 1$ –22 _{13,10/9} $v = 0$	242 277.7167	218.9	–3.3268		
23 _{17,7/6} $v = 1$ –22 _{17,6/5} $v = 0$	242 309.7823	277.8	–3.5027		
23 _{12,12/11} $v = 1$ –22 _{12,11/10} $v = 0$	242 347.0348	206.7	–3.2973		
23 _{18,6/5} $v = 1$ –22 _{18,5/4} $v = 0$	242 369.7298	295.0	–3.5709		
26 _{2,1,25} $v = 0$ –25 _{2,1,24} $v = 1$	242 389.2838	166.9	–3.1601	W51/e2 and G34.3+0.2	
23 _{11,13/12} $v = 1$ –22 _{11,12/11} $v = 0$	242 466.6909	195.4	–3.2714		
23 _{10,14/13} $v = 1$ –22 _{10,13/12} $v = 0$	242 656.2283	185.2	–3.2486		
23 _{3,20} $v = 1$ –22 _{3,19} $v = 0$	242 897.4293	143.6	–3.7464		
23 _{9,15/14} $v = 1$ –22 _{9,14/13} $v = 0$	242 948.2909	175.9	–3.2282		W51/e2
24 _{6,18} $v = 0$ –23 _{6,17} $v = 1$	243 259.7398	166.3	–3.8001		
23 _{8,16} $v = 1$ –22 _{8,15} $v = 0$	243 396.0258	167.7	–3.5106		
23 _{8,15} $v = 1$ –22 _{8,14} $v = 0$	243 408.4357	167.7	–3.5105		
23 _{5,19} $v = 1$ –22 _{5,18} $v = 0$	243 636.5668	149.1	–3.4704		
23 _{7,17} $v = 1$ –22 _{7,16} $v = 0$	244 054.2878	160.5	–3.4934		
23 _{7,16} $v = 1$ –22 _{7,15} $v = 0$	244 233.4545	160.5	–3.4927		
24 _{3,22} $v = 1$ –23 _{3,21} $v = 0$	244 399.6722	150.1	–3.4754		
24 _{2,22} $v = 1$ –23 _{2,21} $v = 0$	244 685.1477	150.1	–3.4399		
23 _{6,18} $v = 1$ –22 _{6,17} $v = 0$	244 879.9193	154.4	–3.5188		
27 _{1,0,27} $v = 0$ –26 _{1,0,26} $v = 1$	245 022.7624	171.4	–3.1407		
24 _{6,19} $v = 1$ –23 _{6,17} $v = 1$	245 410.9218	166.3	–3.7580		

Notes. Catalog values for the $(\text{CH}_2\text{OH})_2$ transitions that can be excited in the observed frequency range for W51/e2 and G34.3+0.2. Some faint transitions have been excluded from this table, please Sect. 3. The source names are listed for the lines that are used in the rotational diagram analysis.

Fig. 1. Observed (black) and synthetic (red) spectra of the five transitions of $(\text{CH}_2\text{OH})_2$ in W51/e2 that are used for the analysis. Also shown are the synthetic spectra of all other species investigated in this study (blue) to demonstrate that the $(\text{CH}_2\text{OH})_2$ lines in question are not blended. The transitions are located at 239 883.56, 240 807.88, 242 656.23, 242 948.29 and 100 333.64 MHz – denoted by black vertical lines in the plot. The displayed frequency region in each plot corresponds to $\sim 200 \text{ km s}^{-1}$.

Fig. 2. Same as for Fig. 1 but for G34.3+0.2. The transitions are located at 240 807.88 and 242 656.23 MHz – indicated by black vertical lines in the plot.

have a peak temperature above 3σ were selected. For W51/e2 we included the lines at $\sim 100\,333$ and $\sim 242\,656$ MHz, although they are partially blended, because it is possible to distinguish the $(\text{CH}_2\text{OH})_2$ peak from the other peaks and perform a multiple Gaussian fit that includes all relevant peaks.

Figures 1 and 2 show a zoom-in of the area of $\sim 200 \text{ km s}^{-1}$, which corresponds to ~ 160 MHz in the 1 mm observations and ~ 70 MHz in the 3 mm observations, around each detected line in both sources after the local baseline subtraction. Superimposed onto the observed spectra are the synthetic spectra of $(\text{CH}_2\text{OH})_2$ as well as the other species investigated here, as

to demonstrate that the chosen $(\text{CH}_2\text{OH})_2$ lines are not blended. The fit to the entire observed spectra for both sources are shown in Figs. B.1–B.8 in the appendix. Table A.1 in the appendix lists the estimated column densities of the molecules in the reference model. Table 2 lists spectroscopic parameters and the observed quantities from the fits of the $(\text{CH}_2\text{OH})_2$ lines: the integrated line intensity ($\int T_{\text{mb}} d\nu$), position (V_{LSR}), line width ($\Delta\nu$) and peak temperature (Peak T_{mb}).

A total of 35 and 52 well separated lines have been detected above the 3σ level in the 1 mm and 3 mm data for HCOOCH_3 in W51/e2 and G34.3+0.2, respectively. For $(\text{CH}_2\text{OH})_2$, four and

Table 2. Transitions of $(\text{CH}_2\text{OH})_2$ observed toward W51/e2 and G34.3+0.2 with the IRAM 30-m telescope.

Transition $J'_{K_a, K_c} v' - J''_{K_a, K_c} v''$	Freq. [MHz]	E_{up} [K]	$\log_{10} A_{\text{ul}}$ [s^{-1}]	$\int T_{\text{mb}} \Delta v$ [K km s $^{-1}$]	V_{LSR} [km s $^{-1}$]	Δv [km s $^{-1}$]	Peak T_{mb} [K]
W51/e2							
$9_{1,8} v = 1 - 8_{1,7} v = 0$	100 333.64	24	-4.6773	0.2	55.1	5.5	0.03
$24_{10,15/14} v = 0 - 23_{10,14/13} v = 1$	239 883.56	197	-3.2555	2.7	55.6	6.8	0.38
$24_{8,17} v = 0 - 23_{8,16} v = 1$	240 807.88	179	-3.5201	2.0	56.7	5.9	0.32
$23_{10,14/13} v = 1 - 22_{10,13/12} v = 0$	242 656.23	185	-3.5496	4.0	56.9	7.4	0.50
$23_{9,15/14} v = 1 - 22_{9,14/13} v = 0$	242 948.29	176	-3.5292	1.4	56.5	5.0	0.27
G34.3+0.2							
$24_{8,17} v = 0 - 23_{8,16} v = 1$	240 807.88	179	-3.5201	1.0	57.7	4.1	0.23
$23_{10,14/13} v = 1 - 22_{10,13/12} v = 0$	242 656.23	185	-3.5496	1.0	58.4	5.0	0.19

Notes. The table lists spectroscopic parameters and observed quantities from Gaussian fits to the detected $(\text{CH}_2\text{OH})_2$ lines: integrated line intensity ($\int T_{\text{mb}} \Delta v$), line position (V_{LSR}), line width (Δv) and peak temperature (Peak T_{mb}). The error of $\int T_{\text{mb}} \Delta v$ is estimated to $\sim 30\%$ as determined by the observational uncertainty, while the errors on V_{LSR} and Δv are $\sim 1.0 \text{ s}^{-1}$ and $\sim 2.0 \text{ km s}^{-1}$, respectively. The line intensities have been added together for the hyper fine structure transitions (denoted by / in the quantum numbers).

two lines toward W51/e2 and G34.3+0.2 respectively, are detected in the 1 mm observations; while only one line is detected at 3 mm toward W51/e2. Many other $(\text{CH}_2\text{OH})_2$ lines, as well as some potential CH_2OHCHO lines are present in both data sets, but they are either blended with other species or too faint to be properly detected above a 3σ limit.

3.1. Modeling

Assuming LTE and optically thin emission, the rotational diagram method can be used to determine the column density, N_{tot} , and the rotational temperature, T_{rot} (Goldsmith & Langer 1999). The approach used in this work follows the formalism described by Goldsmith & Langer (1999) with the following assumptions:

1. $(\text{CH}_2\text{OH})_2$, CH_2OHCHO , and HCOOCH_3 are emitting from the same region and thus have the same source size, θ_{source} .
2. $(\text{CH}_2\text{OH})_2$, CH_2OHCHO , and HCOOCH_3 are in LTE, which implies that the excitation temperature, T_{ex} , is equal to the kinematic temperature, T_{kin} , for all three species. Using the rotational diagram method, one obtains the rotational temperature, which in LTE is $T_{\text{kin}} = T_{\text{rot}} = T_{\text{ex}}$.
3. The observations at 1 mm and 3 mm trace the same gas.

According to our assumptions, the source size and T_{rot} derived from the HCOOCH_3 analysis can be used to derive the column density of $(\text{CH}_2\text{OH})_2$ and set an upper limit on the column density of CH_2OHCHO . A possible caveat is that the large beam size of our observations compared to the source sizes does not guarantee that the measured lines arise from species present in the same gas. Specifically, we obtain similar mean values of V_{LSR} for $(\text{CH}_2\text{OH})_2$ and HCOOCH_3 in both sources ($56.4 \pm 0.5 \text{ km s}^{-1}$ and $56.0 \pm 0.8 \text{ km s}^{-1}$ in W51/e2 along with $57.7 \pm 0.5 \text{ km s}^{-1}$ and $58.4 \pm 1.2 \text{ km s}^{-1}$ in G34.3+0.2 for $(\text{CH}_2\text{OH})_2$ and HCOOCH_3 , respectively), so here the assumption appears reasonable.

The same formalism in Goldsmith & Langer (1999) as was used to create a rotational diagram can also be used to generate a synthetic spectrum of the line emission of a specific molecule by using the source size, θ_{source} , the rotational temperature, T_{rot} , the line width, Δv , and the column density, N_{tot} , as input parameters. It is possible to correct for the optical depth of the line emission in case it deviates from being completely optically thin (Goldsmith & Langer 1999). A synthetic spectrum generated with input parameters derived from the rotational diagram

therefore serves as a check for the self-consistency of the result. We use adopted source sizes from the literature and determine the rotational temperatures and column densities in the following analysis.

The observed width of the detected lines have been determined from the Gaussian fit. For HCOOCH_3 in W51/e2, we obtain mean values of $\Delta v = 6.4 \pm 0.8 \text{ km s}^{-1}$ in the 1 mm data and $\Delta v = 6.1 \pm 1.1 \text{ km s}^{-1}$ in the 3 mm data. In the same source, the mean value of the line width of the $(\text{CH}_2\text{OH})_2$ lines is $6.3 \pm 0.9 \text{ km s}^{-1}$ for the 1 mm data, and the only detected value is 5.5 km s^{-1} in the 3 mm data. For G34.3+0.2, we find $\Delta v = 6.5 \pm 1.5 \text{ km s}^{-1}$ in the 1 mm data and $\Delta v = 7.3 \pm 1.3 \text{ km s}^{-1}$ in the 3 mm data for HCOOCH_3 and $\Delta v = 4.5 \pm 0.5 \text{ km s}^{-1}$ for the $(\text{CH}_2\text{OH})_2$ lines in the 1 mm data. In the analysis below, a fixed line width of 6.0 km s^{-1} was chosen as input parameter in synthetic spectra for all species.

3.2. HCOOCH_3

In the rotational diagram analysis for W51/e2, a source size of $2.4''$ (Zhang et al. 1998) is applied and results in a rotational temperature of $T_{\text{rot}} = 120 \text{ K}$ and a column density of $1.1 \times 10^{18} \text{ cm}^{-2}$. We estimate a 40 K uncertainty on the rotational temperature, which contribute to a $\sim 20\%$ error on the column density. This, combined with an observational uncertainty of $\sim 30\%$ returns an estimated overall error of 30%–40% for the column density. For G34.3+0.2 a source size of $7.6''$ (Remijan et al. 2003) is applied and results in $N_{\text{tot}} = 5.8 \times 10^{16} \text{ cm}^{-2}$, and $T_{\text{rot}} = 140 \text{ K}$ for HCOOCH_3 . As in the case for W51/e2, the estimated uncertainty of the column density is 30%–40% and 40 K for the temperature. Results from both sources are given in Table 3, and we have checked the validity of these results by generating synthetic spectra and comparing these to the observed spectra.

3.3. $(\text{CH}_2\text{OH})_2$

Numerous $(\text{CH}_2\text{OH})_2$ lines are blended with other species or have line intensities below 3σ . A total of two and five reasonable well separated lines above the 3σ limit toward G34.3+0.2 and W51/e2, respectively, were chosen for this analysis (see Tables 2 and 1 for the spectroscopic data and Figs. 1 and 2 for the zoom-in of the spectra around the lines). With only two to

Table 3. Input parameters for synthetic spectra.

Parameter	G34.3+0.2	W51/e2
$\theta_{\text{source}} ["]$	7.6	2.4
$T_{\text{rot}} [\text{K}]$	140	120
$\Delta v [\text{km s}^{-1}]$	6.0	6.0
$\text{HCOOCH}_3 N_{\text{tot}} [\text{cm}^{-2}]$	5.8×10^{16}	1.1×10^{18}
$(\text{CH}_2\text{OH})_2 N_{\text{tot}} [\text{cm}^{-2}]$	1.9×10^{15}	3.1×10^{16}
$\text{CH}_2\text{OHCHO } N_{\text{tot}} [\text{cm}^{-2}]$	$\leq 3 \times 10^{14}$	$\leq 2 \times 10^{15}$

Notes. The source sizes, rotational temperatures, line widths and column densities which are used as input parameters when creating synthetic spectra. As described in the text, the estimated uncertainties are ± 40 K for T_{rot} and $\pm 30\%$ – 40% for the column density.

five unblended lines, the assignment of $(\text{CH}_2\text{OH})_2$ cannot be considered as a firm detection. However, even if our tentative detection of $(\text{CH}_2\text{OH})_2$ is not confirmed, this measurement represents a useful upper limit for the column density of $(\text{CH}_2\text{OH})_2$, which still can provide important information when compared to the HCOOCH_3 detection.

When only a few data points are available, a statistically reliable result of the rotational temperature cannot be obtained from the traditional use of the rotational diagram method. Thus, we assume that $(\text{CH}_2\text{OH})_2$ and HCOOCH_3 emit at the same T_{ex} , which in LTE is equal to T_{rot} . The uncertainty of the column density is, as for HCOOCH_3 , estimated to 30% – 40% .

Using $\theta_{\text{source}} = 7.6''$ and $T_{\text{rot}} = 140$ K, a column density of $1.9 \times 10^{15} \text{ cm}^{-2}$ is derived for $(\text{CH}_2\text{OH})_2$ toward G34.3+0.2. For W51/e2, a source size of $2.4''$ and $T_{\text{rot}} = 120$ K returns $N_{\text{tot}} = 3.1 \times 10^{16} \text{ cm}^{-2}$ for $(\text{CH}_2\text{OH})_2$. These results, listed in Table 3, are used as input parameters for synthetic spectra in order to perform a sanity check. We checked each line in the synthetic spectra against the observed spectra for each source, and they all seem to provide a reasonable match, at least within the estimated uncertainty. Figures 1 and 2 shows the comparison of the synthetic spectra against the observed spectra. It is evident from Fig. 1 that the synthetic spectrum in the 1 mm data toward W51/e2 slightly overproduces the observed spectrum, while it reproduces the observed line in the 3 mm data. Since this line has a lower E_{up} this could indicate that a lower excitation temperature would give a better fit. Indeed a fixed $T_{\text{rot}} = 70$ K in the rotational diagram returns the same column density, $N_{\text{tot}} = 3.1 \times 10^{16} \text{ cm}^{-2}$.

3.4. CH_2OHCHO

Several lines in the data might be assigned to CH_2OHCHO . However, they are either blended with the emission of other molecules or too faint (i.e., below the 3σ limit), thus we cannot claim a detection. Nevertheless, we are able to obtain an upper limit for the column density. Following the assumptions stated in Sect. 3.1, synthetic spectra were generated using θ_{source} , T_{rot} and Δv in Table 3, allowing N_{tot} to vary. More specifically, the upper limit of the column density is then determined by increasing the value until the synthetic spectra overproduces the observed spectra intensities at the locations of the CH_2OHCHO lines in the observed spectra. The upper limit on the column density is $\leq 3 \times 10^{14} \text{ cm}^{-2}$ toward G34.3+0.2 and $\leq 2 \times 10^{15} \text{ cm}^{-2}$ toward W51/e2. The uncertainty of the column density is, as for HCOOCH_3 , estimated to 30% – 40% .

3.5. Relative abundances

Following the three assumptions listed in Sect. 3.1, it is possible to calculate the relative abundance of the species at the rotational temperature and source size found for each source. The following abundance ratios have been computed: $\text{HCOOCH}_3/(\text{CH}_2\text{OH})_2$, $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ and $(\text{CH}_2\text{OH})_2/\text{CH}_2\text{OHCHO}$. As CH_2OHCHO is not detected, it is only possible to set an upper limit on the column density. The $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ and $(\text{CH}_2\text{OH})_2/\text{CH}_2\text{OHCHO}$ ratios are therefore *lower limits*. All three relative abundance ratios for W51/e2 and G34.3+0.2 are listed in Table 4 along with previous measurements toward high-mass stars-forming regions, a hot core, an intermediate-mass protostar, low-mass protostars, molecular clouds toward the Galactic center and comets.

4. Discussion

$(\text{CH}_2\text{OH})_2$ has previously been detected in several other sources (Sgr B2(N), NGC 7129 FIRS2, NGC 1333 IRAS 2A and Orion-KL), with additional marginal/tentative detections in W51 e1/e2 and IRAS 16293–2422 (Hollis et al. 2002; Fuente et al. 2014; Maury et al. 2014; Coutens et al. 2015; Kalenskii & Johansson 2010; Jørgensen et al. 2012). In this paper we have identified $(\text{CH}_2\text{OH})_2$ and HCOOCH_3 in two high-mass protostellar sources, W51/2 and G34.3+0.2, and in addition been able to give an upper limit for the column density of CH_2OHCHO in the same sources. The results from this study are roughly similar to the estimates ratios seen in Orion KL (Favre et al. 2011; Brouillet et al. 2015) for the $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ and $\text{HCOOCH}_3/(\text{CH}_2\text{OH})_2$ ratios while the upper limits for $(\text{CH}_2\text{OH})_2/\text{CH}_2\text{OHCHO}$ are similar to the results for NGC 1333 IRAS 2A (Coutens et al. 2015), as well as the upper limits results for comets (Biver et al. 2014; Bockelée-Morvan et al. 2000; Crovisier et al. 2004a,b) (Table 4).

When investigating the conditions leading to differences in observed abundance ratios, it is important to take both the formation processes and the destruction processes of the molecules into consideration. Garrod et al. (2008) combined a gas-grain chemical network with a physical model to test whether the chemistry can reproduce the observed abundances of previously detected organic molecules in physical conditions characteristic of star-forming regions. The physical model used in Garrod et al. (2008) is based on Viti et al. (2004) and consist of an isothermal collapse followed by a warm-up phase with temperatures from 10 K to 200 K, assuming absolute time scales for the warm-up phases are 1×10^6 , 2×10^5 , and 5×10^4 yr representing low-, intermediate-, and high-mass star formation respectively. However, Aikawa et al. (2008) argue that the relation should be reversed, because the warm-up time scale should be relative and should depend on the ratio of the size of the warm region to the infall speed instead of the overall speed of star formation. Either way, Garrod et al. (2008) and Aikawa et al. (2008) agree that the time scales, whether absolute or relative, at the different temperature ranges are important for the chemistry.

For all the sources in Table 4, HCOOCH_3 is more abundant than CH_2OHCHO from a factor of >550 in W51/e2 to a factor of >2 in comet Hale-Bopp. According to Garrod et al. (2008), HCOOCH_3 and CH_2OHCHO have similar formation pathways, which are based on the addition of HCO and CH_3O or CH_2OH at 30 K–40 K. Garrod et al. (2008) find that the production rates of CH_3O and CH_2OH are the same, which leads to similar abundances for HCOOCH_3 and CH_2OHCHO . Intuitively this makes sense because the two molecules are isomers, but it

Table 4. Relative abundances of $(\text{CH}_2\text{OH})_2$, HCOOCH_3 and CH_2OHCHO in different sources.

Source	$\text{HCOOCH}_3/(\text{CH}_2\text{OH})_2$	$\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$	$(\text{CH}_2\text{OH})_2/\text{CH}_2\text{OHCHO}$	$L_{\text{bol}}[L_{\odot}]$	References
W51/e2 (this study)	35	>550	>16	4.7×10^6	1, 2
Orion-KL ^a	35	>200–300	>12	10^5	3, 4
G34.3+0.2 (this study)	31	>193	>6	2.8×10^5	1, 5
Sgr B2(N) LMH ^b	–	52	–	10^7	6, 7
G31.41 + 0.31 ^c	–	<34	–	1.8×10^5	8, 5
NGC 7129 FIRS2 ^d	~15	~30	~2	500	9
IRAS NGC 1333 2A ^e	4	20	5	20	10, 11
IRAS 16293–2422 ^e	~13	~13	~1	27	12, 13
IRAS NGC 1333 4A ^e	–	10	–	7.7	14
MC G + 0.693 ^f	4.3	5.2	1.2	–	15
MC G-0.11 ^f	2.8	4.3	1.6	–	15
MC G-0.02 ^f	2.5	3.3	1.3	–	15
Lemmon ^g	<0.7	–	>3	–	16
LoveJoy ^g	<0.6	–	>5	–	16
Hale-Bopp ^g	0.32	>2	>6.25	–	17

Notes. The table show the results from similar studies of: ^(a) the Orion Kleinmann-Low nebula, a high-mass star-forming region; ^(b) the Large Molecule Heimat hot core source toward Sgr B2(N); ^(c) high-mass star-forming region; ^(d) intermediate-mass protostar; ^(e) low-mass Class 0 protostars; ^(f) molecular clouds in the Sgr A complex (MC G – 0.02 – 0.07 (“the 50 km s^{–1} cloud”) and MC G – 0.11 – 0.08 (“the 20 km s^{–1} cloud”)) and in the Sgr B2 complex (MC G + 0.693 – 0.03); and ^(g) comets.

References. (1) this study; (2) [Urquhart et al. \(2014\)](#); (3) [Favre et al. \(2011\)](#), [Brouillet et al. \(2015\)](#); (4) [Crockett et al. \(2014\)](#); (5) [van Dishoeck et al. \(2011\)](#); (6) [Hollis et al. \(2001\)](#); (7) [Goldsmith et al. \(1990\)](#); (8) [Beltrán et al. \(2009\)](#); (9) [Fuente et al. \(2014\)](#); (10) [Coutens et al. \(2015\)](#); (11) [Jørgensen et al. \(2009\)](#); (12) [Jørgensen et al. \(2012, in prep.\)](#); (13) [Schöier et al. \(2002\)](#); (14) [Taquet et al. \(2015\)](#); (15) [Requena-Torres et al. \(2008\)](#); (16) [Biver et al. \(2014\)](#); (17) [Bockelée-Morvan et al. \(2000\)](#), [Crovisier et al. \(2004a,b\)](#).

contradicts observations because HCOOCH_3 is observed to be much more abundant than CH_2OHCHO in all the sources reported so far. As suggested by [Garrod et al. \(2008\)](#), this discrepancy could be due to the differences in the $\text{CH}_3\text{O}/\text{CH}_2\text{OH}$ branching ratio. According to [Öberg et al. \(2009\)](#), HCOOCH_3 forms at a lower temperature than CH_2OHCHO , which can also have an impact on the resulting ratio of the two species. Another explanation for the high $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ ratio is the assumptions regarding thermal evaporation for these two species. [Garrod et al. \(2008\)](#) suggest that CH_2OHCHO remains on the grains until is co-desorbs with water (at ~110 K) while HCOOCH_3 evaporates at 70–80 K. This leaves CH_2OHCHO to be destroyed by OH radicals at higher temperatures on the grains prior to evaporation. As [Öberg et al. \(2009\)](#) conclude, the ratio of $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ does not depend greatly on the initial ice composition, and so the observed variations will most likely be linked to the different temperature conditions of the different sources.

In Table 4 the sources are listed in order with a decreasing $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ ratio, which in turn also roughly correspond to a descending order of luminosity, which is also listed in the table. The top plot in Fig. 3 shows a schematic bar plot of $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ against L_{bol} . On the x -axis the sources in Table 4 have been plotted in descending order from left to right, but not to scale. As illustrated by Fig. 3 (top) a rough correlation between $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ and L_{bol} exists: more luminous sources show a high $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ ratio, while low-luminosity sources show a low $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ ratio with intermediate values in between. The apparent correlation between $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ and source luminosity supports the hypothesis that the $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ ratio depends mainly on the temperature, which in turns depends on the luminosity of the source. Even if the chemistry and the temperature profile in all the sources were quite similar, the differences in time scales of the different temperature

ranges (low, intermediate, to high temperature) are not. A higher $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ ratio in more luminous sources could simply be a consequence of i) more luminous sources having experienced a longer time scale at temperatures that are either more favorable to the formation of HCOOCH_3 and/or to the destruction of CH_2OHCHO ; or ii) less luminous sources experience a shorter time scale at high temperature, which would conserve a greater fraction of CH_2OHCHO than their more luminous counterparts. One should of course keep in mind that the sources discussed here have temperature profiles that covers a range of temperatures falling off with radius and that hot core regions are permeated by shocks that also produce a range of temperatures. For the Galactic center molecular clouds from the study by [Requena-Torres et al. \(2008\)](#), no luminosities are listed: these are warm, low-density clouds with no sign of star formation. However, judging by the $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ and $\text{HCOOCH}_3/(\text{CH}_2\text{OH})_2$ ratios, they appear to be closer to the low-mass protostars than to the hot cores and high-mass star-forming regions.

In the bottom plot in Fig. 3, the $\text{HCOOCH}_3/(\text{CH}_2\text{OH})_2$ abundance ratio also shows a decrease with L_{bol} similar to that of $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$. If the same temperature time scale argument is applied to this correlation, one would expect an opposite trend, because $(\text{CH}_2\text{OH})_2$ is formed at high temperatures ([Garrod et al. 2008](#)). A possible explanation for this seeming contradiction is that less luminous sources might experience high temperatures on time scales, that are just long enough for $(\text{CH}_2\text{OH})_2$ to form, but not long enough for $(\text{CH}_2\text{OH})_2$ to be destroyed again. Another possible explanation is that the initial ice composition affects the abundance ratio. While the $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ ratio is independent of initial ice composition, then the formation of $(\text{CH}_2\text{OH})_2$ is strongly correlated to the $\text{CH}_3\text{OH}:\text{CO}$ composition of the ice ([Öberg et al. 2009](#)). [Öberg et al. \(2009\)](#) show that pure CH_3OH ice enhances the $(\text{CH}_2\text{OH})_2$ abundance as compared to ice mixes containing CO. This is in agreement with the predictions by [Garrod et al. \(2008\)](#)

Fig. 3. Schematic bar plot of $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$ (top) and $\text{HCOOCH}_3/(\text{CH}_2\text{OH})_2$ (bottom) against L_{bol} . The sources from Table 4 have been plotted in descending order of luminosity from left to right on the x-axis, but not to scale, and the sources have been grouped into high-mass sources (blue), intermediate-mass protostar (red) and low-mass protostars (green). The white bars for four of the high-mass sources are upper or lower levels, which is indicated by the direction of the arrow. The luminosity for the top plot spans from Sgr B2(N) with $L_{\text{bol}} = 10^7 L_{\odot}$ to IRAS NGC 1333 4A with $L_{\text{bol}} = 7.7 L_{\odot}$, while it spans from W51/e2 with $L_{\text{bol}} = 4.7 \times 10^6 L_{\odot}$ to IRAS NGC 1333 4A with $L_{\text{bol}} = 20 L_{\odot}$ in the bottom plot.

where the $(\text{CH}_2\text{OH})_2$ abundance actually drops two to three magnitudes when the initial CH_3OH ice-composition in their model is reduced by a factor of 10. However, to date there is no observational evidence that the ice contents on the grains vary in any statistically significant way from high-mass protostars to low-mass protostars (Öberg et al. 2011).

Until recently it has been speculated that a high $(\text{CH}_2\text{OH})_2/\text{CH}_2\text{OHCHO}$ ratio is a specific property of comets (Biver et al. 2014). But since Coutens et al. (2015) report a value of around five for a low-mass protostar, and both we and Brouillet et al. (2015), report lower limits of >6 – 16 for high-mass sources, then a $(\text{CH}_2\text{OH})_2/\text{CH}_2\text{OHCHO}$ ratio greater than three can be expected to be observed in other sources as well.

5. Conclusions

In summary, we have tentatively detected $(\text{CH}_2\text{OH})_2$ in G34.3+0.2 for the first time, and our tentative detection in W51/e2 confirms the previous marginally detection by Kalenskii & Johansson (2010). In addition, we derived upper limits for

the column density of CH_2OHCHO emission in both sources. From these data we determined the relative abundance ratios of $(\text{CH}_2\text{OH})_2$, HCOOCH_3 , and CH_2OHCHO and compared these to measurements from the literature covering a wide range of source environments and luminosities. The data show what appears to be a correlation between source luminosity and $\text{HCOOCH}_3/(\text{CH}_2\text{OH})_2$, as well as $\text{HCOOCH}_3/\text{CH}_2\text{OHCHO}$. This apparent correlation is proposed to be a consequence of the relative time scales each source spends at different temperature ranges in their evolution. Using the upper limit for the column density of CH_2OHCHO gives a lower limit for $(\text{CH}_2\text{OH})_2/\text{CH}_2\text{OHCHO}$ of >16 and >6 for W51/2 and G34.3+0.2, respectively. These results, together with an upper limit of >12 for Orion-KL (Brouillet et al. 2015) and $(\text{CH}_2\text{OH})_2/\text{CH}_2\text{OHCHO} = 5$ for IRAS NGC 1333 2A (Coutens et al. 2015), shows that one can expect to find a high $(\text{CH}_2\text{OH})_2/\text{CH}_2\text{OHCHO}$ abundance ratio in multiple types of environments.

Additional systematic surveys of these and other relevant molecules in additional sources, as well as more model and laboratory work, is needed to fully constrain the formation pathway of complex molecules. In particular, the Atacama Large Millimeter/submillimeter Array (ALMA) shows great potential for successfully revealing the formation processes with its high sensitivity and resolution, making it possible to map the relative spatial distributions of these sources.

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Appendix A: Reference model

Table A.1. Column densities of species in our reference model.

Molecule	G34.3+0.2 [cm ⁻²]	W51/e2 [cm ⁻²]
CH ₃ OCH ₃	4×10^{16}	3×10^{17}
HCOOH t	1×10^{15}	1×10^{16}
CH ₃ CHO	2×10^{15}	1×10^{16}
CH ₃ OH	1×10^{17}	3×10^{18}
C ₂ H ₅ OH	1×10^{16}	1×10^{17}
CH ₃ CN	2×10^{15}	6×10^{16}

Notes. Estimated column densities of other relevant organic species. These values are used to create synthetic spectra, which serves as a reference model when identifying lines.

Appendix B: Observed and synthetic spectra

Fig. B.1. Synthetic spectra (red: (CH₂OH)₂, yellow: HCOOCH₃, green: CH₂OHCHO, blue: the molecules listed in Table A.1) on top of observed spectrum (black) at 1 mm for W51/e2 in the frequency range ~238–242 GHz.

Fig. B.2. Same as Fig. B.1 but for ~242–246 GHz.

Fig. B.3. Synthetic spectra (red: $(\text{CH}_2\text{OH})_2$, yellow: HCOOCH_3 , green: CH_2OHCHO , blue: the molecules listed in Table A.1) on top of observed spectrum (black) at 1 mm for G34.3+0.2 in the frequency range $\sim 238\text{--}242$ GHz.

Fig. B.4. Same as for Fig. B.3 but for $\sim 242\text{--}246$ GHz.

Fig. B.5. Synthetic spectra (red: $(\text{CH}_2\text{OH})_2$, yellow: HCOOCH_3 , green: CH_2OHCHO , blue: the molecules listed in Table A.1) on top of observed spectrum (black) at 3 mm for W51/e2 in the frequency range $\sim 100\text{--}103$ GHz.

Fig. B.6. Same as for Fig. B.5 but for ~ 103 – 106 GHz.

Fig. B.7. Synthetic spectra (red: $(\text{CH}_2\text{OH})_2$, yellow: HCOOCH_3 , green: CH_2OHCHO , blue: the molecules listed in Table A.1) on top of observed spectrum (black) at 3 mm for G34.3+0.2 in the frequency range ~100–103 GHz.

Fig. B.8. Same as for Fig. B.7 but for ~ 103 – 106 GHz.