Observations of CH₃OH and CH₃CHO in a Sample of Protostellar Outflow Sources

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ABSTRACT

Iram 30-m Observations towards eight protostellar outflow sources were taken in the 96-176 GHz range. Transitions of CH_3OH and CH_3CHO were detected in seven of them. The integrated emission of the transitions of each species that fell into the observed frequency range were measured and fit using RADEX and LTE models. Column densities and gas properties inferred from this fitting are presented. The ratio of the A and E-type isomers of CH_3OH indicate that the methanol observed in these outflows was formed on the grain surface. Both species demonstrate a reduction of terminal velocity in their line profiles in faster outflows, indicating destruction in the post-shock gas phase. This destruction, and a near constant ratio of the CH_3OH and CH_3CHO column densities imply it is most likely that CH_3CHO also forms on the grain surface.

Keywords: ISM: molecules, ISM: jets and outflows, astrochemistry

1. INTRODUCTION

In the early stages of their evolution, low mass protostars launch outflows: fast flows of gas that can generate shocks when colliding with the surrounding medium. These shocked regions often have a rich chemistry with many species experiencing significant enhancement in abundance (van Dishoeck & Blake 1998). They are warm and bright, making them excellent locations to observe molecules (Bachiller & Pérez Gutiérrez 1997; Jørgensen et al. 2004).

Further, the shocks driven by the outflow are of sufficient speed to sputter the ice mantles of dust grains, and even the dust grain material itself, into the gas phase (May et al. 2000). Thus shocked regions along protostellar outflows represent complex and interesting locations where the chemistry may be dominated by material recently released from the ices.

This is particularly relevant in the case of complex organic molecules (COMs). Debate over the main formation routes of these molecules (eg. Chuang et al. 2017; Skouteris et al. 2019) is ongoing. The most simple of these COMs, methanol (CH₃OH), is known to form efficiently on the grains (Fuchs et al. 2009) but other more complex molecules are not well understood.

However, shocks present an interesting case in that it is possible that the majority of CH_3OH on the grains is destroyed in the sputtering process (Suutarinen et al. 2014). Thus, it is possible that some of the CH_3OH observed towards outflows may be formed in the postshock gas phase, despite the efficiency of methanol formation in interstellar ices.

Acetaldehyde (CH₃CHO) has been detected in outflows (Codella et al. 2015) as well as hot corinos (Cazaux et al. 2003) and cold cores (Jiménez-Serra et al. 2016). There exist viable routes to forming the molecule on

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the grain surface through diffusion reactions (Garrod & Herbst 2006) and UV processing (Öberg et al. 2009) as well as in the gas phase (Charnley 2004, and references therein).

In this work, observations towards eight protostellar outflows, seven of which were found to contain many transitions of CH_3OH and CH_3CHO , are presented. By considering the trends in the column densities of these molecules and the ratio of CH_3OH isomers across different shocked regions and with different shock speeds, it is expected some information as to the origin of each molecule can be extracted.

Moreover, the set of outflows presented here are a sample that was initially chosen to investigate the chemical differences between NH₃ and H₂O in shocked regions (Gómez-Ruiz et al. 2016). In the outflow source L1157-B1, it was was observed that NH₃ transitions had a much lower terminal velocity than H₂O despite arising from the same source (Codella et al. 2010). Through chemical and radiative transfer modelling, this was attributed to gas phase reactions in the hot post-shock gas (Viti et al. 2011). Both species were sputtered by the shock and enhanced, but in the hot, fast moving gas NH₃ was destroyed through reactions with H atoms. The same behaviour was observed in MHD shock models with radiative transfer (Flower & Pineau des Forêts 2012).

The difference between NH_3 and H_2O were found to hold across the outflows presented here (Gómez-Ruiz et al. 2016) and a search for other species that followed similar trends was attempted. In observations targeting sulfur-bearing species, a large number of CH_3OH and CH_3CHO were serendipitously detected by student researchers as part of the ORBYTS researchers in schools programme ¹. In this work, the emission from those species is analysed to find the trends of their emission and abundance with shock velocity

In Section 2, the observations and basic measurements are described. In Section, 3 the column density inference procedure is detailed. In Section 4, the results of these measurements are presented and in Section 5, the implications of the results are discussed. Finally, the work is summarized in Section 6.

2. OBSERVATIONS AND PROCESSING

Observations of eight outflow sources were obtained using the IRAM-30m telescope. The sources were chosen to match the sample observed by Gómez-Ruiz et al. (2016). The sources, listed by central object, are presented in Table 1. Given that the offset from the central object is generally much larger than the beam width, it is assumed that the contribution from those protostars is negligible.

The observations contain two frequency ranges, the first from 96 GHz to 104 GHz and the second from 152 GHz to 176 GHz. In the case of L1448-B2 and IRAS2A-B, only the second range was observed. These ranges were intended to capture transitions of many sulfur bearing species, the exploitation of which will be presented in future work.

Observations were carried out between the 2nd and 4th of June 2016 in wobbler switching mode. Pointing was monitored regularly, using Mercury, and found to be stable. The atmospheric opacity was low, $\tau < 0.15$. The observations were taken using the IRAM-30m telescope's EMIR receivers and the Fourier Transform Spectrometer back end. This gave a spectral resolution of 200 kHz or, equivalently, velocity resolutions between $0.35 \,\mathrm{km \, s^{-1}}$ and $0.6 \,\mathrm{km \, s^{-1}}$. All spectra were smoothed and resampled to a common velocity resolution of $1.0 \,\mathrm{km \, s^{-1}}$ for analysis. This allowed comparison between sources and greatly improved the signal to noise ratio of weak lines.

The data were manually inspected using the GILDAS CLASS software package². This was primarily for initial line identification. Where a peak in the spectrum was above three times the noise level, it was identified by comparing the rest frequency of the brightest channel to the JPL catalog (Pickett 1985) accessed via Splatalogue³. Transitions of the E isomer of CH₃CHO and both the A and E isomers of CH₃OH were detected in every source except L1448-R4. The L1448-R4 spectra were badly affected by absorption at the systematic velocity of L1448 and so this source is not discussed further.

Whilst many transitions of the species were detected, many more transitions are present in the observed frequency ranges. In order to make use of these nondetections, the CLASS WEEDS library and the JPL catalog were used to extract every transition in the observed frequency range. However, this was a prohibitively large number of transitions and so limits on E_u and A_{ij} were chosen based on the properties of the manually detected lines. Only transitions within these limits were exported for further processing. This included every CH₃OH transition with an $E_u < 250$ K and $A_{ij} > 10^{-6}$ s⁻¹ and every CH₃CHO transition with an $E_u < 100$ K and $A_{ij} > 10^{-5}$ s⁻¹. These ranges include every detected transition in the observed frequency range but limited the number of non-detections in the data set. Spectra

¹ http://www.twinkle-spacemission.co.uk/orbyts/

² http://www.iram.fr/IRAMFR/GILDAS

³ http://www.splatalogue.net/

COMS IN OUTFLOWS

Source	α (h:m:s)	$\overset{\delta}{(\circ : ' : '')}$	V_{LSR} km s ⁻¹	L_{bol} L_{\odot}	d pc	Offsets Blue/Red arcseconds
NGC1333-IRAS2A	03:28:55.4	31:14:35.0	+6.0	25	235	B(-100,+25), R(70,-15)
NGC1333-IRAS4A	03:29:10.4	31:13:31.0	+6.5	8	235	B(-6,-19), R(14,25)
L1157	20:39:06.2	68:02:16.0	+2.6	4	250	B2(35,-95), R(-30,140)
L1448	03:25:38.9	30:44:05.0	+4.7	6	235	B2(-13,+29), R4(26,-125)

Table 1. Sources and relevant parameters adapted from (Gómez-Ruiz et al. 2016).

covering a velocity range of $200 \,\mathrm{km \, s^{-1}}$ centred on each transition were exported regardless of whether a peak had been identified in the spectrum.

The exported spectra were baseline subtracted in python by fitting polynomials of up to order 3 to the spectra using numpy's polyfit. The rms difference between the baseline and the spectra was then calculated to give the spectrum rms. The smoothed spectra have rms values between 3 and 10 mK. Transitions were classed as detections if the peak emission was above three times the rms noise level. The spectra of detected lines were median stacked and the velocities at which the median stacked peak fell to the rms emission level were recorded. These were considered to be the minimum and maximum velocity limits of the emission of that species in that source. All transitions of the species were then integrated between these limits even if a peak was not detected. The uncertainty on the integrated emission of each transition was found by propagating the uncertainties due to the noise and velocity resolution of their spectra as well as a 20% calibration error.

Finally, transitions where the integrated emission was larger than the noise level were inspected visually. Any transition which was blended with the emission of another species was removed from the data set. Two groups of three CH₃OH transitions were blended in every source. For these, the distance between the peaks of the blended transitions in velocity space was added to the integration limits such that all blended lines were integrated together. The total flux of these lines was treated specially as detailed in Section 3.1.

In the online appendix, the measured properties of every transition in the observed frequency ranges are presented in tables for each source in Appendix A. In Appendix B, plots of the spectra of every detected line of each species in each source are also presented.

3. INFERENCE OF GAS PROPERTIES

The integrated emission of the CH_3OH and CH_3CHO transitions were used to infer the column density of each species towards each source as well as the gas properties through model fitting. Since any model that predicts strong emission for an undetected transition cannot be

correct, the measured emission of every line of each species was included in the fits regardless of whether or not a peak was detected. In this section, the model used for each species and the fitting procedure is detailed.

3.1. CH₃OH Fluxes

The LAMDA database⁴ contains collisional data for the two isomers of CH_3OH (A- CH_3OH and E- CH_3OH) orginally computed by Rabli & Flower (2010). This allowed the use of RADEX (van der Tak et al. 2007) to predict the emission of each transition. RADEX requires the column density of each isomer, the gas temperature, and the linewidth as input parameters.

RADEX assumes the source fills the telescope beam and so the fluxes had to be adjusted for a fifth free parameter, the source size. To do this the source size was used to calculate a filling factor,

$$\eta_{ff} = \frac{\theta_S^2}{\theta_S^2 + \theta_{MB}^2} \tag{1}$$

where θ_S is the source size and θ_{MB} is the beamsize which is a function of frequency. The RADEX outputs were multiplied by this factor to account for the beam dilution present for an assumed source size.

Fitting the integrated emission directly provided a convenient solution to the blended transitions of CH₃OH. The total integrated area of each set of blended transitions was measured from the spectra and compared to the sum of the RADEX emission for those transitions. If a RADEX model fits the individual transitions in a data set, it follows that it would fit the sum of any set of transitions. Therefore, fitting the sum of blended transitions allows them to contribute information to the fit, avoiding any approximations that are often used to separate the flux from blended transitions such as assuming LTE. However, it does create a degeneracy in the fits as the relative emission of each line is not considered. Where many other transitions are detected, this degeneracy is resolved. If few other transitions are detected, the reported uncertainties are significantly larger.

⁴ http://home.strw.leidenuniv.nl/~moldata/CH3OH.html

3.2. CH₃CHO Fluxes

For CH₃CHO, no collisional data was available and so the integrated emission was predicted by assuming optically thin emission and LTE conditions. Assuming every transition has an upper state column density (N_u) given by a Boltzmann distribution, the upper state column density can be related to the integrated emission (F_T) and rearranged to give that emission as a function of the column density (N), rotational temperature (T_{rot}) , and the source size or filling factor,

$$F_t = \frac{hc^3}{8\pi k_B} \frac{A_{ij}g_u}{\nu^2} \eta_{ff} \frac{N}{Z} \exp\left(\frac{-E_u}{k_B T}\right)$$
(2)

The result is an approach that is effectively equivalent to the rotation diagram method (Goldsmith & Langer 1999) but allows the source size to be accounted for in a more direct fashion and is more similar to the method used for CH_3OH .

3.3. Inference Procedure

The likelihood of having obtained the data given a set of parameters can be defined as,

$$P(\mathbf{F_d}|\boldsymbol{\theta}) = \exp\left(-\frac{1}{2}\sum_{i}\frac{(F_{d,i} - F_{t,i})^2}{\sigma_{F,i}^2}\right) \qquad (3)$$

where $F_{d,i}$ and $F_{t,i}$ are the observed and model integrated emission of transition i, σ_F is the observational uncertainty, and θ is the set of parameters which may include the gas temperature and column density. From here, Bayes' theorem can be applied to obtain the probability distribution of the parameters given the observed data,

$$P(\boldsymbol{\theta}|\boldsymbol{d}) = \frac{P(\boldsymbol{d}|\boldsymbol{\theta})P(\boldsymbol{\theta})}{P(\boldsymbol{d})}$$
(4)

where $P(\boldsymbol{\theta})$ is the prior probability of the parameters and $P(\boldsymbol{d})$ is the Bayesian evidence, which can simply be treated as a normalizing factor.

An advantage of this method is that poorly constrained variables can be marginalized over. For example, the angular size of each source is an unknown in this work. However, if it is treated as a free parameter, the uncertainty this introduces to the model will be reflected in the marginalized posterior distributions of the other parameters.

The posterior distribution was sampled using the python package emcee (Foreman-Mackey et al. 2013). This is an affine-invariant sampler (Goodman & Weare 2010) in which multiple chains of samples are created by "walkers" which each sample the space. Each walker moves through the parameter space generating a chain

of parameter samples, starting with a random value of the parameters of interest drawn from the prior distributions. However, unlike many MCMC samplers, walkers do not move randomly and are instead informed by each other.

The prior probability distributions were simply assumed to be flat between limits. The temperature prior was non-zero between 0 and 150 K and the source size prior was non-zero between 0 and 200". The column density prior was non-zero between 10^{11} and 10^{17} cm⁻² and, in the case of CH₃OH, the H₂ density prior was non-zero between 10^3 and 10^8 cm⁻³. The column density and gas density were sampled in log-space for numerical reasons as large values will otherwise dominate the sampling.

For the parameter inference, 12 walkers were used and the chains were run for 10^5 steps per walker. The Geweke diagnostic (Geweke 1992) was used to verify that the chains had converged.

4. RESULTS

The gas densities and kinetic temperature of the gas traced by CH_3OH as well as the column densities of both species in each object obtained from the parameter inference are given in Tables 2 and 3. Most likely values are presented for the column densities as well as the 67% probability intervals of all parameters. This implies that if the model is correct, there is 67% chance the true value of each parameter lies within the given range.

These values should be treated with some caution as RADEX gives an imperfect representation of a slab of gas described by a single density and temperature and this not the ideal model for a shocked region. This is even more of an issue for the LTE results presented for CH₃CHO. Further, in the best case, the parameter values obtained will represent the average values of the gas encompassed by the telescope beam. However, in both cases, the model results do give some insight and represent the best models available to us. All of the results of the fitting are discussed below.

4.1. CH₃OH - Gas Properties

In Table 2, third and fourth columns give the 67% probability range of the gas density and temperature. In the weakest emitting sources, the kinetic temperature is poorly constrained and only an upper limit is reported. This is due to the low range of E_u values of the detected transitions. The temperature only needs to be sufficiently low not to excite the higher energy undetected transitions and beyond this, there is no change in the fit.

In sources with a large number of detected lines, the gas temperatures are well constrained. There is no clear variation between these sources, most giving values between 40 and 50 K. Whilst this is much lower than the maximum temperature typically reached in the shocks used to model outflows (Flower & Pineau des Forêts 2015), a single temperature and gas density is being fit to a shock structure that will encompass a wide range of gas conditions. Further, it is consistent with that found in other protostellar shock sources (eg. CO in L1157-B1 Lefloch et al. 2012), including that found previously for CH₃OH in L1157-B2 (McGuire et al. 2015).

The gas densities do not vary greatly, only the sources associated with IRAS4A have most likely ranges that are differ significantly from $\sim 4 \times 10^5$ cm⁻³. However, it is interesting to note that each pair of sources associated with the same central objects are very similar. Whilst the IRAS2A-B gas density posterior distribution is quite wide, the majority of the probability density is in the same range as that reported for IRAS2A-R. Further, the IRAS4A and L1157 sources are remarkably consistent.

4.2. CH₃OH - Column Density

In Figure 1, the measured flux of each observed CH₃OH transition is plotted. In red, the fluxes obtained from RADEX using the most likely values of the parameters are also plotted. The agreement is good considering the use of a single gas component to fit a shocked region, with χ^2 values of ~1.5. In Table 2, the most likely column density of each CH₃OH isomer is given along with the 67% confidence interval. In the case of L1448-B2 and IRAS2A-B, only an upper limit can be given for A-CH₃OH.

CH₃OH has been previously detected towards each of these sources. The most likely column densities from this work were compared to the column density of CH₃OH found towards the outflows of IRAS-2A (Jørgensen et al. 2004), IRAS-4A (Blake et al. 1995), L1448 (Tafalla et al. 2010), and L1157 (Burkhardt et al. 2016). The observations in those works covered fewer lines so only total CH₃OH column densities were reported. However, for every source, the sum of the isomer column densities obtained through this analysis is consistent with the value reported in those works.

4.3. CH₃CHO Column Density

The results of the LTE parameter inference for CH_3CHO emission from the observed sources are summarized in Table 3. No transitions of CH_3CHO were detected at a significant level towards IRAS2A-B, L1157-R and L1448-B2. As a result, the posterior distribution of N only has upper bounds in these sources and only the upper limit is reported.

The fits to the CH_3CHO fluxes are presented as rotation diagrams in Figure 2. The best fit N and T are

used to plot the expected Boltzmann distribution as a straight line. The points are the upper state column density of each transition, calculated from the measured integrated emission and adjusted for the filling factor using the most likely value of θ_S .

4.4. "Nuisance" Parameters

There are two parameters that are not of particular interest to the analysis but are important for the fitting, these are the line width in the case of the RADEX fits and the filling factor for both the RADEX and LTE fits.

In Figure 3, it can be seen that when the linewidth is allowed to vary freely, the probability distribution tends to large values. From the RADEX manual ⁵, one finds that the manner in which the flux and line intensity are calculated means that the line width is irrelevant in the limit of low optical depth. Thus the fits are tending to a regime that is consistent with optically thin CH_3OH emission.

The line width is only constrained in the case of IRAS2A-R, in which the most likely value is half the full width of the detected lines. A second parameter inference was run, fixing the line widths to their FWHM values and consistent results were found for the other parameters. Thus it is considered that the linewidth is unimportant and is left as a free parameter as this increases the reported uncertainties and is thus more conservative. This is appropriate because the lines are not Gaussian and RADEX assumes they are.

Figure 3 also shows a common result for the source size: it also tends to large values. In these cases, it is reasonable to assume the source fills the beam. For source sizes much larger than the beam, the filling factor tends to unity so the actual value becomes irrelevant and thus any source that fills the beam will have a posterior that simply tends to high values rather than a specific value. From the figure, it can be seen the column densities and the source size are correlated below $\sim 80^{\circ}$. This broadens the column density distributions and is thus included in the reported column density uncertainty.

In other sources, the filling factor probability distribution is close to constant across transitions for many source sizes. Most transitions of CH_3OH in the observed frequency range are associated with beam sizes of 15" with only a small number of transitions reaching 25" thus, in a source with few detections the source size is not constrained. This manifests as a broader variation of column densities as the filling factor is a constant offset and a low source size can be compensated by a smaller column density and vice versa.

⁵ http://home.strw.leidenuniv.nl/~moldata/radex_manual.pdf

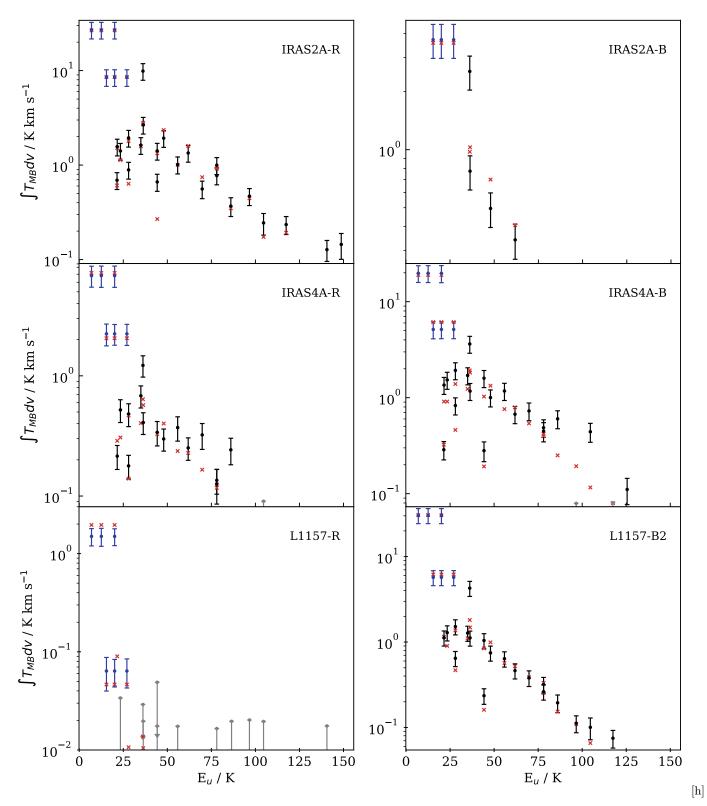


Figure 1. Measured flux (black points and error bars) of CH_3OH transitions plotted against E_u . The blue points are those transitions that are blended, the total emission across all three transitions is plotted in each case along with the sum of the RADEX model emission. The grey upper limits show undetected transitions. The red crosses indicate the fluxes produced by RADEX for the most likely parameter values.

Source	Lines	${\rm T}_{Kin} \atop {\rm K}$	${ m n}_{H2} \ imes 10^5 { m cm}^{-3}$	$ \begin{vmatrix} N(A-CH_3OH) \\ cm^{-2} \end{vmatrix} $	$N(A-CH_3OH)$ Range cm^{-2}	$\begin{array}{c} \mathrm{N(E-CH_{3}OH)}\\ \mathrm{cm^{-2}} \end{array}$	$N(E-CH_3OH)$ Range cm^{-2}
IRAS2A-R	28	49.1 - 57.8	3.8 - 5.3	9.8×10^{14}	7.8×10^{14} - 1.3×10^{15}	5.2×10^{14}	4.7×10^{14} - 5.9×10^{14}
IRAS2A-B	7	< 41.7	2.1 - 27.6	-	$<2.23\times10^{15}$	7.3×10^{13}	6.7×10^{13} - 2.3×10^{14}
IRAS4A-R	21	38.0 - 45.6	4.9 - 6.1	1.9×10^{14}	1.5×10^{14} - 2.4×10^{14}	1.1×10^{14}	9.6×10^{13} - 1.2×10^{14}
IRAS4A-B	25	40.7 - 46.4	4.9 - 6.0	6.9×10^{14}	5.8×10^{14} - 8.0×10^{14}	3.1×10^{14}	2.8×10^{14} - 3.4×10^{14}
L1157-R	3	$<\!136.5$	1.7 - 5.0	3.9×10^{13}	2.7×10^{13} - 6.7×10^{13}	3.7×10^{12}	2.0×10^{12} - 8.2×10^{12}
L1157-B2	25	41.9 - 47.1	2.8 - 4.1	9.1×10^{14}	7.7×10^{14} - 1.1×10^{15}	3.8×10^{14}	3.3×10^{14} - 4.3×10^{14}
L1448-B2	1	< 22.9	1.6 - 8.0	-	$< 1.54 \times 10^{14}$	4.4×10^{12}	3.0×10^{12} - 8.8×10^{12}

Table 2. Summary of the RADEX fits to CH_3OH . The first column gives the number of lines with peaks above three times the noise level, the second and third are the 67% probability intervals for the gas temperature and density. The remaining columns are the best fit column density and 67% probability interval for each isomer of CH_3OH . 3 sigma upper limits are given where no lines were detected.

Source	Lines	T_{rot}	Ν	$N(CH_3CHO)$ Range	CH ₃ CHO/CH ₃ OH
		Κ	cm^{-2}	cm^{-2}	
IRAS2A-R	17	12.6 - 15.5	1.0×10^{13}	5.8×10^{12} - 2.4×10^{13}	6.7×10^{-3}
IRAS2A-B	0	-	-	$< 1.44 \times 10^{12}$	$< 4.3 \times 10^{-3}$
IRAS4A-R	3	6.1 - 15.2	$7.6 imes 10^{11}$	5.5×10^{11} - 1.0×10^{12}	2.6×10^{-3}
IRAS4A-B	9	11.1 - 13.7	2.6×10^{12}	2.1×10^{12} - 3.2×10^{12}	2.6×10^{-3}
L1157-R	0	-	-	$< 7.47 \times 10^{11}$	$< 5.2 \times 10^{-3}$
L1157-B2	9	8.4 - 12.1	9.7×10^{11}	8.1×10^{11} - 6.3×10^{12}	$7.6 imes 10^{-4}$
L1448-B2	0	-	-	$< 3.40 \times 10^{11}$	$< 3.8 \times 10^{-3}$

Table 3. Summary of the LTE fits to CH_3CHO . The first column gives the number of lines with peaks above three times the noise level, the second is the best fit rotation temperature and the third and fourth columns are the best fit column density and 67% probability interval. Where only an upper limit on the column density was found, the three sigma upper limit is given. The final column is the ratio of the CH_3CHO column density to the CH_3OH column density measured in the source.

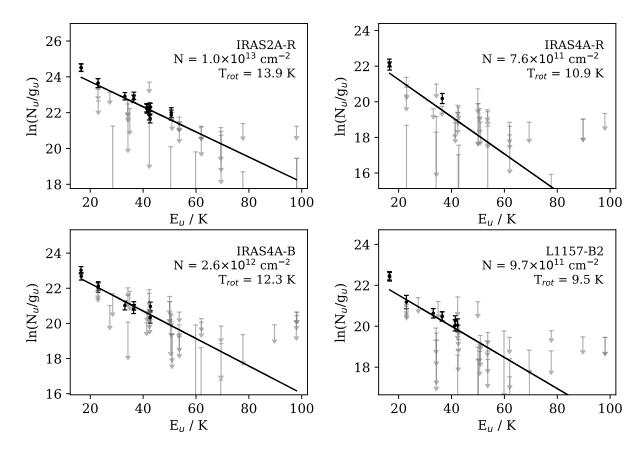


Figure 2. Rotation Diagrams of CH_3CHO in each source. The black line shows the Boltzmann distribution given by the most likely values of N and T for each source. Black points are detected transitions adjusted for the best fit filling factor and grey points are the upper limits calculated from the non-detections.

5. DISCUSSION

5.1. E/A Methanol Ratio

Methanol has two spin isomers referred to as E and A- CH_3OH respectively. Since the conversion of one isomer to another is a strongly forbidden process, it is often assumed in that this ratio is fixed at formation and then preserved (Kawakita & Kobayashi 2009).

Whilst this assumption is typically applied to methanol observed in cometary ices, Wirström et al. (2011) argue this should also be true for the interstellar medium. They argue that the timescale for the reactions that would alter the ratio are long compared to the lifetime of an average methanol molecule and thus conversion must be negligible. The ratio of the E and A isomers of CH₃OH can be used to calculate a characteristic temperature (T_{spin}) through the equation,

$$\frac{E}{A} = \frac{\sum_{i} g_{i} \exp\left(\frac{-E_{i}}{kT_{spin}}\right)}{\sum_{j} g_{j} \exp\left(\frac{-E_{j}}{kT_{spin}}\right)}$$
(5)

where the sums over i and j are sums over all transitions of E and A-CH₃OH respectively. If the methanol was thermalized at formation, T_{spin} represents the temperature of the formation environment.

Assuming this is the case, the ratio of E to A-CH₃OH in the observed sources can be calculated to give the spin temperature and hence the temperature at which the methanol in those sources formed. Figure 4 shows that the ratio in every source. Most sources are consistent with a spin temperature between 5 and 10 K. The one source which has an unusually low ratio but is not an upper limit is L1157-R. Only one A-CH₃OH transition was detected in this source and it was part of the blended triplet at ~96 GHz.

Such low and similar spin temperatures are inconsistent with a scenario in which methanol forms in the post-shock gas in the outflow. If thermalization is assumed, the spin temperature would equal the post-shock gas temperature, which is ~ 50 K in each source. Thus it is concluded that that the methanol observed in these outflows formed before the shock on the grain surfaces before being released by shock sputtering. This is corroborated by Fuchs et al. (2009) who showed CO efficiently hydrogenates to form methanol between 12 and 20 K on interstellar ice analogues.

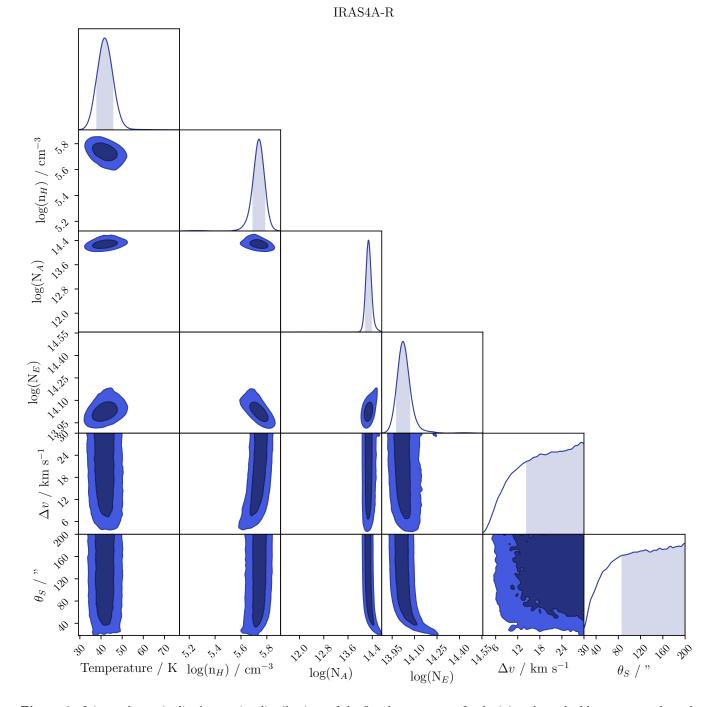


Figure 3. Joint and marginalized posterior distributions of the fitted parameters. In the joint plots, the blue contours show the 67% and 95% probability intervals. In the marginalized plots, the shaded area shows the 67% interval. The source size tends to large values indicating the best fits are found assuming source fills the beam.

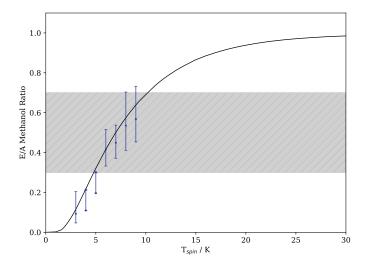


Figure 4. Ratio of E/A methanol column densities towards each source plotted as points with errorbars. Black curve indicates the expected value of the ratio for methanol formed at a given temperature. Grey band shows the range of ratios expected for methanol formed between 5 and 10 K. Lower limits are those sources for which only an upper limit on A isomer of methanol were found.

5.2. Velocity Trends of CH₃OH

In section 1, the difference in terminal velocities between NH_3 and H_2O in the observed sources is discussed. The terminal velocity of H₂O in these sources was taken from Gómez-Ruiz et al. (2016) and compared to CH₃OH. The terminal velocity is the velocity at which the emission peak reaches the rms level and is given as an absolute value relative to the local standard of rest. Figure 5 shows that CH_3OH follows the same trend as NH₃ (Figure 8, Gómez-Ruiz et al. 2016). Up to a H_2O terminal velocity of $30 \,\mathrm{km \, s^{-1}}$, the CH₃OH terminal velocity increases with the H₂O velocity. However, the difference between the H₂O and CH₃OH terminal velocity increases steadily and at much higher velocities, the CH₃OH terminal velocity decreases drastically. This is consistent with previous observations of H_2O and CH₃OH transitions towards IRAS2A and IRAS4A (Suutarinen et al. 2014).

The velocity trend is consistent with CH₃OH behaving similarly to NH₃. That is, it is released from the ice mantles by the sputtering in the shock and is then destroyed in the post-shock gas phase to a degree that is dependent on the shock speed. This is corroborated by the results of Section 5.1, which showed that the isomer ratio of methanol is consistent with a grain surface origin. It is also the case that the fractional abundance of CH₃OH is lower in sources with higher H₂O terminal velocities.

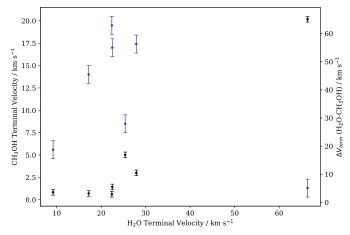


Figure 5. Terminal velocity of CH_3OH against terminal velocity of H_2O used as a proxy for the outflow velocity. The blue points show the terminal velocity (left axis) and the black show the difference between the two species' terminal velocities (right axis).

There are no gas phase destruction routes for CH_3OH in the KIDA or UMIST databases that have large energetic barriers. However, a reaction with H with an energetic barrier of ~3000 K exists in the atmospheric chemistry literature (Sander et al. 2011). Alternatively, as suggested by Suutarinen et al. (2014), the sputtering process could destroy the CH_3OH molecules if the shock is sufficiently high speed. Suutarinen et al. (2014) find speeds >25 km s⁻¹ are required to observe the destruction of methanol which is confirmed here as the first major drop in CH_3OH abundance occurs in L1157-R which has a H_2O terminal velocity of 27 km s⁻¹.

5.3. Velocity Trends of CH₃CHO

 CH_3CHO also shows an extremely similar terminal velocity trend to that seen in figure 5. This implies that CH_3CHO is also destroyed through a process that is more efficient in faster shocks.

Figure 6 shows the ratio of the column densities of CH_3CHO and e- CH_3OH in each source. By drawing random column densities from the MCMC chains, probability distributions for the ratios can be calculated and their most likely values and 67% probability distributions, the relationship between the ratios and the H_2O terminal velocity can also be found. The most likely case is that the ratio is independent of the shock velocity and is constant at 0.002. This constant ratio and the variation due to uncertainty in the fit are plotted as a blue line and shaded region respectively.

Taken together, these two facts indicate a grain surface origin of CH_3CHO . The velocity behaviour shows

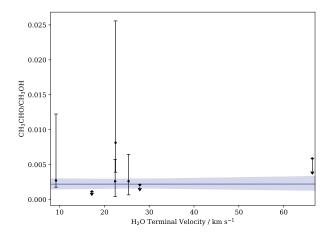


Figure 6. Ratio of CH₃CHO and CH₃OH column densities against a proxy for the outflow velocity. The ratio appears to is no evidence for variation of the ratio with velocity.

that in the post-shock gas of fast outflows, CH_3CHO is largely destroyed in the gas phase. Whereas the approximately constant ratio of CH_3CHO and CH_3OH in lower velocity outflows is inconsistent with CH_3OH being formed in the pre-shock grains and CH_3CHO being formed in post-shock gas. The initial abundance of CH_3OH should be independent of the shock properties (assuming a fast enough shock for complete sputtering of the ice mantles) but the amount of gas phase synthesis of CH_3CHO would be strongly tied to the conditions of the post-shock gas before it reaches temperatures that destroy CH_3CHO .

6. CONCLUSIONS

Eight outflow sources have been observed and, in seven, transitions of CH_3OH and CH_3CHO were detected. These have been analysed to determine the origin of those species in outflows and their post-shock behaviour.

The integrated emission of a large set of transitions of each species in the observed frequency range were measured and used to infer the column density of each species as well as the gas density and temperature fits from RADEX for CH_3OH . All of these quantities are summarized in Tables 2 and 3. Whilst these are informative, shock structures are likely to contain regions with highly varying gas properties. The higher resolution view provided by interferometry such as that being performed for CH_3OH by the SOLIS project (e.g. De Simone et al in prep.) would greatly improve our understanding of such objects.

From column density ratios of CH_3OH isomers, it is concluded that the most likely case is that CH_3OH is formed on the pre-shock ice mantles and released into the gas phase via sputtering. This assumes the spin temperature of the isomers was set at the formation of the molecules and reflects the temperature of the formation environment. Spin temperature of 5 to 10 K are considered inconsistent with formation in shocked gas.

From the terminal velocity trends of the CH_3OH transitions and the CH_3OH fractional abundance as a function of H_2O , it is concluded that in sufficiently fast shocks CH_3OH is destroyed either during the sputtering process or by chemistry in the post shock gas phase.

There is no direct evidence for the formation route of CH_3CHO . However, the near constant ratio of CH_3CHO to CH_3OH casts doubt on a gas phase origin. The amount of gas phase production of CH_3CHO would vary from source to source depending on the gas properties which makes a constant ratio unlikely if CH_3OH is formed on dust grains.

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Software: GILDAS/CLASShttp://www.iram.fr/IRAMFR/GILI Emcee (Foreman-Mackey et al. 2013), RADEX (van der Tak et al. 2007)

APPENDIX

A. OBSERVED TRANSITIONS

In this section, the observed transitions of CH₃OH and CH₃CHO are tabulated. Every CH₃OH transition with an $E_u < 250$ K and $A_{ij} > 10^{-6}$ s⁻¹ that fell into the observed frequency range was extracted for processing. For CH₃CHO transitions with an $E_u < 100$ K and $A_{ij} > 10^{-5}$ s⁻¹ were extracted. These ranges were selected to include every 3σ detection in the data set and then limit the number of non-detections that contribute to the fit. These are all listed

regardless of whether or not they were detected. For non-detections, only the spectroscopic properties of the transition and the integrated emission are presented.

Note, the CH₃OH transitions between 96.739 and 96.745 GHz and those between 157.271 and 157.276 GHz are blended. The total extent in velocity space of those blended lines are given in the V_{min} and V_{max} columns and thus, the ranges are much broader than the other transitions.

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Frequency GHz	E_u K	$\log(A_{ij})$	g_u	θ_s	V_{min} km s ⁻¹	V_{max} km s ⁻¹	V_{peak} km s ⁻¹	$\begin{array}{c} \mathbf{T}_{peak} \\ \mathbf{K} \end{array}$	$\int T_{MB} dv \mathrm{Kkms^{-1}}$
96.739	12.54	-5.59	5	25.4	-11.00	24.0	8.0	1.697(0.006)	27.08 (5.42)
96.741	6.97	-5.47	5	25.4	-5.00	30.0	8.0	1.651 (0.006)	26.88(5.38)
96.745	20.09	-5.47	5	25.4	5.00	40.0	9.0	0.436(0.006)	27.04 (5.41)
96.756	28.01	-5.58	5	25.4	6.00	15.0	9.0	0.134(0.006)	0.89(0.18)
97.583	21.56	-5.58	5	25.2	6.00	16.0	9.0	0.219(0.006)	1.56(0.31)
155.321	140.60	-4.81	21	15.8	8.00	10.0	9.0	$0.026 \ (0.005)$	0.13(0.03)
155.998	117.46	-4.78	19	15.8	6.00	13.0	9.0	0.027 (0.004)	0.23(0.05)
156.128	86.47	-5.17	13	15.8	-	-	-	- (0.005)	$0.01 \ (0.02)$
156.489	96.61	-4.75	17	15.7	6.00	16.0	9.0	$0.062 \ (0.005)$	0.47(0.10)
156.602	21.44	-5.05	10	15.7	6.00	15.0	9.0	$0.115\ (0.005)$	0.69(0.14)
156.829	78.08	-4.73	15	15.7	6.00	15.0	9.0	0.106(0.005)	0.77(0.16)
157.049	61.85	-4.71	13	15.7	6.00	17.0	9.0	$0.175\ (0.005)$	1.34(0.27)
157.179	47.94	-4.69	11	15.7	5.00	19.0	9.0	$0.247 \ (0.005)$	1.93(0.39)
157.246	36.34	-4.68	9	15.6	5.00	20.0	9.0	$0.325\ (0.006)$	2.66(0.53)
157.271	15.45	-4.66	3	15.6	-5.00	22.0	10.0	$0.444 \ (0.005)$	8.48(1.70)
157.272	27.05	-4.67	7	15.6	-2.00	26.0	10.0	$0.485\ (0.005)$	8.51(1.70)
157.276	20.09	-4.66	5	15.6	5.00	33.0	9.0	$0.385\ (0.005)$	8.52(1.70)
165.050	23.37	-4.63	3	14.9	5.00	16.0	8.0	$0.194\ (0.008)$	$1.41 \ (0.28)$
165.061	28.01	-4.63	5	14.9	6.00	16.0	9.0	$0.254\ (0.009)$	1.94(0.39)
165.099	34.98	-4.63	7	14.9	5.00	15.0	8.0	0.223(0.009)	1.62(0.33)
165.190	44.26	-4.63	9	14.9	6.00	16.0	8.0	0.180(0.008)	$1.41 \ (0.28)$
165.369	55.87	-4.64	11	14.9	6.00	15.0	9.0	0.139(0.010)	$1.01 \ (0.21)$
165.679	69.80	-4.64	13	14.8	6.00	13.0	9.0	$0.090 \ (0.009)$	$0.56\ (0.12)$
166.169	86.05	-4.64	15	14.8	7.00	12.0	9.0	$0.048\ (0.009)$	0.37(0.08)
166.899	104.62	-4.64	17	14.7	9.00	11.0	10.0	$0.029 \ (0.009)$	$0.24 \ (0.06)$
167.931	125.52	-4.64	19	14.6	-	-	-	- (0.007)	$0.08\ (0.03)$
168.578	44.26	-5.36	9	14.6	6.00	15.0	10.0	$0.085\ (0.007)$	0.66(0.14)
169.335	148.73	-4.64	21	14.5	7.00	9.0	8.0	$0.026\ (0.008)$	0.14(0.04)
170.061	36.17	-4.59	7	14.5	5.00	20.0	9.0	$1.279\ (0.009)$	9.87(1.97)
172.446	78.08	-4.94	15	14.3	6.00	15.0	10.0	$0.142 \ (0.010)$	1.00(0.20)

Table 4. Observed transitions of CH₃OH in IRAS2A-R. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

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Frequency GHz	E_u K	$\log(\mathbf{A}_{ij})$	g_u	θ_s	V_{min} km s ⁻¹	V_{max} km s ⁻¹	V_{peak} km s ⁻¹	$\begin{array}{c} \mathbf{T}_{peak} \\ \mathbf{K} \end{array}$	$\int T_{MB} dv \mathrm{Kkms^{-1}}$
155.321	140.60	-4.81	21	15.8	-	-	-	- (0.006)	0.01 (0.02)
155.998	117.46	-4.78	19	15.8	-	-	-	- (0.005)	0.06(0.02)
156.128	86.47	-5.17	13	15.8	-	-	-	- (0.005)	-0.00 (0.02)
156.489	96.61	-4.75	17	15.7	-	-	-	- (0.005)	$0.06 \ (0.03)$
156.829	78.08	-4.73	15	15.7	-	-	-	- (0.006)	0.13(0.04)
157.049	61.85	-4.71	13	15.7	-6.00	6.0	2.0	$0.035\ (0.004)$	0.34(0.07)
157.179	47.94	-4.69	11	15.7	-5.00	7.0	2.0	$0.056\ (0.004)$	$0.50 \ (0.10)$
157.246	36.34	-4.68	9	15.6	-6.00	7.0	2.0	0.089(0.004)	0.77(0.16)
157.271	15.45	-4.66	3	15.6	-17.00	10.0	2.0	$0.205\ (0.004)$	3.72(0.74)
157.272	27.05	-4.67	7	15.6	-14.00	13.0	2.0	0.175(0.004)	3.72(0.74)
157.276	20.09	-4.66	5	15.6	-7.00	20.0	3.0	$0.137 \ (0.004)$	3.72(0.74)
167.931	125.52	-4.64	19	14.6	-	-	-	- (0.006)	$0.03 \ (0.03)$
168.578	44.26	-5.36	9	14.6	-	-	-	- (0.007)	$0.06 \ (0.03)$
169.335	148.73	-4.64	21	14.5	-	-	-	- (0.006)	$0.02 \ (0.03)$
170.061	36.17	-4.59	7	14.5	-7.00	10.0	2.0	$0.263 \ (0.006)$	2.55(0.51)
172.446	78.08	-4.94	15	14.3	-	-	-	- (0.010)	$0.11 \ (0.05)$

Table 5. Observed transitions of CH₃OH in IRAS2A-B. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

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Frequency GHz	E_u K	$\log(\mathbf{A}_{ij})$	\mathbf{g}_u	θ_s	V_{min} km s ⁻¹	V_{max} km s ⁻¹	V_{peak} km s ⁻¹	$\begin{array}{c} \mathbf{T}_{peak} \\ \mathbf{K} \end{array}$	$\int T_{MB} dv \\ \mathrm{Kkms^{-1}}$
96.739	12.54	-5.59	5	25.4	-11.00	17.0	8.0	1.066 (0.005)	6.84 (1.37)
96.741	6.97	-5.47	5	25.4	-5.00	9.0	8.0	1.337 (0.006)	6.75(1.35)
96.745	20.09	-5.47	5	25.4	5.00	19.0	8.0	0.252 (0.005)	6.84(1.37)
96.756	28.01	-5.58	5	25.4	6.00	9.0	8.0	0.063(0.005)	0.18 (0.04)
97.583	21.56	-5.58	5	25.2	6.00	9.0	7.0	0.061(0.006)	0.21(0.05)
155.321	140.60	-4.81	21	15.8	-	-	-	- (0.005)	0.04(0.02)
155.998	117.46	-4.78	19	15.8	-	-	-	- (0.006)	0.07(0.02)
156.128	86.47	-5.17	13	15.8	-	-	-	- (0.006)	-0.00 (0.02)
156.489	96.61	-4.75	17	15.7	-	-	-	- (0.006)	0.03(0.02)
156.602	21.44	-5.05	10	15.7	-	-	-	- (0.004)	0.06(0.02)
156.829	78.08	-4.73	15	15.7	6.00	10.0	8.0	0.031 (0.005)	0.14(0.03)
157.049	61.85	-4.71	13	15.7	5.00	11.0	7.0	0.047 (0.005)	0.25(0.05)
157.179	47.94	-4.69	11	15.7	5.00	10.0	7.0	$0.056\ (0.005)$	0.30(0.06)
157.246	36.34	-4.68	9	15.6	4.00	11.0	8.0	$0.079\ (0.005)$	0.41 (0.08)
157.271	15.45	-4.66	3	15.6	-6.00	12.0	8.0	$0.396\ (0.006)$	2.30(0.46)
157.272	27.05	-4.67	7	15.6	-3.00	15.0	8.0	$0.153\ (0.006)$	2.22(0.45)
157.276	20.09	-4.66	5	15.6	4.00	22.0	8.0	$0.243 \ (0.005)$	2.19(0.44)
165.050	23.37	-4.63	3	14.9	6.00	9.0	8.0	0.164(0.012)	0.52(0.11)
165.061	28.01	-4.63	5	14.9	5.00	9.0	8.0	0.153(0.011)	0.48(0.10)
165.099	34.98	-4.63	7	14.9	5.00	10.0	8.0	0.135(0.012)	0.68(0.14)
165.190	44.26	-4.63	9	14.9	6.00	9.0	7.0	$0.094\ (0.011)$	0.34(0.08)
165.369	55.87	-4.64	11	14.9	6.00	9.0	8.0	$0.073 \ (0.012)$	$0.37\ (0.08)$
165.679	69.80	-4.64	13	14.8	6.00	8.0	7.0	$0.076\ (0.013)$	0.32(0.08)
166.169	86.05	-4.64	15	14.8	5.00	9.0	8.0	$0.052 \ (0.010)$	$0.24\ (0.06)$
166.899	104.62	-4.64	17	14.7	-	-	-	- (0.011)	0.09(0.04)
167.931	125.52	-4.64	19	14.6	-	-	-	- (0.012)	$0.03 \ (0.04)$
168.578	44.26	-5.36	9	14.6	-	-	-	- (0.007)	$0.01 \ (0.02)$
169.335	148.73	-4.64	21	14.5	-	-	-	- (0.007)	$0.03 \ (0.02)$
170.061	36.17	-4.59	$\overline{7}$	14.5	3.00	12.0	8.0	$0.333\ (0.008)$	1.22(0.25)
172.446	78.08	-4.94	15	14.3	6.00	8.0	7.0	$0.031 \ (0.009)$	$0.13\ (0.04)$

Table 6. Observed transitions of CH₃OH in IRAS4A-R. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

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Frequency	E_u	$\log(A_{ij})$	\mathbf{g}_u	θ_s	V_{min} km s ⁻¹	V_{max} km s ⁻¹	V_{peak} km s ⁻¹	T_{peak}	$\int T_{MB} dv$
GHz	K				km s	km s		К	${\rm Kkms^{-1}}$
96.739	12.54	-5.59	5	25.4	-19.00	9.0	6.0	$0.824\ (0.019)$	19.74(3.95)
96.741	6.97	-5.47	5	25.4	-13.00	15.0	6.0	$1.336\ (0.021)$	19.60(3.92)
96.745	20.09	-5.47	5	25.4	-3.00	25.0	6.0	$0.501 \ (0.022)$	19.98(4.00)
96.756	28.01	-5.58	5	25.4	-4.00	9.0	6.0	$0.113\ (0.005)$	$0.83\ (0.17)$
97.583	21.56	-5.58	5	25.2	-4.00	9.0	6.0	$0.177 \ (0.005)$	$1.35\ (0.27)$
99.611	61.85	-9.83	13	24.7	-	-	-	- (0.005)	$0.04\ (0.03)$
101.097	39.83	-8.89	7	24.3	-	-	-	- (0.005)	-0.04 (0.03)
101.102	49.11	-8.40	9	24.3	-	-	-	- (0.004)	-0.01(0.02)
101.103	32.86	-9.59	5	24.3	-	-	-	- (0.005)	$0.02 \ (0.02)$
101.127	60.73	-8.02	11	24.3	-	-	-	- (0.005)	-0.03(0.03)
101.185	74.66	-7.70	13	24.3	-	-	-	- (0.004)	-0.01(0.02)
101.293	90.91	-7.43	15	24.3	-	-	-	- (0.004)	$0.01 \ (0.02)$
101.470	109.49	-7.19	17	24.2	-	-	-	- (0.005)	$0.02 \ (0.03)$
101.737	130.40	-6.97	19	24.2	-	-	-	- (0.004)	$0.01 \ (0.02)$
155.321	140.60	-4.81	21	15.8	-	-	-	- (0.006)	$0.05\ (0.03)$
155.998	117.46	-4.78	19	15.8	-	-	-	- (0.006)	0.08(0.04)
156.128	86.47	-5.17	13	15.8	-	-	-	- (0.004)	$0.04 \ (0.02)$
156.489	96.61	-4.75	17	15.7	-	-	-	- (0.006)	0.08(0.04)
156.602	21.44	-5.05	10	15.7	-1.00	8.0	6.0	$0.041 \ (0.005)$	$0.29\ (0.06)$
156.829	78.08	-4.73	15	15.7	-2.00	8.0	4.0	$0.044 \ (0.005)$	0.49(0.10)
157.049	61.85	-4.71	13	15.7	-5.00	9.0	6.0	$0.063 \ (0.005)$	$0.67 \ (0.14)$
157.179	47.94	-4.69	11	15.7	-5.00	9.0	6.0	$0.087 \ (0.004)$	1.00(0.20)
157.246	36.34	-4.68	9	15.6	-6.00	9.0	6.0	$0.112 \ (0.005)$	$1.17 \ (0.24)$
157.271	15.45	-4.66	3	15.6	-15.00	9.0	4.0	$0.264\ (0.006)$	5.18(1.04)
157.272	27.05	-4.67	7	15.6	-14.00	12.0	6.0	$0.237 \ (0.005)$	5.12(1.02)
157.276	20.09	-4.66	5	15.6	-7.00	19.0	6.0	$0.240\ (0.005)$	5.12(1.02)
159.030	133.15	-8.80	21	15.5	-	-	-	- (0.005)	-0.02(0.02)
165.050	23.37	-4.63	3	14.9	-4.00	9.0	6.0	$0.141 \ (0.007)$	$1.53\ (0.31)$
165.061	28.01	-4.63	5	14.9	-5.00	9.0	6.0	$0.189\ (0.007)$	1.92(0.39)
165.099	34.98	-4.63	7	14.9	-4.00	9.0	6.0	$0.194\ (0.008)$	1.70(0.34)
165.190	44.26	-4.63	9	14.9	-4.00	8.0	6.0	$0.182\ (0.010)$	1.60(0.32)
165.369	55.87	-4.64	11	14.9	-4.00	8.0	6.0	$0.150\ (0.008)$	1.17(0.24)
165.679	69.80	-4.64	13	14.8	-1.00	9.0	6.0	$0.087 \ (0.008)$	$0.73\ (0.15)$
165.934	117.46	-8.71	19	14.8	-	-	-	- (0.009)	-0.01(0.05)
166.169	86.05	-4.64	15	14.8	0.00	8.0	5.0	$0.059\ (0.008)$	0.60(0.13)
166.899	104.62	-4.64	17	14.7	2.00	9.0	6.0	$0.040\ (0.008)$	0.44 (0.10)

Table 7. Observed transitions of CH₃OH in IRAS4A-B. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

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Frequency GHz	E_u K	$\log(\mathbf{A}_{ij})$	g_u	θ_s	$\frac{V_{min}}{\rm kms^{-1}}$	V_{max} km s ⁻¹	V_{peak} km s ⁻¹	$\begin{array}{c} \mathbf{T}_{peak} \\ \mathbf{K} \end{array}$	$\int T_{MB} dv \\ \mathrm{Kkms^{-1}}$
167.931	125.52	-4.64	19	14.6	3.00	5.0	4.0	$0.019 \ (0.005)$	$0.11 \ (0.03)$
168.464	112.71	-7.91	15	14.6	-	-	-	- (0.005)	-0.01(0.03)
168.578	44.26	-5.36	9	14.6	3.00	6.0	4.0	$0.028 \ (0.006)$	0.28(0.07)
169.335	148.73	-4.64	21	14.5	-	-	-	- (0.007)	0.05 (0.04)
170.061	36.17	-4.59	7	14.5	-5.00	9.0	6.0	$0.341 \ (0.007)$	3.63(0.73)
172.446	78.08	-4.94	15	14.3	4.00	7.0	6.0	$0.036\ (0.009)$	$0.45\ (0.10)$

Table 8. Observed transitions of CH₃OH in IRAS4A-B. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection. continued.

Frequency GHz	E_u K	$\log(A_{ij})$	\mathbf{g}_u	$ heta_s$,,	V_{min} $\mathrm{kms^{-1}}$	V_{max} $km s^{-1}$	V_{peak} $km s^{-1}$	$\begin{array}{c} \mathbf{T}_{peak} \\ \mathbf{K} \end{array}$	$\int T_{MB} dv \mathrm{K} \mathrm{km} \mathrm{s}^{-1}$
96.739	12.54	-5.59	5	25.4	-4.00	18.0	17.0	0.030(0.007)	1.55(0.31)
96.741	6.97	-5.47	5	25.4	2.00	25.0	17.0	0.065 (0.005)	1.49(0.30)
96.745	20.09	-5.47	5	25.4	12.00	34.0	17.0	$0.054 \ (0.006)$	1.45(0.29)
96.756	28.01	-5.58	5	25.4	-	-	-	- (0.006)	-0.03 (0.02)
97.583	21.56	-5.58	5	25.2	-	-	-	- (0.008)	0.00(0.02)
155.321	140.60	-4.81	21	15.8	-	-	-	- (0.004)	0.02(0.01)
155.998	117.46	-4.78	19	15.8	-	-	-	- (0.003)	-0.00 (0.01)
156.128	86.47	-5.17	13	15.8	-	-	-	- (0.004)	0.02(0.01)
156.489	96.61	-4.75	17	15.7	-	-	-	- (0.004)	0.02(0.01)
156.602	21.44	-5.05	10	15.7	-	-	-	- (0.003)	-0.02(0.01)
156.829	78.08	-4.73	15	15.7	-	-	-	- (0.003)	0.02(0.01)
157.049	61.85	-4.71	13	15.7	-	-	-	- (0.003)	0.00(0.01)
157.179	47.94	-4.69	11	15.7	-	-	-	- (0.003)	-0.00 (0.01)
157.246	36.34	-4.68	9	15.6	-	-	-	- (0.004)	0.02(0.01)
157.271	15.45	-4.66	3	15.6	-	-	-	- (0.004)	0.08(0.02)
157.272	27.05	-4.67	7	15.6	-	-	-	- (0.004)	0.06(0.02)
157.276	20.09	-4.66	5	15.6	-	-	-	- (0.004)	0.05 (0.02)
165.050	23.37	-4.63	3	14.9	-	-	-	- (0.009)	$0.03 \ (0.03)$
165.061	28.01	-4.63	5	14.9	-	-	-	- (0.009)	-0.04(0.03)
165.099	34.98	-4.63	$\overline{7}$	14.9	-	-	-	- (0.010)	$0.01 \ (0.03)$
165.190	44.26	-4.63	9	14.9	-	-	-	- (0.010)	$0.05 \ (0.03)$
165.369	55.87	-4.64	11	14.9	-	-	-	- (0.008)	0.02(0.03)
165.679	69.80	-4.64	13	14.8	-	-	-	- (0.011)	-0.01 (0.03)
166.169	86.05	-4.64	15	14.8	-	-	-	- (0.010)	-0.02(0.03)
166.899	104.62	-4.64	17	14.7	-	-	-	- (0.011)	0.02(0.03)
167.931	125.52	-4.64	19	14.6	-	-	-	- (0.005)	-0.02 (0.02)
168.578	44.26	-5.36	9	14.6	-	-	-	- (0.004)	$0.02 \ (0.01)$
169.335	148.73	-4.64	21	14.5	-	-	-	- (0.004)	$0.01 \ (0.01)$
170.061	36.17	-4.59	$\overline{7}$	14.5	-	-	-	- (0.004)	$0.03 \ (0.02)$
172.446	78.08	-4.94	15	14.3	-	-	-	- (0.007)	-0.01(0.02)

Table 9. Observed transitions of CH₃OH in L1157-R. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

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Frequency GHz	E_u K	$\log(\mathbf{A}_{ij})$	g_u	θ_s	V_{min} km s ⁻¹	V_{max} km s ⁻¹	V_{peak} km s ⁻¹	T_{peak} K	$\int T_{MB} dv \\ \mathrm{Kkms^{-1}}$
96.739	12.54	-5.59	5	25.4	-20.00	7.0	2.0	2.659(0.004)	30.36 (6.07)
96.739 96.741	6.97	-5.47	5	25.4 25.4	-20.00 -14.00	14.0	2.0 2.0	3.378(0.004)	30.38(0.07) 30.38(6.08)
96.741 96.745	20.09	-5.47	5	25.4 25.4	-14.00 -4.00	23.0	2.0 2.0	0.699 (0.005)	30.38(0.08) 30.40(6.08)
96.745 96.756	28.01	-5.58	5	25.4	-3.00	4.0	2.0 2.0	0.099 (0.005) 0.192 (0.005)	0.65 (0.13)
97.583	20.01 21.56	-5.58	5	25.4	-3.00	4.0 5.0	2.0 2.0	0.192(0.003) 0.307(0.004)	1.12(0.22)
155.321	140.60	-4.81	21	15.8	-5.00	-	-	- (0.004)	0.01 (0.01)
155.921 155.998	117.46	-4.78	19	15.8	0.00	4.0	2.0	0.018 (0.003)	$0.01 (0.01) \\ 0.07 (0.02)$
156.128	86.47	-5.17	13	15.8	-	-	-	- (0.004)	-0.00(0.01)
156.489	96.61	-4.75	17	15.7	0.00	4.0	2.0	0.027 (0.004)	0.11 (0.03)
156.602	21.44	-5.05	10	15.7	-	-	-	-(0.003)	-0.03(0.01)
156.829	78.08	-4.73	15	15.7	-2.00	5.0	2.0	0.068 (0.003)	0.26 (0.01)
150.029 157.049	61.85	-4.71	13	15.7	-3.00	5.0	2.0 2.0	0.109 (0.003)	0.26(0.09) 0.46(0.09)
157.179	47.94	-4.69	11	15.7	-3.00	5.0	2.0	0.178 (0.003)	0.75(0.15)
157.246	36.34	-4.68	9	15.6	-3.00	5.0	2.0	0.237 (0.003)	1.12(0.22)
157.271	15.45	-4.66	3	15.6	-14.00	6.0	2.0	0.580 (0.003)	5.69(1.14)
157.272	27.05	-4.67	7	15.6	-11.00	9.0	3.0	0.396 (0.003)	5.72(1.14)
157.276	20.09	-4.66	5	15.6	-4.00	16.0	2.0	$0.380 \ (0.003)$	5.71(1.14)
165.050	23.37	-4.63	3	14.9	-3.00	5.0	2.0	0.312 (0.008)	1.29(0.26)
165.061	28.01	-4.63	5	14.9	-2.00	5.0	2.0	0.380 (0.007)	1.52(0.30)
165.099	34.98	-4.63	7	14.9	-3.00	5.0	2.0	0.332 (0.008)	1.27 (0.26)
165.190	44.26	-4.63	9	14.9	-3.00	5.0	2.0	0.282 (0.008)	1.04(0.21)
165.369	55.87	-4.64	11	14.9	-2.00	4.0	2.0	0.184 (0.008)	0.64 (0.13)
165.679	69.80	-4.64	13	14.8	-1.00	4.0	2.0	0.097 (0.008)	0.38 (0.08)
166.169	86.05	-4.64	15	14.8	0.00	4.0	2.0	0.060 (0.008)	0.19(0.05)
166.899	104.62	-4.64	17	14.7	0.00	3.0	1.0	0.034 (0.007)	0.10 (0.03)
167.931	125.52	-4.64	19	14.6	-	-	-	- (0.005)	0.05(0.02)
168.578	44.26	-5.36	9	14.6	-1.00	4.0	2.0	0.065 (0.005)	0.24(0.05)
169.335	148.73	-4.64	21	14.5	-	-	-	- (0.005)	0.03 (0.01)
170.061	36.17	-4.59	7	14.5	-3.00	5.0	2.0	1.217 (0.004)	4.27 (0.85)
172.446	78.08	-4.94	15	14.3	-1.00	4.0	2.0	0.086(0.007)	0.32(0.07)

Table 10. Observed transitions of CH₃OH in L1157-B2. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

COMS IN OUTFLOWS

Frequency GHz	E_u K	$\log(\mathbf{A}_{ij})$	g_u	$\left \begin{array}{c} \theta_s \\ , \end{array} \right $	V_{min} km s ⁻¹	V_{max} km s ⁻¹	V_{peak} km s ⁻¹	$\begin{array}{c} \mathbf{T}_{peak} \\ \mathbf{K} \end{array}$	$\int T_{MB} dv \\ \mathrm{Kkms^{-1}}$
155.321	140.60	-4.81	21	15.8	-	-	-	- (0.007)	0.02(0.01)
155.998	117.46	-4.78	19	15.8	-	-	-	- (0.006)	-0.01 (0.01)
156.128	86.47	-5.17	13	15.8	-	-	-	- (0.007)	0.01 (0.01)
156.489	96.61	-4.75	17	15.7	-	-	-	- (0.004)	-0.01 (0.01)
156.602	21.44	-5.05	10	15.7	-	-	-	- (0.004)	0.00(0.01)
156.829	78.08	-4.73	15	15.7	-	-	-	- (0.005)	-0.01 (0.01)
157.049	61.85	-4.71	13	15.7	-	-	-	- (0.004)	-0.00 (0.01)
157.179	47.94	-4.69	11	15.7	-	-	-	- (0.004)	-0.00(0.01)
157.246	36.34	-4.68	9	15.6	-	-	-	- (0.005)	$0.01 \ (0.01)$
157.271	15.45	-4.66	3	15.6	-	-	-	- (0.004)	0.17 (0.04)
157.272	27.05	-4.67	$\overline{7}$	15.6	6.00	9.0	7.0	0.052(0.004)	0.18(0.04)
157.276	20.09	-4.66	5	15.6	-	-	-	- (0.004)	0.16(0.03)
168.578	44.26	-5.36	9	14.6	-	-	-	- (0.006)	-0.01(0.01)
169.335	148.73	-4.64	21	14.5	-	-	-	- (0.006)	$0.01 \ (0.01)$
170.061	36.17	-4.59	7	14.5	-	-	-	- (0.007)	-0.02(0.01)
172.446	78.08	-4.94	15	14.3	-	-	-	- (0.007)	0.00(0.01)

Table 11. Observed transitions of CH₃OH in L1448-B2. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

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Frequency	\mathbf{E}_{u}	$\log(A_{ij})$	\mathbf{g}_u	θ_s	V _{min}	V _{max}	V_{peak}	T_{peak}	$\int T_{MB} dv$
GHz	Κ			"	${\rm kms^{-1}}$	${\rm kms^{-1}}$	${\rm kms^{-1}}$	К	${\rm Kkms^{-1}}$
96.274	22.93	-4.60	22	25.6	-	-	-	- (0.007)	0.06(0.02)
96.343	50.06	-4.97	22	25.5	-	-	-	- (0.006)	-0.02(0.02)
96.343	50.06	-4.97	22	25.5	-	-	-	- (0.006)	-0.02(0.02)
96.353	49.99	-4.97	22	25.5	-	-	-	- (0.006)	-0.02(0.02)
96.361	49.95	-4.97	22	25.5	-	-	-	- (0.006)	-0.00(0.02)
96.368	34.26	-4.72	22	25.5	-	-	-	- (0.007)	$0.03 \ (0.02)$
96.368	34.26	-4.72	22	25.5	-	-	-	- (0.006)	0.02(0.02)
96.372	34.26	-4.72	22	25.5	-	-	-	- (0.006)	$0.01 \ (0.02)$
96.384	34.16	-4.72	22	25.5	-	-	-	- (0.006)	$0.03 \ (0.02)$
96.426	22.91	-4.60	22	25.5	6.00	8.0	7.0	$0.028\ (0.005)$	0.09(0.02)
96.476	23.03	-4.60	22	25.5	-	-	-	- (0.006)	$0.03\ (0.02)$
96.633	22.96	-4.60	22	25.5	6.00	9.0	7.0	$0.019\ (0.005)$	0.09(0.02)
98.863	16.59	-4.51	22	24.9	6.00	13.0	7.0	$0.058\ (0.005)$	$0.27 \ (0.06)$
98.901	16.51	-4.51	22	24.9	6.00	12.0	8.0	$0.052\ (0.006)$	$0.27 \ (0.06)$
152.635	33.10	-3.91	34	16.1	6.00	12.0	7.0	$0.048\ (0.005)$	$0.27 \ (0.06)$
153.004	28.48	-4.97	26	16.1	-	-	-	- (0.005)	0.00(0.01)
153.873	42.33	-3.93	34	16.0	6.00	9.0	8.0	$0.030\ (0.005)$	$0.12 \ (0.03)$
154.027	42.33	-3.93	34	16.0	6.00	8.0	7.0	$0.024\ (0.006)$	0.09(0.02)
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.005)	-0.01(0.01)
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.005)	-0.01(0.01)
154.183	89.69	-4.11	34	16.0	-	-	-	- (0.006)	-0.02(0.02)
154.189	89.65	-4.11	34	16.0	-	-	-	- (0.018)	-0.00(0.05)
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.021)	$0.02 \ (0.06)$
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.021)	$0.03 \ (0.06)$
154.230	69.38	-4.02	34	16.0	-	-	-	- (0.021)	$0.04\ (0.06)$
154.275	53.69	-3.96	34	15.9	-	-	-	- (0.006)	0.04(0.02)
154.296	53.69	-3.96	34	15.9	-	-	-	- (0.006)	0.06(0.02)
154.322	53.60	-3.96	34	15.9	-	-	-	- (0.005)	0.06(0.02)
154.323	53.69	-3.96	34	15.9	-	-	-	- (0.006)	$0.07 \ (0.02)$
155.180	42.54	-3.92	34	15.9	6.00	11.0	7.0	$0.035\ (0.005)$	0.11 (0.03)
155.342	42.50	-3.91	34	15.8	6.00	9.0	8.0	$0.030 \ (0.005)$	0.15(0.03)
156.807	34.94	-4.94	30	15.7	-	-	-	- (0.005)	0.01 (0.01)
157.938	36.50	-3.87	34	15.6	6.00	14.0	7.0	$0.050 \ (0.006)$	0.30(0.06)
157.975	36.43	-3.87	34	15.6	6.00	12.0	7.0	0.055 (0.005)	0.25(0.05)
159.692	42.33	-4.95	34	15.4	-	-	-	- (0.006)	0.01 (0.02)
161.172	42.33	-4.91	34	15.3	-	-	-	- (0.007)	0.06 (0.02)

Table 12. Observed transitions of CH₃CHO in IRAS2A-R. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

COMS IN OUTFLOWS

Frequency GHz	E_u K	$\log(\mathbf{A}_{ij})$	\mathbf{g}_u	$\left \begin{array}{c} \theta_s \\ , \end{array} \right $	V_{min} km s ⁻¹	V_{max} km s ⁻¹	V_{peak} km s ⁻¹	$\begin{array}{c} \mathbf{T}_{peak} \\ \mathbf{K} \end{array}$	$\int T_{MB} dv \\ \mathrm{Kkms^{-1}}$
162.044	50.44	-4.79	42	15.2	-	-	-	- (0.008)	0.00 (0.02)
164.727	50.64	-4.90	38	14.9	-	-	-	- (0.008)	-0.02(0.02)
167.981	27.42	-4.74	30	14.6	-	-	-	- (0.006)	0.04(0.02)
168.089	42.73	-3.79	38	14.6	6.00	13.0	9.0	$0.031 \ (0.006)$	0.20(0.04)
168.093	42.66	-3.79	38	14.6	6.00	10.0	7.0	$0.031 \ (0.006)$	0.11(0.03)
170.293	59.86	-4.86	42	14.4	-	-	-	- (0.008)	-0.03(0.02)
171.265	41.42	-3.76	38	14.4	6.00	9.0	8.0	0.048(0.009)	$0.20 \ (0.05)$
171.297	41.32	-3.76	38	14.4	6.00	9.0	8.0	$0.050 \ (0.009)$	$0.21 \ (0.05)$
171.606	59.85	-4.84	42	14.3	-	-	-	- (0.008)	0.00(0.02)
173.026	50.63	-3.77	38	14.2	7.00	9.0	8.0	$0.042 \ (0.010)$	$0.15 \ (0.04)$
173.124	50.64	-3.77	38	14.2	7.00	9.0	8.0	$0.033\ (0.009)$	0.13(0.04)
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.009)	$0.01 \ (0.02)$
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.009)	$0.01 \ (0.02)$
173.470	98.01	-3.90	38	14.2	-	-	-	- (0.010)	$0.05\ (0.03)$
173.476	97.98	-3.90	38	14.2	-	-	-	- (0.013)	-0.02(0.04)
173.519	77.75	-3.83	38	14.2	-	-	-	- (0.018)	$0.07\ (0.05)$
173.534	77.70	-3.83	38	14.2	-	-	-	- (0.012)	0.00(0.03)
173.595	62.02	-3.79	38	14.2	-	-	-	- (0.010)	$0.04\ (0.03)$
173.638	62.03	-3.79	38	14.2	-	-	-	- (0.014)	$0.07 \ (0.04)$
173.664	61.93	-3.79	38	14.2	-	-	-	- (0.012)	0.07 (0.04)
174.982	50.94	-3.75	38	14.1	-	-	-	- (0.011)	0.16(0.05)
175.091	50.91	-3.75	38	14.0	-	-	-	- (0.011)	0.10(0.04)

Table 13. Observed transitions of CH₃CHO in IRAS2A-R. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection. continued.

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Frequency	\mathbf{E}_{u}	$\log(\mathbf{A}_{ij})$	\mathbf{g}_u	θ_s	V_{min}	V_{max}	V_{peak}	T_{peak}	$\int T_{MB} dv$
GHz	Κ			"	${\rm kms^{-1}}$	${\rm kms^{-1}}$	${\rm kms^{-1}}$	Κ	${ m Kkms^{-1}}$
152.635	33.10	-3.91	34	16.1	-	-	-	- (0.005)	0.03(0.02)
153.004	28.48	-4.97	26	16.1	-	-	-	- (0.006)	-0.01 (0.02)
153.873	42.33	-3.93	34	16.0	-	-	-	- (0.006)	-0.05(0.03)
154.027	42.33	-3.93	34	16.0	-	-	-	- (0.006)	$0.06 \ (0.03)$
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.005)	-0.01 (0.02)
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.005)	-0.01 (0.02)
154.183	89.69	-4.11	34	16.0	-	-	-	- (0.005)	-0.03 (0.02)
154.189	89.65	-4.11	34	16.0	-	-	-	- (0.006)	-0.01 (0.02)
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.006)	-0.02(0.03)
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.006)	-0.00 (0.03)
154.230	69.38	-4.02	34	16.0	-	-	-	- (0.004)	-0.02(0.02)
154.275	53.69	-3.96	34	15.9	-	-	-	- (0.005)	$0.00 \ (0.02)$
154.296	53.69	-3.96	34	15.9	-	-	-	- (0.005)	$0.02 \ (0.02)$
154.322	53.60	-3.96	34	15.9	-	-	-	- (0.004)	$0.00 \ (0.02)$
154.323	53.69	-3.96	34	15.9	-	-	-	- (0.005)	$0.01 \ (0.02)$
155.180	42.54	-3.92	34	15.9	-	-	-	- (0.006)	$0.01 \ (0.02)$
155.342	42.50	-3.91	34	15.8	-	-	-	- (0.005)	$0.01 \ (0.02)$
156.807	34.94	-4.94	30	15.7	-	-	-	- (0.006)	-0.00(0.03)
157.938	36.50	-3.87	34	15.6	-	-	-	- (0.004)	$0.04 \ (0.02)$
157.975	36.43	-3.87	34	15.6	-	-	-	- (0.005)	-0.01(0.02)
159.692	42.33	-4.95	34	15.4	-	-	-	- (0.004)	$0.02 \ (0.02)$
167.981	27.42	-4.74	30	14.6	-	-	-	- (0.005)	$0.03 \ (0.02)$
168.089	42.73	-3.79	38	14.6	-	-	-	- (0.006)	$0.02 \ (0.03)$
168.093	42.66	-3.79	38	14.6	-	-	-	- (0.006)	$0.04 \ (0.03)$
170.293	59.86	-4.86	42	14.4	-	-	-	- (0.006)	$0.03\ (0.03)$
171.265	41.42	-3.76	38	14.4	-	-	-	- (0.007)	-0.02(0.03)
171.297	41.32	-3.76	38	14.4	-	-	-	- (0.008)	-0.04(0.03)
171.606	59.85	-4.84	42	14.3	-	-	-	- (0.007)	$0.03\ (0.03)$
173.124	50.64	-3.77	38	14.2	-	-	-	- (0.009)	$0.01 \ (0.04)$
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.010)	$0.02 \ (0.04)$
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.010)	$0.02 \ (0.04)$
173.470	98.01	-3.90	38	14.2	-	-	-	- (0.010)	-0.08(0.05)
173.476	97.98	-3.90	38	14.2	-	-	-	- (0.008)	-0.01 (0.03)
173.519	77.75	-3.83	38	14.2	-	-	-	- (0.009)	$0.01 \ (0.04)$
173.534	77.70	-3.83	38	14.2	-	-	-	- (0.008)	$0.02 \ (0.04)$
173.595	62.02	-3.79	38	14.2	-	-	-	- (0.009)	0.01 (0.04)

Table 14. Observed transitions of CH₃CHO in IRAS2A-B. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

COMS IN OUTFLOWS

Frequency GHz	E_u K	$\log(\mathbf{A}_{ij})$	g_u	θ_s	V_{min} km s ⁻¹	V_{max} km s ⁻¹	V_{peak} $km s^{-1}$	$\begin{array}{c} \mathbf{T}_{peak} \\ \mathbf{K} \end{array}$	$\int T_{MB} dv \\ \mathrm{Kkms^{-1}}$
173.638	62.03	-3.79	38	14.2	-	-	-	- (0.009)	$0.01 \ (0.04)$
173.664	61.93	-3.79	38	14.2	-	-	-	- (0.009)	$0.07 \ (0.04)$
174.982	50.94	-3.75	38	14.1	-	-	-	- (0.012)	$0.04 \ (0.05)$
175.091	50.91	-3.75	38	14.0	-	-	-	- (0.011)	$0.06\ (0.05)$

Table 15. Observed transitions of CH₃CHO in IRAS2A-B. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection. continued.

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Frequency GHz	E_u K	$\log(\mathbf{A}_{ij})$	\mathbf{g}_u	θ_s	V_{min} km s ⁻¹	V_{max} km s ⁻¹	V_{peak} km s ⁻¹	T_{peak} K	$\int T_{MB} dv \\ \mathrm{Kkms^{-1}}$
96.274	22.93	-4.60	22	25.6	-	-	-	- (0.006)	0.02(0.01)
96.343	50.06	-4.97	22	25.5	-	-	-	- (0.006)	0.00(0.01)
96.343	50.06	-4.97	22	25.5	-	-	-	- (0.006)	0.00 (0.01)
96.353	49.99	-4.97	22	25.5	-	-	-	- (0.007)	-0.00 (0.01)
96.361	49.95	-4.97	22	25.5	-	-	-	- (0.007)	0.01 (0.01)
96.368	34.26	-4.72	22	25.5	-	-	-	- (0.007)	0.02(0.01)
96.368	34.26	-4.72	22	25.5	-	-	-	- (0.007)	0.00(0.01)
96.372	34.26	-4.72	22	25.5	-	-	-	- (0.007)	-0.02(0.01)
96.384	34.16	-4.72	22	25.5	-	-	-	- (0.007)	0.00(0.01)
96.426	22.91	-4.60	22	25.5	-	-	-	- (0.008)	0.05~(0.02)
96.476	23.03	-4.60	22	25.5	-	-	-	- (0.006)	$0.03\ (0.01)$
96.633	22.96	-4.60	22	25.5	-	-	-	- (0.007)	0.00(0.01)
98.863	16.59	-4.51	22	24.9	6.00	9.0	8.0	$0.047 \ (0.006)$	0.10(0.02)
98.901	16.51	-4.51	22	24.9	6.00	9.0	8.0	$0.060\ (0.006)$	0.12(0.03)
152.635	33.10	-3.91	34	16.1	-	-	-	- (0.005)	$0.03\ (0.01)$
153.004	28.48	-4.97	26	16.1	-	-	-	- (0.005)	-0.00 (0.01)
153.873	42.33	-3.93	34	16.0	-	-	-	- (0.006)	$0.03\ (0.01)$
154.027	42.33	-3.93	34	16.0	-	-	-	- (0.005)	$0.01 \ (0.01)$
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.006)	$0.01 \ (0.01)$
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.006)	0.01 (0.01)
154.183	89.69	-4.11	34	16.0	-	-	-	- (0.005)	-0.00 (0.01)
154.189	89.65	-4.11	34	16.0	-	-	-	- (0.005)	-0.01 (0.01)
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.005)	-0.00 (0.01)
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.005)	-0.00 (0.01)
154.230	69.38	-4.02	34	16.0	-	-	-	- (0.005)	0.01(0.01)
154.275	53.69	-3.96	34	15.9	-	-	-	- (0.005)	0.00(0.01)
154.296	53.69	-3.96	34	15.9	-	-	-	- (0.005)	0.01(0.01)
154.322	53.60	-3.96	34	15.9	-	-	-	- (0.005)	0.02(0.01)
154.323	53.69	-3.96	34	15.9	-	-	-	- (0.006)	0.02(0.01)
155.180	42.54	-3.92	34	15.9	-	-	-	- (0.005)	0.00(0.01)
155.342	42.50	-3.91	34	15.8	-	-	-	- (0.006)	0.02(0.01)
156.807	34.94	-4.94	30	15.7	-	-	-	- (0.006)	-0.03 (0.01)
157.938	36.50	-3.87	34	15.6	6.00	8.0	7.0	0.023 (0.006)	0.05(0.01)
157.975	36.43	-3.87	34	15.6	-	-	-	- (0.005)	0.03 (0.01)
159.692	42.33	-4.95	34	15.4	-	-	-	- (0.005)	-0.01 (0.01)
161.172	42.33	-4.91	34	15.3	-	-	-	- (0.009)	-0.02(0.02)

Table 16. Observed transitions of CH₃CHO in IRAS4A-R. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

COMS IN OUTFLOWS

Frequency GHz	E_u K	$\log(\mathbf{A}_{ij})$	g_u	$\substack{ heta_s \\ ,,}$	V_{min} km s ⁻¹	V_{max} km s ⁻¹	V_{peak} km s ⁻¹	$\begin{array}{c} \mathbf{T}_{peak} \\ \mathbf{K} \end{array}$	$\int T_{MB} dv \\ \mathrm{Kkms^{-1}}$
162.044	50.44	-4.79	42	15.2	-	-	-	- (0.008)	-0.00 (0.01)
164.727	50.64	-4.90	38	14.9	-	-	-	- (0.011)	-0.01 (0.02)
167.981	27.42	-4.74	30	14.6	-	-	-	- (0.011)	-0.02(0.02)
168.089	42.73	-3.79	38	14.6	-	-	-	- (0.012)	0.00(0.02)
168.093	42.66	-3.79	38	14.6	-	-	-	- (0.010)	0.04(0.02)
170.293	59.86	-4.86	42	14.4	-	-	-	- (0.007)	-0.01 (0.01)
171.265	41.42	-3.76	38	14.4	-	-	-	- (0.008)	$0.02 \ (0.01)$
171.297	41.32	-3.76	38	14.4	-	-	-	- (0.008)	$0.02 \ (0.02)$
171.606	59.85	-4.84	42	14.3	-	-	-	- (0.008)	-0.01 (0.01)
173.026	50.63	-3.77	38	14.2	-	-	-	- (0.008)	$0.02 \ (0.01)$
173.124	50.64	-3.77	38	14.2	-	-	-	- (0.009)	$0.03 \ (0.02)$
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.008)	-0.01 (0.01)
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.008)	-0.01 (0.01)
173.470	98.01	-3.90	38	14.2	-	-	-	- (0.008)	$0.02 \ (0.01)$
173.476	97.98	-3.90	38	14.2	-	-	-	- (0.008)	-0.02(0.01)
173.519	77.75	-3.83	38	14.2	-	-	-	- (0.009)	-0.02(0.02)
173.534	77.70	-3.83	38	14.2	-	-	-	- (0.009)	$0.00 \ (0.02)$
173.595	62.02	-3.79	38	14.2	-	-	-	- (0.007)	$0.01 \ (0.01)$
173.638	62.03	-3.79	38	14.2	-	-	-	- (0.008)	$0.01 \ (0.01)$
173.664	61.93	-3.79	38	14.2	-	-	-	- (0.008)	$0.01 \ (0.01)$
174.982	50.94	-3.75	38	14.1	-	-	-	- (0.010)	-0.01 (0.02)
175.091	50.91	-3.75	38	14.0	-	-	-	- (0.010)	0.02(0.02)

Table 17. Observed transitions of CH₃CHO in IRAS4A-R. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection. continued.

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Frequency	\mathbf{E}_{u}	$\log(\mathbf{A}_{ij})$	g_u	θ_s	V_{min}	V_{max}	V_{peak}	T_{peak}	$\int T_{MB} dv$
GHz	Κ			"	$\rm kms^{-1}$	${\rm kms^{-1}}$	$\rm kms^{-1}$	К	${\rm Kkms^{-1}}$
96.274	22.93	-4.60	22	25.6	-	-	-	- (0.006)	0.10(0.03)
96.343	50.06	-4.97	22	25.5	-	-	-	- (0.006)	0.02(0.02)
96.343	50.06	-4.97	22	25.5	-	-	-	- (0.006)	0.02(0.02)
96.353	49.99	-4.97	22	25.5	-	-	-	- (0.006)	$0.03 \ (0.02)$
96.361	49.95	-4.97	22	25.5	-	-	-	- (0.005)	-0.02(0.02)
96.368	34.26	-4.72	22	25.5	-	-	-	- (0.005)	$0.08 \ (0.02)$
96.368	34.26	-4.72	22	25.5	-	-	-	- (0.006)	$0.05 \ (0.02)$
96.372	34.26	-4.72	22	25.5	-	-	-	- (0.006)	$0.01 \ (0.02)$
96.426	22.91	-4.60	22	25.5	-	-	-	- (0.007)	$0.09\ (0.03)$
96.476	23.03	-4.60	22	25.5	5.00	8.0	7.0	$0.023\ (0.005)$	$0.12 \ (0.03)$
96.633	22.96	-4.60	22	25.5	5.00	8.0	7.0	$0.021 \ (0.005)$	$0.11 \ (0.03)$
98.863	16.59	-4.51	22	24.9	3.00	8.0	7.0	$0.052 \ (0.005)$	0.25~(0.05)
98.901	16.51	-4.51	22	24.9	1.00	9.0	7.0	$0.060 \ (0.005)$	$0.35\ (0.07)$
152.635	33.10	-3.91	34	16.1	6.00	8.0	7.0	$0.026\ (0.005)$	$0.12 \ (0.03)$
153.004	28.48	-4.97	26	16.1	-	-	-	- (0.005)	$0.02 \ (0.02)$
153.873	42.33	-3.93	34	16.0	-	-	-	- (0.006)	$0.06 \ (0.02)$
154.027	42.33	-3.93	34	16.0	-	-	-	- (0.006)	$0.09\ (0.03)$
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.006)	-0.03(0.02)
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.006)	-0.03(0.02)
154.183	89.69	-4.11	34	16.0	-	-	-	- (0.006)	$0.03 \ (0.02)$
154.189	89.65	-4.11	34	16.0	-	-	-	- (0.006)	-0.05(0.02)
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.005)	$0.01 \ (0.02)$
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.005)	$0.03\ (0.02)$
154.230	69.38	-4.02	34	16.0	-	-	-	- (0.005)	0.00(0.02)
154.275	53.69	-3.96	34	15.9	-	-	-	- (0.006)	$0.07 \ (0.03)$
154.296	53.69	-3.96	34	15.9	-	-	-	- (0.005)	$0.02 \ (0.02)$
154.322	53.60	-3.96	34	15.9	-	-	-	- (0.005)	$0.04 \ (0.02)$
154.323	53.69	-3.96	34	15.9	-	-	-	- (0.005)	$0.02 \ (0.02)$
155.180	42.54	-3.92	34	15.9	-	-	-	- (0.006)	$0.08\ (0.03)$
155.342	42.50	-3.91	34	15.8	-	-	-	- (0.006)	$0.05 \ (0.02)$
156.807	34.94	-4.94	30	15.7	-	-	-	- (0.005)	0.02(0.02)
157.938	36.50	-3.87	34	15.6	5.00	7.0	6.0	$0.023 \ (0.005)$	0.12(0.03)
157.975	36.43	-3.87	34	15.6	5.00	7.0	6.0	$0.021 \ (0.005)$	0.10(0.03)
159.692	42.33	-4.95	34	15.4	-	-	-	- (0.005)	0.02(0.02)
161.172	42.33	-4.91	34	15.3	-	-	-	- (0.005)	0.03 (0.02)
162.044	50.44	-4.79	42	15.2	-	-	-	- (0.007)	0.01 (0.02)

Table 18. Observed transitions of CH₃CHO in IRAS4A-B. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

COMS IN OUTFLOWS

Frequency GHz	E_u K	$\log(\mathbf{A}_{ij})$	g_u	$\left \begin{array}{c} \theta_s \\ , \end{array} \right $	V_{min} km s ⁻¹	V_{max} km s ⁻¹	V_{peak} km s ⁻¹	$\begin{array}{c} \mathbf{T}_{peak} \\ \mathbf{K} \end{array}$	$\int T_{MB} dv \\ \mathrm{Kkms^{-1}}$
164.727	50.64	-4.90	38	14.9	-	-	-	- (0.009)	-0.03 (0.03)
167.981	27.42	-4.74	30	14.6	-	-	-	- (0.004)	$0.01 \ (0.02)$
168.089	42.73	-3.79	38	14.6	6.00	8.0	7.0	$0.021 \ (0.005)$	0.14(0.03)
168.093	42.66	-3.79	38	14.6	5.00	8.0	6.0	$0.021 \ (0.005)$	0.08(0.02)
170.293	59.86	-4.86	42	14.4	-	-	-	- (0.008)	-0.03(0.03)
171.265	41.42	-3.76	38	14.4	-	-	-	- (0.009)	0.11(0.04)
171.297	41.32	-3.76	38	14.4	-	-	-	- (0.008)	0.06(0.03)
171.606	59.85	-4.84	42	14.3	-	-	-	- (0.007)	0.00(0.03)
173.026	50.63	-3.77	38	14.2	-	-	-	- (0.010)	0.09(0.04)
173.124	50.64	-3.77	38	14.2	-	-	-	- (0.010)	0.06(0.04)
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.009)	0.07(0.03)
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.009)	0.07 (0.03)
173.470	98.01	-3.90	38	14.2	-	-	-	- (0.010)	0.06(0.04)
173.476	97.98	-3.90	38	14.2	-	-	-	- (0.010)	0.04(0.04)
173.519	77.75	-3.83	38	14.2	-	-	-	- (0.010)	0.02(0.04)
173.534	77.70	-3.83	38	14.2	-	-	-	- (0.011)	-0.06 (0.04)
173.595	62.02	-3.79	38	14.2	-	-	-	- (0.009)	0.05(0.04)
173.638	62.03	-3.79	38	14.2	-	-	-	- (0.009)	0.07(0.03)
173.664	61.93	-3.79	38	14.2	-	-	-	- (0.010)	0.01(0.03)
174.982	50.94	-3.75	38	14.1	-	-	-	- (0.011)	0.03(0.04)
175.091	50.91	-3.75	38	14.0	-	-	-	- (0.014)	0.03 (0.05)

Table 19. Observed transitions of CH₃CHO in IRAS4A-B. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection. continued.

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Frequency	E_u	$\log(A_{ij})$	\mathbf{g}_u	θ_s	V_{min}	V_{max}	V_{peak}	T_{peak}	$\int T_{MB} dv$
GHz	Κ			"	${\rm kms^{-1}}$	${\rm kms^{-1}}$	${\rm kms^{-1}}$	Κ	${\rm Kkms^{-1}}$
96.274	22.93	-4.60	22	25.6	-	-	-	- (0.007)	-0.03 (0.02)
96.343	50.06	-4.97	22	25.5	-	-	-	- (0.006)	0.02(0.02)
96.343	50.06	-4.97	22	25.5	-	-	-	- (0.006)	$0.02 \ (0.02)$
96.353	49.99	-4.97	22	25.5	-	-	-	- (0.006)	$0.02 \ (0.02)$
96.361	49.95	-4.97	22	25.5	-	-	-	- (0.007)	0.00(0.02)
96.368	34.26	-4.72	22	25.5	-	-	-	- (0.007)	-0.01 (0.02)
96.368	34.26	-4.72	22	25.5	-	-	-	- (0.007)	-0.02(0.02)
96.372	34.26	-4.72	22	25.5	-	-	-	- (0.007)	-0.00 (0.02)
96.384	34.16	-4.72	22	25.5	-	-	-	- (0.007)	-0.05(0.02)
96.426	22.91	-4.60	22	25.5	-	-	-	- (0.007)	$0.00 \ (0.02)$
96.476	23.03	-4.60	22	25.5	-	-	-	- (0.006)	$0.01 \ (0.02)$
96.633	22.96	-4.60	22	25.5	-	-	-	- (0.006)	-0.01(0.02)
98.863	16.59	-4.51	22	24.9	-	-	-	- (0.006)	-0.01(0.02)
98.901	16.51	-4.51	22	24.9	-	-	-	- (0.006)	-0.00(0.02)
152.635	33.10	-3.91	34	16.1	-	-	-	- (0.004)	-0.01 (0.01)
153.004	28.48	-4.97	26	16.1	-	-	-	- (0.004)	-0.01(0.01)
153.873	42.33	-3.93	34	16.0	-	-	-	- (0.004)	$0.02 \ (0.01)$
154.027	42.33	-3.93	34	16.0	-	-	-	- (0.004)	-0.04(0.02)
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.005)	-0.00 (0.01)
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.005)	-0.00 (0.01)
154.183	89.69	-4.11	34	16.0	-	-	-	- (0.004)	-0.02(0.01)
154.189	89.65	-4.11	34	16.0	-	-	-	- (0.004)	$0.03\ (0.01)$
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.004)	$0.00\ (0.01)$
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.004)	$0.03\ (0.01)$
154.230	69.38	-4.02	34	16.0	-	-	-	- (0.004)	$0.01 \ (0.01)$
154.275	53.69	-3.96	34	15.9	-	-	-	- (0.004)	$0.00\ (0.01)$
154.296	53.69	-3.96	34	15.9	-	-	-	- (0.004)	-0.03(0.01)
154.322	53.60	-3.96	34	15.9	-	-	-	- (0.004)	-0.00 (0.01)
154.323	53.69	-3.96	34	15.9	-	-	-	- (0.004)	-0.02(0.01)
155.180	42.54	-3.92	34	15.9	-	-	-	- (0.004)	$0.01 \ (0.01)$
155.342	42.50	-3.91	34	15.8	-	-	-	- (0.004)	-0.00 (0.01)
156.807	34.94	-4.94	30	15.7	-	-	-	- (0.003)	-0.01 (0.01)
157.938	36.50	-3.87	34	15.6	-	-	-	- (0.003)	-0.01 (0.01)
157.975	36.43	-3.87	34	15.6	-	-	-	- (0.003)	$0.02 \ (0.01)$
159.692	42.33	-4.95	34	15.4	-	-	-	- (0.003)	0.00(0.01)
161.172	42.33	-4.91	34	15.3	_	_	-	- (0.008)	-0.02 (0.02)

Table 20. Observed transitions of CH₃CHO in L1157-R. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

COMS IN OUTFLOWS

Frequency GHz	E_u K	$\log(\mathbf{A}_{ij})$	g_u	θ_s ,,	${\rm V}_{min} \\ {\rm kms^{-1}}$	V_{max} km s ⁻¹	V_{peak} km s ⁻¹	$\begin{array}{c} \mathbf{T}_{peak} \\ \mathbf{K} \end{array}$	$\int T_{MB} dv \mathrm{Kkms^{-1}}$
162.044	50.44	-4.79	42	15.2	_	_	_	- (0.007)	-0.01 (0.02)
164.727	50.64	-4.90	38	14.9	-	-	-	- (0.011)	-0.00 (0.03)
167.981	27.42	-4.74	30	14.6	-	-	-	- (0.005)	-0.00 (0.02)
168.089	42.73	-3.79	38	14.6	-	-	-	- (0.005)	0.01(0.01)
168.093	42.66	-3.79	38	14.6	-	-	-	- (0.005)	0.01 (0.02)
170.293	59.86	-4.86	42	14.4	-	-	-	- (0.005)	-0.02 (0.02)
171.265	41.42	-3.76	38	14.4	-	-	-	- (0.005)	-0.02(0.02)
171.297	41.32	-3.76	38	14.4	-	-	-	- (0.004)	$0.05 \ (0.02)$
171.606	59.85	-4.84	42	14.3	-	-	-	- (0.005)	$0.03 \ (0.02)$
173.026	50.63	-3.77	38	14.2	-	-	-	- (0.006)	-0.01 (0.02)
173.124	50.64	-3.77	38	14.2	-	-	-	- (0.006)	$0.01 \ (0.02)$
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.007)	-0.01 (0.02)
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.007)	-0.01 (0.02)
173.470	98.01	-3.90	38	14.2	-	-	-	- (0.007)	$0.05 \ (0.02)$
173.476	97.98	-3.90	38	14.2	-	-	-	- (0.006)	-0.02 (0.02)
173.519	77.75	-3.83	38	14.2	-	-	-	- (0.007)	$0.02 \ (0.02)$
173.534	77.70	-3.83	38	14.2	-	-	-	- (0.006)	$0.01 \ (0.02)$
173.595	62.02	-3.79	38	14.2	-	-	-	- (0.007)	$0.04 \ (0.02)$
173.638	62.03	-3.79	38	14.2	-	-	-	- (0.006)	-0.00 (0.02)
173.664	61.93	-3.79	38	14.2	-	-	-	- (0.006)	$0.05 \ (0.02)$
174.982	50.94	-3.75	38	14.1	-	-	-	- (0.008)	-0.00 (0.02)
175.091	50.91	-3.75	38	14.0	-	-	-	- (0.008)	$0.04\ (0.03)$

Table 21. Observed transitions of CH₃CHO in L1157-R. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection. continued.

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Frequency	E_u	$\log(A_{ij})$	g_u	θ_s	V_{min}	V_{max}	V_{peak}	T_{peak}	$\int T_{MB} dv$
GHz	K				${\rm kms^{-1}}$	$\rm kms^{-1}$	${\rm kms^{-1}}$	К	${ m Kkms^{-1}}$
96.274	22.93	-4.60	22	25.6	1.00	3.0	2.0	$0.020 \ (0.005)$	$0.04\ (0.01)$
96.343	50.06	-4.97	22	25.5	-	-	-	- (0.005)	$0.00\ (0.01)$
96.343	50.06	-4.97	22	25.5	-	-	-	- (0.005)	$0.00\ (0.01)$
96.353	49.99	-4.97	22	25.5	-	-	-	- (0.005)	$0.00\ (0.01)$
96.361	49.95	-4.97	22	25.5	-	-	-	- (0.005)	$0.02 \ (0.01)$
96.368	34.26	-4.72	22	25.5	-	-	-	- (0.004)	$0.01 \ (0.01)$
96.368	34.26	-4.72	22	25.5	-	-	-	- (0.004)	$0.00\ (0.01)$
96.372	34.26	-4.72	22	25.5	-	-	-	- (0.005)	$0.00\ (0.01)$
96.384	34.16	-4.72	22	25.5	-	-	-	- (0.004)	$0.01 \ (0.01)$
96.426	22.91	-4.60	22	25.5	-	-	-	- (0.005)	$0.03\ (0.01)$
96.476	23.03	-4.60	22	25.5	-	-	-	- (0.004)	$0.03\ (0.01)$
96.633	22.96	-4.60	22	25.5	-	-	-	- (0.004)	$0.03\ (0.01)$
98.863	16.59	-4.51	22	24.9	0.00	4.0	2.0	$0.053\ (0.004)$	$0.15\ (0.03)$
98.901	16.51	-4.51	22	24.9	-1.00	4.0	2.0	$0.057 \ (0.004)$	$0.16\ (0.03)$
152.635	33.10	-3.91	34	16.1	1.00	4.0	2.0	$0.033\ (0.004)$	$0.07 \ (0.02)$
153.004	28.48	-4.97	26	16.1	-	-	-	- (0.004)	-0.01 (0.01)
153.873	42.33	-3.93	34	16.0	1.00	3.0	2.0	$0.017 \ (0.005)$	$0.04\ (0.01)$
154.027	42.33	-3.93	34	16.0	-	-	-	- (0.005)	$0.03\ (0.01)$
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.005)	-0.01 (0.01)
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.005)	-0.01 (0.01)
154.183	89.69	-4.11	34	16.0	-	-	-	- (0.005)	$0.01 \ (0.01)$
154.189	89.65	-4.11	34	16.0	-	-	-	- (0.005)	-0.03(0.01)
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.005)	-0.00(0.01)
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.005)	$0.00\ (0.01)$
154.230	69.38	-4.02	34	16.0	-	-	-	- (0.004)	$0.01\ (0.01)$
154.275	53.69	-3.96	34	15.9	-	-	-	- (0.005)	$0.03\ (0.01)$
154.296	53.69	-3.96	34	15.9	-	-	-	- (0.004)	$0.01 \ (0.01)$
154.322	53.60	-3.96	34	15.9	-	-	-	- (0.005)	$0.02\ (0.01)$
154.323	53.69	-3.96	34	15.9	-	-	-	- (0.004)	$0.01\ (0.01)$
155.180	42.54	-3.92	34	15.9	-	-	-	- (0.006)	$0.03\ (0.01)$
155.342	42.50	-3.91	34	15.8	-	-	-	- (0.005)	$0.01 \ (0.01)$
156.807	34.94	-4.94	30	15.7	-	-	-	- (0.003)	$0.01 \ (0.01)$
157.938	36.50	-3.87	34	15.6	0.00	4.0	2.0	$0.029\ (0.003)$	0.07~(0.01)
157.975	36.43	-3.87	34	15.6	0.00	4.0	2.0	$0.020\ (0.003)$	0.07~(0.01)
159.692	42.33	-4.95	34	15.4	-	-	-	- (0.003)	$0.00\ (0.01)$
161.172	42.33	-4.91	34	15.3	-	-	-	- (0.005)	0.02(0.01)

Table 22. Observed transitions of CH₃CHO in L1157-B2. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

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Frequency GHz	E_u K	$\log(\mathbf{A}_{ij})$	g_u	$\left \begin{array}{c} \theta_s \\ , \end{array} \right $	V_{min} km s ⁻¹	V_{max} km s ⁻¹	V_{peak} km s ⁻¹	$\begin{array}{c} \mathbf{T}_{peak} \\ \mathbf{K} \end{array}$	$\int T_{MB} dv \\ \mathrm{Kkms^{-1}}$
162.044	50.44	-4.79	42	15.2	-	-	-	- (0.005)	-0.00 (0.01)
164.727	50.64	-4.90	38	14.9	-	-	-	- (0.008)	-0.00(0.02)
167.981	27.42	-4.74	30	14.6	-	-	-	- (0.005)	0.02(0.01)
168.089	42.73	-3.79	38	14.6	-	-	-	- (0.006)	0.05(0.02)
168.093	42.66	-3.79	38	14.6	-	-	-	- (0.005)	0.03(0.01)
170.293	59.86	-4.86	42	14.4	-	-	-	- (0.004)	-0.01 (0.01)
171.265	41.42	-3.76	38	14.4	1.00	3.0	2.0	$0.030 \ (0.005)$	0.07(0.02)
171.297	41.32	-3.76	38	14.4	1.00	3.0	2.0	$0.017 \ (0.005)$	0.05~(0.01)
171.606	59.85	-4.84	42	14.3	-	-	-	- (0.006)	0.00(0.01)
173.026	50.63	-3.77	38	14.2	-	-	-	- (0.007)	0.02(0.01)
173.124	50.64	-3.77	38	14.2	-	-	-	- (0.007)	0.01 (0.01)
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.007)	0.02(0.01)
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.007)	0.02(0.01)
173.470	98.01	-3.90	38	14.2	-	-	-	- (0.007)	-0.00 (0.01)
173.476	97.98	-3.90	38	14.2	-	-	-	- (0.006)	-0.01 (0.01)
173.519	77.75	-3.83	38	14.2	-	-	-	- (0.005)	0.03(0.01)
173.534	77.70	-3.83	38	14.2	-	-	-	- (0.006)	0.01 (0.01)
173.595	62.02	-3.79	38	14.2	-	-	-	- (0.006)	0.01 (0.01)
173.638	62.03	-3.79	38	14.2	-	-	-	- (0.008)	0.00(0.02)
173.664	61.93	-3.79	38	14.2	-	-	-	- (0.008)	0.03(0.02)
174.982	50.94	-3.75	38	14.1	-	-	-	- (0.008)	0.02(0.02)
175.091	50.91	-3.75	38	14.0	-	-	-	- (0.008)	0.03(0.02)

Table 23. Observed transitions of CH₃CHO in L1157-B2. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection. continued.

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Frequency	\mathbf{E}_{u}	$\log(A_{ij})$	g_u	θ_s	Vmin	V _{max}	V_{peak}	T_{peak}	$\int T_{MB} dv$
GHz	K			"	${\rm kms^{-1}}$	${\rm kms^{-1}}$	${\rm kms^{-1}}$	Κ	${ m Kkms^{-1}}$
152.635	33.10	-3.91	34	16.1	-	-	-	- (0.005)	-0.01 (0.01)
153.004	28.48	-4.97	26	16.1	-	-	-	- (0.006)	0.01 (0.01)
153.873	42.33	-3.93	34	16.0	-	-	-	- (0.006)	-0.01 (0.01)
154.027	42.33	-3.93	34	16.0	-	-	-	- (0.006)	$0.01 \ (0.01)$
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.006)	$0.01 \ (0.01)$
154.161	89.76	-4.11	34	16.0	-	-	-	- (0.006)	$0.01 \ (0.01)$
154.183	89.69	-4.11	34	16.0	-	-	-	- (0.006)	$0.01 \ (0.01)$
154.189	89.65	-4.11	34	16.0	-	-	-	- (0.006)	-0.01 (0.01)
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.006)	$0.01 \ (0.01)$
154.201	69.48	-4.02	34	16.0	-	-	-	- (0.006)	0.02(0.01)
154.230	69.38	-4.02	34	16.0	-	-	-	- (0.006)	$0.01 \ (0.01)$
154.275	53.69	-3.96	34	15.9	-	-	-	- (0.007)	-0.01 (0.01)
154.296	53.69	-3.96	34	15.9	-	-	-	- (0.006)	$0.01 \ (0.01)$
154.322	53.60	-3.96	34	15.9	-	-	-	- (0.006)	0.00(0.01)
154.323	53.69	-3.96	34	15.9	-	-	-	- (0.006)	-0.01 (0.01)
155.180	42.54	-3.92	34	15.9	-	-	-	- (0.006)	0.00(0.01)
155.342	42.50	-3.91	34	15.8	-	-	-	- (0.006)	-0.02(0.01)
156.807	34.94	-4.94	30	15.7	-	-	-	- (0.005)	0.00(0.01)
157.938	36.50	-3.87	34	15.6	-	-	-	- (0.004)	-0.01 (0.01)
157.975	36.43	-3.87	34	15.6	-	-	-	- (0.004)	0.00(0.01)
159.692	42.33	-4.95	34	15.4	-	-	-	- (0.004)	-0.01 (0.01)
170.293	59.86	-4.86	42	14.4	-	-	-	- (0.006)	-0.01 (0.01)
171.265	41.42	-3.76	38	14.4	-	-	-	- (0.007)	-0.01 (0.01)
171.297	41.32	-3.76	38	14.4	-	-	-	- (0.007)	0.02(0.01)
171.606	59.85	-4.84	42	14.3	-	-	-	- (0.007)	$0.01 \ (0.01)$
173.026	50.63	-3.77	38	14.2	-	-	-	- (0.008)	-0.03(0.02)
173.124	50.64	-3.77	38	14.2	-	-	-	- (0.009)	$0.05 \ (0.02)$
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.010)	$0.01 \ (0.02)$
173.446	98.09	-3.90	38	14.2	-	-	-	- (0.010)	$0.01 \ (0.02)$
173.470	98.01	-3.90	38	14.2	-	-	-	- (0.010)	$0.01 \ (0.02)$
173.476	97.98	-3.90	38	14.2	-	-	-	- (0.009)	$0.02 \ (0.02)$
173.519	77.75	-3.83	38	14.2	-	-	-	- (0.008)	-0.02 (0.01)
173.534	77.70	-3.83	38	14.2	-	-	-	- (0.009)	$0.01 \ (0.02)$
173.595	62.02	-3.79	38	14.2	-	-	-	- (0.009)	$0.01 \ (0.02)$
173.638	62.03	-3.79	38	14.2	-	-	-	- (0.010)	-0.00 (0.02)
173.664	61.93	-3.79	38	14.2	-	-	-	- (0.009)	0.02 (0.02)

Table 24. Observed transitions of CH₃CHO in L1448-B2. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection.

Frequency GHz	E_u K	$\log(A_{ij})$	g_u	$ heta_s$,,	V_{min} $\mathrm{kms^{-1}}$	V_{max} $km s^{-1}$	V_{peak} km s ⁻¹	$\begin{array}{c} \mathbf{T}_{peak} \\ \mathbf{K} \end{array}$	$\int T_{MB} dv \\ \mathrm{Kkms^{-1}}$
		-3.75 -3.75			- -	- -	- -	. ,	-0.00 (0.01) -0.01 (0.02)

Table 25. Observed transitions of CH₃CHO in L1448-B2. The value of T_{peak} and the velocity measurements of the line are not given where there is no 3σ detection. continued.

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B. SPECTRA

In this appendix, plots of every detected transition of CH_3OH and CH_3CHO in each source are presented. The full set is available in the online journal and an example is shown in Figure 7. Blue lines indicate velocity at which the transition peaks and grey shaded areas show the interval over which the line was integrated to measure the integrated emission. There are two groups of blended CH_3OH lines which can be clearly seen in the spectra. One includes the transitions at 156.271, 156.272 and 157.276 GHz and the other includes the lines at 96.741, 96.745, and 96.756 GHz. For blended lines, the emission was integrated over all blended transitions and the sum of the predicted fluxes was compared to that.

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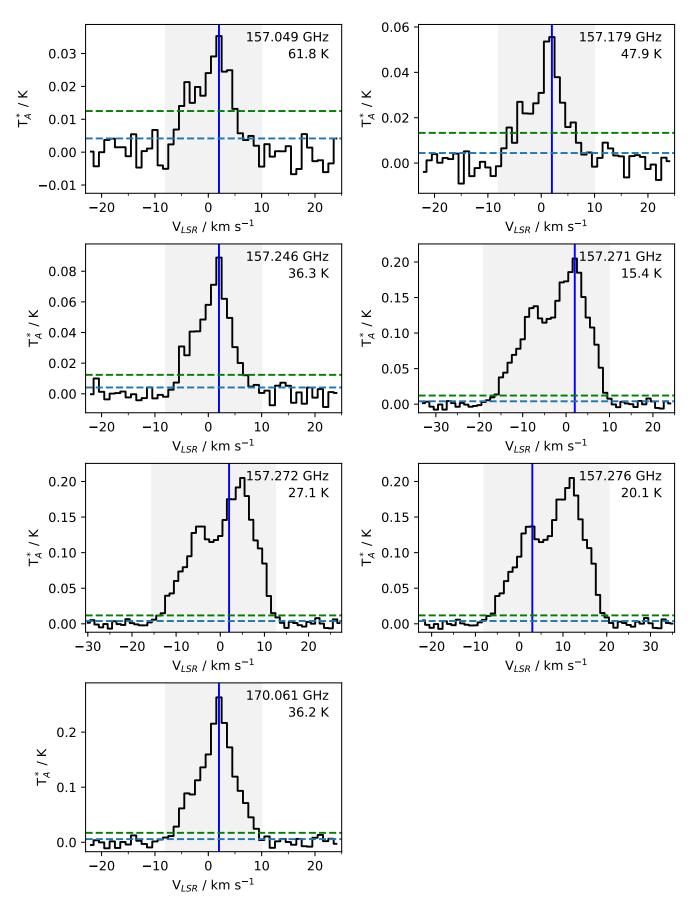


Figure 7. Detected transitions of CH_3OH in IRAS2A-B. The grey shaded range is the velocity interval over which the emission was integrated. The dashed horizontal lines show the rms noise level and three times that value. The vertical line shows the position of the peak.

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