Detection of the propargyl radical at $\lambda$3 mm

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ABSTRACT

We report the detection of the propargyl radical (CH$_2$CCH) in the cold dark cloud TMC-1 in the $\lambda$3 mm wavelength band. We recently discovered this species in space toward the same source at a wavelength of $\lambda$8 mm. In those observations, various hyperfine components of the $2_{0,2}$-$1_{0,1}$ rotational transition, at 37.5 GHz, were detected using the Yebes 40m telescope. Here, we used the IRAM 30m telescope to detect ten hyperfine components of the $5_{0,5}$-$4_{0,4}$ rotational transition, lying at 93.6 GHz. The observed frequencies differ by 0.2 MHz with respect to the predictions from available laboratory data. This difference is significant for a radioastronomical search for CH$_2$CCH in interstellar sources with narrow lines. We thus included the measured frequencies in a new spectroscopic analysis to provide accurate frequency predictions for the interstellar search for propargyl at mm wavelengths. Moreover, we recommend that future searches for CH$_2$CCH in cold interstellar clouds are carried out at $\lambda$3 mm, rather than at $\lambda$8 mm. The $5_{0,5}$-$4_{0,4}$ transition is about five times more intense than the $2_{0,2}$-$1_{0,1}$ one in TMC-1, which implies that detecting the former requires about seven times less telescope time than detecting the latter. We constrain the rotational temperature of CH$_2$CCH in TMC-1 to 9.9 ± 1.5 K, which indicates that the rotational levels of this species are thermalized at the gas kinetic temperature. The revised value of the column density of CH$_2$CCH (including ortho and para species) is $(1.0 \pm 0.2) \times 10^{14}$ cm$^{-2}$, and thus the CH$_2$CCH/CH$_3$CCH abundance ratio is revised from slightly below one to nearly one. This study opens the door for future detections of CH$_2$CCH in other cold interstellar clouds, making possible to further investigate the role of this very abundant hydrocarbon radical in the synthesis of large organic molecules such as aromatic rings.

Key words. astrochemistry – line: identification – molecular processes – ISM: molecules – radio lines: ISM

1. Introduction

The ongoing line surveys of the Taurus Molecular Cloud 1 (TMC-1) at the Green Bank telescope (GOTHAM; McGuire et al. 2020) and at the Yebes 40m telescope (QUIJOTE; Cernicharo et al. 2021a), are demonstrating that complex hydrocarbons, including cyclic and polycyclic aromatic ones, are formed in situ in cold dense clouds. Examples of such molecules detected toward TMC-1 are propylene (CH$_3$CH=CH$_2$), vinyl and allenyl acetylene (CH$_2$CHCC and CH$_2$CHCHC), cyclopentadiene ($\text{C}_5\text{H}_6$), indene ($\text{C}_9\text{H}_8$), and benzene ($\text{C}_6\text{H}_6$) (Marcelino et al. 2007; Cernicharo et al. 2021b,c,d; Burkhardt et al. 2021). Moreover, ethyl acetylene (CH$_3$CH=CH$_2$) and ethynyl benzene ($\text{C}_9\text{H}_8$) have been tentatively detected (Cernicharo et al. 2021a,b), and there is strong evidence for the presence of aromatic rings such as benzene and naphthalene from the detection of their CN derivatives (McGuire et al. 2018, 2021; Cernicharo et al. 2021e).

It is not yet well understood which chemical routes are behind the formation of these aromatic cycles in cold dark clouds like TMC-1. Hydrocarbon radicals are likely key players in the synthesis of these large molecules from smaller species. However, only a few such radicals have been detected. The methylidyne radical CH and the polyacetylenic radicals C$_2$H, C$_3$H, C$_4$H, and even longer ones are known from long time ago. Other radicals such as C$_2$H$_2$, C$_3$H$_2$, or C$_4$H$_2$ are likely important pieces in the synthesis of large hydrocarbons but detecting them has been proven to be difficult due to different possible reasons like spectral dilution due to splitting of rotational lines into numerous fine and hyperfine components, low abundance, low dipole moment, or lack of sufficiently sensitive radioastronomical observations. We recently identified the propargyl radical (CH$_2$CCH) toward TMC-1 as part of the QUIJOTE line survey (Agúndez et al. 2021a). It was found that CH$_2$CCH is one of the most abundant radicals in TMC-1, being present at the level of its closed-shell counterpart CH$_3$CCH. Being that abundant, the propargyl radical becomes a very attractive candidate to play an important role in the synthesis of aromatic molecules. For example, calculations indicate that the propargyl radical self-reaction can lead to cyclization producing the aromatic radical phenyl radical at low temperatures (Miller & Klippenstein 2001; Zhao et al. 2021).

The radical CH$_2$CCH was detected in TMC-1 at $\lambda$8 mm through six hyperfine components belonging to the $2_{0,2}$-$1_{0,1}$ rotational transition. Here we report the detection of CH$_2$CCH toward TMC-1 at $\lambda$3 mm. We observed the $5_{0,5}$-$4_{0,4}$ transition in ten hyperfine components, with frequencies that differ by 0.2 MHz from previous available predictions. We thus used the observed frequencies to improve the spectroscopic parameters of CH$_2$CCH and provide accurate predictions to guide future astro-nomical searches. Moreover, the $\lambda$3 mm line is about five times stronger than the $\lambda$8 mm line.
Fig. 1. Observed spectra of TMC-1 around the 2_{0,2}-1_{0,1} and 5_{0,5}-4_{0,4} rotational transitions of ortho CH$_2$CCH. The spectrum at 37.5 GHz is taken with the Yebes 40m telescope (black histogram in bottom panel) and that at 93.6 GHz is taken with the IRAM 30m telescope (black histogram in top panel). Transition quantum numbers, frequencies, and derived line parameters are given in Table 1. The synthetic spectra (red lines) were computed for a column density of ortho CH$_2$CCH of 7.5 x 10$^{13}$ cm$^{-2}$, a rotational temperature of 9.9 K, an emission size of 40" of radius, and a linewidth of 0.72 km s$^{-1}$ for the 2_{0,2}-1_{0,1} lines and of 0.57 km s$^{-1}$ for the 5_{0,5}-4_{0,4} lines (see text).

more intense than the $J=8$ mm one, which suggests that the search for CH$_2$CCH in other cold dark clouds is more favorable in the $J=3$ mm wavelength band.

2. Observations

The observations of TMC-1 at $J=3$ mm were carried out using the IRAM 30m telescope in September 2021. The observed position corresponds to the cyanopolyne peak of TMC-1, $\alpha_{2000} = 4^h41^m41.9^s$ and $\delta_{2000} = +25^\circ41'27.0''$. The 3 mm EMIR receiver was used connected to a fast Fourier transform spectrometer, providing a spectral resolution of 48.84 kHz. We covered the spectral region around 93.6 GHz, where the 5_{0,5}-4_{0,4} rotational transition of CH$_2$CCH is located. We observed two setups at slightly different central frequencies in order to check for spurious signals, line emission from the image band, and other technical artifacts. The observations were performed in the frequency-switching observing mode with a frequency throw of 18 MHz, large enough to avoid possible contamination from negative frequency-switching artifacts arising from the different hyperfine components of CH$_2$CCH. Pointing scans were performed on strong and nearby quasars every 1-1.5 h, with pointing errors always within 3-5". The antenna focus was checked every ~6 h at the beginning of each observing session and after sunrise. Weather conditions were between good and average for the summer period, with opacities of 0.4-0.5 at 225 GHz and amounts of precipitable water vapor ranging from 1-3 mm to 6-7 mm. The spectra were calibrated in antenna temperature, $T_A^*$, corrected for atmospheric attenuation and for antenna ohmic and spillover losses, using the ATM package (Cernicharo 1985; Pardo et al. 2001). The uncertainty in the calibration is estimated to be 10%.

System temperatures varied between 100 and 140 K and the final $T_A^*$ rms at 93.6 GHz is 1.1 mK after 31.4 h of total on-source telescope time.

The final spectra shown in Fig. 1 is obtained after averaging the data taken in September 2021 with previous spectra from our TMC-1 3 mm line survey (Marcelino et al. 2007; Cernicharo et al. 2012). At the frequency of the 5_{0,5}-4_{0,4} transition of CH$_2$CCH, the observed time in the survey data is 4.0 h. Including these data has improved the final sensitivity down to 0.9 mK, resulting in a total on-source integration time of 35.4 h for each polarization (twice this value after averaging the two polarizations).

We also present a more sensitive spectrum of TMC-1 at the frequency of the 2_{0,2}-1_{0,1} transition of CH$_2$CCH, 37.5 GHz, with respect to that presented by Agúndez et al. (2021a). New data was gathered in several observing sessions between January and May 2021. These data are part of the on going QUIJOTE line survey that is being carried out with the Yebes 40m telescope. The line survey uses a 7 mm receiver covering the Q band, from 31.0 GHz to 50.3 GHz, with horizontal and vertical polarizations. A detailed description of the system is given by Tercero et al. (2021). Receiver temperatures in the observing sessions carried out during 2020 vary from 22 K at 32 GHz to 42 K at 50 GHz. Some power adaptation in the down-conversion chains has reduced the receiver temperatures during 2021 to 16 K at 32 GHz and 25 K at 50 GHz. The backends are 2 x 8 x 2.5 GHz fast Fourier transform spectrometers with a spectral resolution of 38.15 kHz providing the whole coverage of the Q band in both polarizations. The QUIJOTE observations are performed using the frequency-switching observing mode with a frequency throw of 10 MHz in the very first observing runs, during November 2019 and February 2020, and of 8 MHz in the later ones. The
3. Results and discussion

The rotational spectrum of the propargyl radical has been measured in the laboratory at frequencies below 38 GHz by [Tanaka et al. 1997]. Due to the existence of two equivalent H nuclei, the radical has ortho/para statistics. Ortho levels have $K_o$ even and para levels have $K_o$ odd. The statistical ortho-to-para ratio is three. The dipole moment of CH$_3$CH=CH$_2$ has been calculated by Botschwina et al. [1995] to be 0.14 D, while more recently, Kupper et al. [2002] measured a value of 0.150±0.005 D, which is the value we adopt hereafter.

Our IRAM 30m data of TMC-1 show a group of lines spanning 6 MHz around 93646 MHz (see top panel in Fig. 1), which we assign to the hyperfine components of the 5$_{0,5}$-4$_{0,4}$ transition of CH$_3$CCH. The measured frequencies are systematically shifted up by 0.2 MHz with respect to the predicted frequencies in the Cologne Database for Molecular Spectroscopy (CDMS; Müller et al. [2005]). The entry in the CDMS is based on a fit to the laboratory frequencies measured by [Tanaka et al. 1997]. These authors measured the line and hyperfine structure of the rotational transitions $J_{0,0}$, $2_0(2_0-1_0)$, $2_1(2_1-1_1)$, and $2_1(1_1-0_1)$, lying at 18.7 GHz and in the 37-38 GHz range. Although the experimental accuracy is quite good, a few kilohertz, the limited range of $J$ values covered makes that when extrapolating to the 1.3 mm wavelength band, the frequency errors could be significant for radioastronomical purposes. The CDMS quotes frequency errors of just ~ 55 kHz for the hyperfine components of the 5$_{0,5}$-4$_{0,4}$ transition, although our TMC-1 observations shows that the error is in fact as high as ~ 200 kHz. This is significant for radioastronomical searches for CH$_3$CCH in sources with narrow lines, such as TMC-1.

In order to obtain more accurate frequency predictions for CH$_3$CCH we carried out a new spectroscopic analysis using the SPFIT program [Pickert 1991] including the laboratory frequencies of [Tanaka et al. 1997] and the astronomical frequencies measured in TMC-1 for the ten hyperfine components of the 5$_{0,5}$-4$_{0,4}$ transition (see derived line parameters in Table 1). The Hamiltonian used for the analysis is the same than that employed

Table 1. Observed line parameters of CH$_3$CCH in TMC-1.

| Transition $^a$ | $\nu_{obs}$ $^b$ (MHz) | $\nu_{calc}$ $^b$ (MHz) | $\Delta \nu$ $^d$ (km s$^{-1}$) | $T_A^*$ peak (mK) | $\int T_A^*dv$ (mK km s$^{-1}$) | S/N $^e$ |
|----------------|------------------------|------------------------|----------------|$\sigma$ |
| $2_0-1_0$ | $J = 3/2-1/2$ | $F_1 = 2-1$ | $F = 2-1$ | 37457.515 | 37457.542(20) | 0.55(35) | 0.60 | 0.35(22) | 4.5 |
| $2_0-1_0$ | $J = 5/2-3/2$ | $F_1 = 3-2$ | $F = 4-3$ | 37457.965 | 37457.981(10) | 0.71(16) | 1.92 | 1.45(27) | 16.4 |
| $2_0-1_0$ | $J = 5/2-3/2$ | $F_1 = 2-1$ | $F = 3-2$ | 37458.382 | 37458.390(13) | 0.80(27) | 1.28 | 1.09(29) | 11.6 |
| $2_0-1_0$ | $J = 5/2-3/2$ | $F_1 = 2-1$ | $F = 2-2$ | 37459.186 | 37459.187(10) | 0.65(14) | 1.58 | 1.09(22) $^f$ | 12.9 |
| $2_0-1_0$ | $J = 5/2-3/2$ | $F_1 = 2-1$ | $F = 2-2$ | 37461.057 | 37461.078(11) | 0.85(15) | 1.53 | 1.38(25) $^e$ | 14.3 |
| $2_0-1_0$ | $J = 3/2-1/2$ | $F_1 = 2-1$ | $F = 2-2$ | 37462.481 | 37462.489(10) | 0.76(17) | 1.63 | 1.31(25) | 14.3 |

The line parameters $\nu_{obs}$, $\Delta \nu$, $T_A^*$ peak, and $\int T_A^*dv$ as well as the associated errors were derived from a Gaussian fit to each profile.

$^a$ Quantum numbers from the coupling scheme of [Tanaka et al. 1997].

$^b$ Calculated frequencies $\nu_{calc}$, from the combined radioastronomical fit carried out in this work.

$^c$ Observed frequencies adopting a systemic velocity of 5.83 km s$^{-1}$ for TMC-1 [Cernicharo et al. 2020].

$^d$ $\Delta \nu$ is the full width at half maximum (FWHM).

$^e$ The signal-to-noise ratio is computed as S/N = $\int T_A^*dv / \text{[rms} \times \sqrt{\Delta \nu / \sigma(\nu_{calc})]}$, where $c$ is the speed of light and $\sigma$ is the spectral resolution. For the lines observed with the Yebes 40m telescope at 37.5 GHz $\sigma = 0.03815$ MHz and rms = 0.19 mK, for the lines observed with the IRAM 30m telescope at 93.6 GHz $\sigma = 0.04884$ MHz and rms = 0.9 mK. The rest of parameters are given in the table.

$^f$ Line overlaps with the $2_1,1-1_1,1$ transition of syn-C$_2$H$_5$OH, which lies at 37459.184 MHz (see Agúndez et al. 2021b). The observed intensity is thus the sum of the CH$_3$CCH and the syn-C$_2$H$_5$OH lines.

$^g$ Observed line results from a blend of two unresolved hyperfine components.
Table 2. Spectroscopic parameters of CH$_2$CCH (all in MHz).

| Parameter | Global Fit | Tanaka et al. (1997) |
|-----------|------------|----------------------|
| $A$       | 288055     | 288055               |
| $B$       | 9523.6746/(41) | 9523.6775/(60) |
| $C$       | 9206.8776/(41) | 9206.8805/(60) |
| $\Delta_{HF}$ | 0.003004/(72) | 0.003440/(63) |
| $\Delta_{K}$ | 0.3758/(28) | 0.3753/(28) |
| $\Delta_{K}$ | 22.62$^a$ | 22.62 |
| $\delta_N$ | 0.000103$^a$ | 0.000103 |
| $\gamma_N$ | 0.1575$^a$ | 0.1575 |
| $\sigma_{rot}$ | $-529.3866/(60)$ | $-529.3866/(60)$ |
| $\sigma_{rot}$ | $-11.5243/(31)$ | $-11.5243/(30)$ |
| $\sigma_{rot}$ | $-0.5204/(31)$ | $-0.5204/(30)$ |
| $\sigma_{B}$ | $-36.3225/(25)$ | $-36.3225/(24)$ |
| $T_{rot}(I_1)$ | 17.400/(26) | 17.400/(24) |
| $T_{rot}(I_2)$ | $-17.220/(38)$ | $-17.220/(37)$ |
| $T_{rot}(I_3)$ | $-14.122/(20)$ | $-14.121/(19)$ |
| $T_{rot}(I_4)$ | 12.88$^c$ | 12.88 |
| $N^c$ | 55 | 46 |

Numbers in parentheses are 3$\sigma$ uncertainties in units of the last digits. H$_m$ and H$_a$ refer to the acetylenic and methylenic hydrogen nuclei, respectively. $^a$ Parameter fixed to the value reported by Tanaka et al. (1997). $^b$ Standard deviation of the fit in kHz. $^c$ Number of lines included in the fit.

Table 3. Rotational partition function ($Q_r$) of CH$_2$CCH at different temperatures.

| Temperature (K) | $Q_r$ |
|-----------------|-------|
| 9.375           | 294.5 |
| 18.750          | 718.9 |
| 37.500          | 1959.3|
| 75.000          | 5506.5|
| 150.000         | 14710.5|
| 225.000         | 24377.0|
| 300.000         | 33479.9|

by Tanaka et al. (1997) and it has the following form:

$$H = H^{rot} + H^{cd} + H^{\sigma}_{HF} + H^{\sigma}_{ff}$$

where $H^{rot}$ and $H^{cd}$ contain the rotational and centrifugal distortion parameters, respectively. $H^{\sigma}$ is the spin-rotation term, and $H^{\sigma}_{HF}$ represents the magnetic hyperfine coupling interaction between the unpaired electron and the hydrogen nuclei. A complete description of these terms can be found in Tanaka et al. (1997). The coupling scheme used is $J = N + S$, $F_1 = J + I_1$, and $F = F_1 + I_2$, where $I_1 = I(H_2)$ and $I_2 = I(H_{a2}) + I(H_{a2})$. The radical CH$_2$CCH has two equivalent H nuclei, the methylenic ones, and the hyperfine interaction term $H^{\sigma}_{HF}$ is thus written explicitly as a two spin system:

$$H^{\sigma}_{HF} = a^H_1S_1I_1 + a^H_2S_2I_2 + a^H_{(H_1H_2)}S_1I_1 + a^H_{(H_1H_2)}S_2I_2 + a^H_{(H_1H_2)}S_1I_1 + a^H_{(H_1H_2)}S_2I_2$$

We also present the observed spectrum of TMC-1 at the frequency of the 2$_{0,2}$-1$_{0,1}$ transition of CH$_3$CCH (see bottom panel in Fig. 1). This spectrum is more sensitive than that presented in Agúndez et al. (2021a) because it includes additional observations taken with the Yebes 40m telescope. The rms noise level has decreased from 0.30 mK to 0.19 mK, per 38.15 kHz channel. As a consequence, the CH$_3$CCH lines are now more clearly detected. The new line parameters derived for the six hyperfine components of the 2$_{0,2}$-1$_{0,1}$ transition of CH$_3$CCH are given in Table 1.

3.2. Excitation and abundance of CH$_3$CCH in TMC-1, and guidance for further searches

As can be seen in Fig. 1, the strongest hyperfine component of the 5$_{0,5}$-4$_{0,4}$ transition is about five times more intense than the strongest component of the 2$_{0,2}$-1$_{0,1}$. This is consistent with the rotational temperature of CH$_3$CCH being close to the gas kinetic temperature of TMC-1, ~10 K (Fehér et al. 2016). At this temperature, the 5$_{0,5}$ rotational level, with an energy of ~13.5 K, is expected to be more populated than the 2$_{0,2}$ level, which has an energy of ~2.7 K. In addition, the Einstein coefficient of spontaneous emission is about 20 times larger for the 5$_{0,5}$-4$_{0,4}$ transition than for the 2$_{0,2}$-1$_{0,1}$. These facts make the 5$_{0,5}$-4$_{0,4}$ transition at 93.6 GHz more favorable for detection than the 2$_{0,2}$-1$_{0,1}$ tran-
sition at 37.5 GHz. Indeed, if we assume typical values for the system temperatures, $T_{sys} = 40$ K at 37.5 GHz with the Yebes 40m telescope and $T_{sys} = 120$ K at 93.6 GHz with the IRAM 30m telescope, and we keep in mind that the line at 93.6 GHz is five times more intense than the 37.5 GHz line, the radiometer equation tells us that in order to detect the two lines with the same signal-to-noise ratio (S/N) one must invest ~7 times more integration time at the Yebes 40m telescope than with IRAM 30m telescope. The fact that in our data the $2_{0,2}-1_{0,1}$ transition is detected with similar or even higher S/N than the $5_{0,5}-4_{0,4}$ transition (see Table 1) is a consequence of the much longer integration time invested with the Yebes 40m telescope (238 h) compared to that employed for the IRAM 30m spectrum (35.4 h).

In summary, the rotational transitions in the $\lambda$ 3 mm wavelength band, in particular the $5_{0,5}-4_{0,4}$ at 93.6 GHz (see below), are the most favorable for detection and should be the target in future searches for CH$_2$CH in cold dark clouds.

The availability of two rotational transitions with different upper level energies allows us to constrain the rotational temperature of the propargyl radical in TMC-1. We built a rotation diagram using the velocity-integrated intensities given in Table 1, and assumed that the emission is distributed in the sky as a circle with a radius of 40\degree, as observed for various hydrocarbons in TMC-1 (Fossé et al. 2001). The observed spectra at 37.5 GHz and 93.6 GHz are well reproduced adopting a column density of $7.5 \times 10^{13}$ cm$^{-2}$ (see Fig. 1). Assuming an ortho-to-para ratio of three, the column density of CH$_{2}$CCH (including ortho and para) in TMC-1 is $(1.0 \pm 0.2) \times 10^{14}$ cm$^{-2}$, which is slightly higher than the value derived previously by Agúndez et al. (2021a). The column density of the closed-shell counterpart CH$_3$CCH in TMC-1 is $1.1-1.3 \times 10^{14}$ cm$^{-2}$ (Gratier et al. 2016; Cabezas et al. 2021). Therefore, in this study we confirm that the propargyl radical is thermalized to the gas kinetic temperature of TMC-1 and revise the abundance ratio CH$_2$CCH/CH$_3$CCH from slightly below one to nearly one.

There are other rotational transitions of CH$_3$CCH that lie in the frequency range covered by our Yebes 40m and IRAM 30m data. The two other transitions of ortho CH$_3$CCH that fall in the $\lambda$ 3 mm band, the $4_{0,4}-3_{0,3}$ at 74.9 GHz and the $6_{0,6}-5_{0,5}$ at 112.3 GHz, are predicted to be as intense as the $5_{0,5}-4_{0,4}$. However, our data at these frequencies are not as sensitive as at 93.6 GHz, and thus the strongest hyperfine components of each transition are only marginally detected. System temperatures at 74.9 GHz and 112.3 GHz are higher than at 93.6 GHz, making the $5_{0,5}-4_{0,4}$ transition the most favorable for detection. There are also several lines of para CH$_3$CCH accessible. Two of them, the $2_{1,2}-1_{1,1}$ at 37.2 GHz and the $2_{1,1}-1_{1,0}$ at 37.8 GHz, lie in the Q band and are covered by our Yebes 40m line survey, while two other transitions, the $5_{1,5}-4_{1,4}$ at 92.8 GHz and the $5_{1,4}-4_{1,3}$ at 94.4 GHz, lie in the $\lambda$ 3 mm band and are covered by our IRAM 30m telescope data. These lines are predicted to be less intense than those of ortho CH$_3$CCH, and thus are more difficult to detect. In our data only the strongest hyperfine components of the $5_{1,5}-4_{1,4}$ and $5_{1,4}-4_{1,3}$ transitions are barely visible. The S/N is however low and we have thus not attempted to fit them.

4. Conclusions

We detected the $5_{0,5}-4_{0,4}$ transition of ortho CH$_3$CCH in TMC-1 using the IRAM 30m telescope. The measured frequencies for ten hyperfine components of this transition are 0.2 MHz higher than the frequency predicted available in the CDMS catalog, a difference which is significant for radioastronomical purposes.

We carried out a new spectroscopic analysis of the rotational spectrum of CH$_3$CCH in order to provide accurate frequencies at mm wavelengths. The intensity of the $5_{0,5}-4_{0,4}$ transition, lying at 93.6 GHz, is ~5 times higher in TMC-1 than the $2_{0,2}-1_{0,1}$ previously observed by Agúndez et al. (2021a) using the Yebes 40m telescope. We conclude that a search for CH$_3$CCH in other cold interstellar sources should be carried out in the $\lambda$ 3 mm band, rather than at $\lambda$ 8 mm, where the telescope time investment is estimated to be about seven times cheaper.

The rotational temperature of CH$_3$CCH in TMC-1 is constrained to 9.9 $\pm$ 1.5 K, i.e., equal to the gas kinetic temperature, and the derived value of the column density is $(1.0 \pm 0.2) \times 10^{14}$ cm$^{-2}$, which makes CH$_3$CCH one of the most abundant hydrocarbon radicals in TMC-1.

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