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Multi-line Diagnostics of the Interstellar Medium

The QUIJOTE[1] line survey of TMC-1

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Abstract. We present the recent results obtained with the QUIJOTE line survey of the cold dark core TMC-1. The observations have been carried out with the YEBES 40m radio telescope (see Figure 1) in the Q-band (31-50 GHz). A new set of receivers have been installed in the telescope within the frame of the ERC synergy Nanocosmos project that allows to cover the whole 31-50 GHz band in dual polarization [1]. The spectral resolution is 38.15 kHz. The sensitivity achieved so far varies between 0.12 and 0.25 mK, and allows to search for new molecules in a line by line (no stacking) detection procedure. These new data have permitted to detect the many relatively small protonated species of abundant molecules and eight sulfur-bearing species. The most exciting result is the detection of hydrocarbon chains and cycles with low permanent dipole moment, such as CH_2CHCCH, $CH_2CCHCCH$, the propargyl radical (C_3H_3), cyclopentadiene, indene (the first PAH detected in space), ortho-benzyne and two ethynyl derivatives of cyclopentadiene (c-C_5H_5CCH) ([2–7]). We have found that the gas-phase chemistry of hydrocarbons in TMC-1 has to be revisited in depth.

1 The QUIJOTE[1] line survey

The QUIJOTE[1] line survey of TMC-1 [3] performed with the Yebes 40m radio telescope has permitted to detect near 40 new molecular species in the last two years, most of which are hydrocarbons and cycles such as indene, benzyne, cyclopentadiene, and two isomers of ethynyl cyclopentadiene (see, e.g., [3–7] and references therein). Propargyl (CH_2CCH) has been found to be one of the most abundant hydrocarbon radicals in this source [2, 8]. Other hydrocarbons such as ethynylallene ($CH_2CCHCCH$), vinylacetylene (CH_2CHCCH), and butadiynylallene (CH_2CCHC_4H) have been found to have also large abundances [4, 6, 9]. Moreover, cyano derivatives of benzene and naphthalene have also been found towards TMC-1 [10, 11]. This suggests that benzene and naphthalene are also very abundant in this cold prestellar core.

Although most discoveries performed with QUIJOTE are based on data from the Yebes 40m radio telescope, several species have been identified thanks to high sensitivity data at 3mm gathered with the IRAM 30m radio telescope. Species such as CH_3CO^+, $HCCS^+$, $HCCCO^+$, and $HCCNCH^+$ are examples of molecules detected with both radio telescopes [12–15]

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[1]**Q**-band **U**ltrasensitive **I**nspection **J**ourney to the **O**bscure **T**MC-1 **E**nvironment

Figure 1. The Yebes 40m radio telescope observing TMC-1 in January 2021. The Yebes observatory is placed at 950 m of altitude in the land of Castilla la Mancha (The land of Don Quijote). It is 60 km East of Madrid. The aperture efficiency of the telescope across the Q-band varies between 0.7 at 30 GHz and 0.6 at 50 GHz.

1.1 Observations

New receivers, built within the Nanocosmos project[2], and installed at the Yebes 40m radiotelescope, were used for the observations of TMC-1 ($\alpha_{J2000} = 4^{\rm h}41^{\rm m}41.9^{\rm s}$ and $\delta_{J2000} = +25°41'27.0''$). A detailed description of the system is given by [1]. Details of the QUIJOTE line survey are provided in [3, 12]. The observations were carried out during different observing runs between November 2019 and May 2022. The receiver consists of two cold high electron mobility transistor amplifiers covering the 31.0-50.3 GHz band with horizontal and vertical polarizations. Receiver temperatures in the runs achieved during 2020 vary from 22 K at 32 GHz to 42 K at 50 GHz. Some power adaptation in the down-conversion chains have reduced the receiver temperatures during 2021 to 16 K at 32 GHz and 25 K at 50 GHz. The backends are $2 \times 8 \times 2.5$ GHz fast Fourier transform spectrometers with a spectral resolution of 38.15 kHz providing the whole coverage of the Q-band in both polarisations.

The last version of the QUIJOTE data corresponds to 546 hours of observing time on the source, of which 293 and 253 hours were acquired with a frequency switching throw of 8 MHz and 10 MHz, respectively. The last results of QUIJOTE concern the detection of five isomers of cyano propene and are given by [18], and the detection of $CH_2CCHCCCCH$ by [9]. The intensity scale used in this work, antenna temperature (T_A^*), was calibrated using two absorbers at different temperatures and the atmospheric transmission model ATM [16, 17]. The antenna temperature has an estimated uncertainty of 10 %. All data were analyzed using the GILDAS package[3].

2 Main results

QUIJOTE has reached now a level of sensitivity (0.12-0.25 mK per 38.15 kHz channel across the Q-band) that permits to detect new isotopologues and derivatives of abundant species. Examples of detection and complete spectral characterization of rare isotopologues through

[2] `https://nanocosmos.iff.csic.es/`
[3] `http://www.iram.fr/IRAMFR/GILDAS`

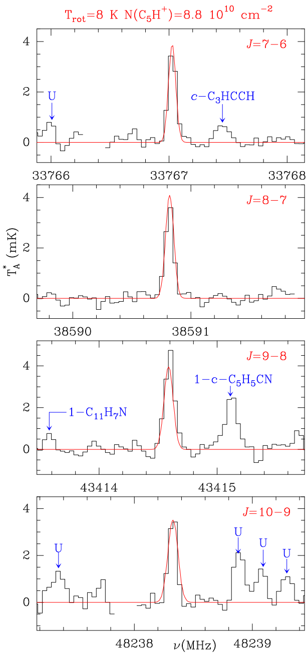

Figure 2. Observed lines of C_5H^+ with QUIJOTE towards TMC-1. The abscissa corresponds to the rest frequency assuming a local standard of rest velocity of 5.83 km s^{-1}. The ordinate is the antenna temperature corrected for atmospheric and telescope losses in mK. The red line shows the synthetic spectrum derived with MADEX [22] for T_{rot}=8 K and N(C_5H^+)=8.8×10^{10} cm^{-2}. Blank channels correspond to negative features produced in the folding of the frequency switching data (from [25]).

QUIJOTE data are: HDCCN [19], CH_2DC_3N [20], CH_2DC_4H [21]. Although QUIJOTE has not yet reached the confusion limit, special care has to be taken when assigning lines to a given molecule as blending with other features often occurs. Line identification in this work was done using the following catalogues: MADEX [22], CDMS [23], and JPL [24]. By July 2022 the MADEX catalogue has 6435 spectral entries corresponding to the ground and vibrationally excited states, together with the corresponding isotopologues, of 1736 molecules.

Contrarily to the GOTHAM survey that detects species through spectral stacking (see, e.g., [10]), all QUIJOTE detections are based on the classical and old fashion method of line by line identification of all expected transitions of a given molecule within the Q-band. With the present level of sensitivity of QUIJOTE we have detected 1591 features above the 1 mK level (5-7 σ below 42 GHz). Of these lines 188 remain unidentified. We note, however, that the number of unknown spectral features above the 3σ level is much larger (around 1200 by July 2022).

As an example of identification of a new molecule with QUIJOTE without previous information of the frequencies of the transitions, we present the detection of the cation C_5H^+ [25]. Inspecting the U-lines we have found that only four of these U-lines have intensities above 3 mK. The frequencies of these four lines are, in addition, in perfect harmonic relation with J_u=7, 8, 9, 10. They are shown in Fig. 2. They do not show any hyperfine structure, and no other nearby lines are present with similar intensities, which discard a symmetric rotor, or a linear radical, as possible carrier. We are, hence, dealing with a linear molecule with a $^1\Sigma$ ground electronic state, or with a slightly asymmetric rotor with electronic state ^1A. By fitting the observed frequencies to the standard Hamiltonian for a linear molecule ($\nu(J \rightarrow J-1) = 2B_0 J - 4D_0 J^3$) we derived B_0=2411.94397±0.00055 MHz and D_0=138±3 Hz. The standard deviation of the fit is 4.4 kHz. The possibility that these four strong lines appear by chance in harmonic relation with such a precision is negligible. Hence, we have detected a new molecular species in TMC-1. We selected all possible configurations of 4-5 atoms of H, C, N, O and S that could reproduce the observed rotational constant and conclude that C_5H^+ was the carrier of these lines. Although the definitive confirmation could arrive from laboratory experiments, the high level of theory ab initio calculations permit, nowadays, to assign with a high degree of confidence the observed lines to C_5H^+ [25]. In the same work we also reported the detection, for the first time in a cold starless core, the cation C_3H^+.

Since June 2020 QUIJOTE has detected near 40 new molecules in space (see [25] and references therein). The detection of cyclopentadiene and of indene [5], together with very abundant hydrocarbons such as CH_2CCH, CH_2CHCCH, $CH_2CCHCCH$, CH_2CCHC_4H [2–4, 9], indicates that many reactions have to be included in the chemical models. In particular reactions between cations and radicals, and cations with large hydrocarbons are missing so far in the best models of cold astrophysical environments [26]. The large abundances of hydrocarbons and PAHs in these unexpected environments require a sensitive survey such as QUIJOTE to unveil all the aspects of the chemical complexity of cold prestellar cores [26].

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