A 4–6 GHz SPECTRAL SCAN AND 8–10 GHz OBSERVATIONS OF THE DARK CLOUD TMC-1

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Received 2003 December 15; accepted 2004 March 27

ABSTRACT

We present the results of the lowest frequency spectral survey carried out toward a molecular cloud and sensitive observations at selected frequencies. The entire Arecibo C band (4–6 GHz) was observed toward the cyanopolyne peak of TMC-1, with an rms sensitivity of about 17–18 mK (about 2–2.5 mJy). In addition, a number of selected frequency ranges within the C band and X band (8–10 GHz) were observed with longer integration times and rms sensitivities of 7–8 mK (≈2 mJy) or higher. In the spectral scan itself, already-known H2CO and HC3N lines were detected. However, in more sensitive observations at selected frequencies, lines of C2S, C3S, C4H, C4H2, HC3N and its 13C substituted isotopic species, as well as HC5N, HC7N, and HC9N were found, about half of them detected for the first time. The rotational temperatures of the detected molecules fall in the range 4–9 K. Cyanopolyne column densities vary from $5.6 \times 10^{12}$ cm$^{-2}$ for HC5N to $2.7 \times 10^{12}$ cm$^{-2}$ for HC9N. Our results show that, for molecular observations at low frequencies (4–10 GHz) to be useful for studying dark clouds, the sensitivity must be of the order of 5–10 mK or better. To date, observations at ~10 GHz have been more productive than those at lower frequencies.

Subject headings: ISM: clouds — ISM: individual (TMC-1) — ISM: molecules — radio lines: ISM

1. INTRODUCTION

Most known interstellar molecules have been detected in the millimeter wavelength range. This is clearly related to the fact that, in general, the simplest and hence the lightest molecules are the most abundant cosmic molecular species. Their strongest rotational lines at the temperatures characteristic of the molecular interstellar medium arise at millimeter and submillimeter wavelengths. Heavier molecules, often with large permanent dipole moments, have detectable rotational lines at lower frequencies in the microwave range. Transitions between low energy levels are more favorable in terms of line intensities, especially in regions of low or modest density and low temperature. The latter include, in particular, the inner parts of dark clouds, which are among the coldest regions of the interstellar medium because they have no internal energy sources and are shielded from external sources of radiation by their own gas and dust.

Another reason why observations at low frequencies are needed is the fact that the line intensities of molecules having a fractional abundance below $\sim 10^{-11}$ relative to H2 fall below the confusion level in the millimeter wavelength range. In such cases, sensitive observations at low frequencies, which are less “contaminated” by the emission of simple molecules, may help. In addition, hyperfine splitting is often negligible at high frequencies but detectable at low frequencies (e.g., for species HC5N, HC7N, etc.). Hyperfine splitting may be used to determine line opacities and thus to obtain more accurate molecular column densities and abundances.

Spectral scans, covering wide ranges of frequencies, are powerful tools for molecular searches. Typically, many lines of the same molecule fall within the observed spectral window, making it possible to more reliably identify observed spectral features. A number of spectral scans of molecular clouds have so far been carried out in atmospheric windows between 17 and 700 GHz, e.g., 17.6–22 GHz (Bell et al. 1993), 72–144 GHz (Cummins et al. 1986; Johansson et al. 1984; Turner 1991), 330–360 GHz (Jewell et al. 1989), 455–507 GHz (White et al. 2003), 607–725 GHz (Schilke et al. 2001), and 780–900 GHz (Comito et al. 2002). Recently, Kaifu et al. (2004) carried out a spectral scan of the dark cloud TMC-1 in the frequency range between 8.8 and 50 GHz. However, no spectral scan has been performed at frequencies below 8.8 GHz. Therefore, we undertook a spectral survey of TMC-1 at 4–6 GHz. This is the lowest frequency spectral survey carried out toward a molecular cloud.4

TMC-1 has the shape of a ridge elongated in the northwest-southeast direction. The structure and chemical composition of TMC-1 have been studied by Hirahara et al. (1992), Pratap et al. (1997), Turner et al. (2000), and Dickens et al. (2001). The temperature of this object is about 10 K, which is typical for dark clouds; the H2 density estimates toward the “cyanopolyne peak” (see below) vary between $4 \times 10^4$ cm$^{-3}$ (Turner et al. 2000) and $2 \times 10^4$ cm$^{-3}$ (Pratap et al. 1997).

4 A similar spectral scan of IRC +10216 has been performed using the Arecibo telescope by Araya et al. (2003).
study by Peng et al. (1998) revealed 45 clumps, which are grouped into three cylindrical features oriented along the ridge. The LSR velocities of these features are approximately 5.7, 5.9, and 6.1 km s\(^{-1}\). TMC-1 has proven to be an excellent object for the study of chemistry in dark clouds under quiescent conditions. It shows a carbon-rich chemistry with chemical gradients across the densest part of the ridge extending over 0.2 pc \(\times 0.6\) pc. The most prominent chemical feature of TMC-1 is the high abundance of various carbon-chain molecules, such as cyanopolyynes, HC\(_{2n+1}\)N, and radicals, C\(_2\)H. The peak position of the line intensities of cyanopolyynes (the cyanopolyyne peak) was found to be located \(\approx 7\)\(^\circ\) southeast from another prominent position in TMC-1, the peak of the ammonia line emission. The heaviest known interstellar molecule, HC\(_{11}\)N, as well as a number of other heavy molecules have been found exactly toward the cyanopolyyne peak, making it an especially interesting object for observations at low frequencies.

2. OBSERVATIONS

The observations were performed with the 305 m radio telescope of the Arecibo Observatory. The entire Arecibo C band (4–6 GHz) was observed toward the cyanopolyyne peak position (\(\alpha_{J2000} = 04^\mathrm{h} 38^\mathrm{m} 38^\mathrm{s}\), \(\delta_{J2000} = 25^\circ 35^\prime 45^\prime\)). The C band observations were performed in total power mode, which is effective as a result of the excellent system stability and maximizes the signal-to-noise ratio. Two senses of linear polarization were independently observed, and the two outputs were averaged together. The four correlator boards of the spectrometer were offset in frequency by 5.25 MHz, and each was set to a bandwidth of 6.25 MHz, thus yielding an instantaneous continuous frequency coverage of 21 MHz, with a frequency resolution of 3 kHz (0.183 km s\(^{-1}\) at 5 GHz). Each frequency setup was observed for 5 minutes. The entire C band was observed three times, with one observation shifted by 3 MHz, yielding an rms sensitivity of about 17–18 mK (about 2–2.3 mJy).

In addition, a number of selected frequency ranges within the C band and X band (8–10 GHz) were observed with longer integration times and rms sensitivities of 7–8 mK or higher. The X band observations were performed in two senses of circular polarization. The beam size was about 0.9\(^\prime\) \(\times 1.0\) in the C band and about 0.5\(^\prime\) \(\times 0.5\) in the X band. The gain was \(\approx 8\) K Jy\(^{-1}\) in the C band and \(\approx 4\) K Jy\(^{-1}\) in the X band. The frequency ranges were centered at the frequencies of different molecular transitions taken from the Jet Propulsion Laboratory (JPL) catalog of line positions and intensities\(^2\) and the Cologne database for molecular spectroscopy,\(^3\) as well as from the catalog of known molecular lines by F. Lovas.\(^4\)

Each scan of the total power observations consisted of fifty 6 s on-source observations followed by two 10 s calibration scans. The first of these calibration scans was taken with a noise diode switched on and the second with the noise diode off. The data were calibrated by dividing the on-source spectra by the calibration spectra; the latter were calculated as the difference of the two calibration signal scans. To optimize the accuracy of the calibration while minimizing the effect of noise in the calibration scans, the calibration scans were approximated by polynomials of order 20–29. Polynomials of low order (up to 3) were applied to remove residual baselines from the calibrated spectra. Both the calibration and subsequent data reduction were performed with the CLASS software package.

Lines with resolved hyperfine structure (i.e., when the hyperfine components are presented as different entries in Table 1) were fitted using the standard CLASS method HFS. This method enables us to derive the optical depth of the strongest component from the relative intensities of the observed components, assuming that the excitation temperatures, LSR velocities, and line widths of individual components are the same.

3. RESULTS AND ANALYSIS

TMC-1 has very narrow lines of less than 0.4 km s\(^{-1}\) width. In order to achieve high velocity resolution of 0.18 km s\(^{-1}\) with the available number of spectrometer channels, the entire band of 4–6 GHz was divided into 381 spectra. A portion of one of the C band spectra is shown in Figure 1.\(^5\) As a result of the spectral scan itself, we detected only lines of H\(_2\)CO and HC\(_3\)N. However, in more sensitive observations at selected frequencies in the C and X bands, we detected lines of C\(_2\)S, C\(_3\)S, C\(_3\)H, C\(_5\)H\(_2\), HC\(_4\)N, and its \(^{13}\)C substituted isotopic species, as well as HC\(_3\)N, HC\(_2\)N, and HC\(_2\)N. The \(J = 5–4\) line of HC\(_3\)N and all lines of HC\(_4\)N, C\(_5\)H\(_2\), CCS, and C\(_3\)S are new, i.e., they were not included in the catalog of known interstellar lines by F. Lovas at the time of writing this paper. The list of the detected lines with their fitted Gaussian parameters is presented in Table 1.

Most of our results were analyzed with rotational diagrams. To construct these, we derived a rotational level population from the total intensity of relevant hyperfine components.

For optically thin emission, the integrated line intensity, \(W\) (K cm s\(^{-1}\)), is related to the upper-level column density \(N_u\) by the well-known relation

\[
\frac{N_u}{g_u} = \frac{3kW}{8\pi^2\nu_0S\mu^2} J(\nu, T_{ex}) - J(\nu, T_{bg}),
\]

where \(S\) is the line strength, \(\mu\) is the permanent electric dipole moment, and \(J(\nu, T_{ex}) = (h\nu/k)[e^{(h\nu/kT_{ex})} - 1]^{-1}\). At low frequencies, where \(h\nu \ll kT\), \(J(\nu, T) \approx T\). The parameters \(T_{ex}\) and \(T_{bg}\) are the excitation temperature and the background brightness temperature, respectively. If \(J(\nu, T_{ex}) \gg J(\nu, T_{bg})\), the term \(J(\nu, T_{ex})/[J(\nu, T_{ex}) - J(\nu, T_{bg})]\) approaches unity. In this case, assuming LTE and applying Boltzmann’s equation, one can obtain from equation (1)

\[
\ln \frac{3kW}{8\pi^2\nu_0S\mu^2} = \ln \frac{N}{Q_{rot}} - \frac{E_u}{kT_{rot}},
\]

where \(E_u\) is the energy of the upper level of the transition, \(Q_{rot}\) is the partition function, and \(T_{rot}\) is the excitation temperature characterizing the rotational transitions of interest. Using equation (2), one can obtain the total molecular column density \(N\) and rotational temperature \(T_{rot}\) from observations of several lines of the same molecule. However, in the case of HC\(_3\)N and some other molecules the rotational temperature is fairly low; hence, the assumption \(J(T_{ex}, \nu) \gg J(T_{bg}, \nu)\) is not valid, and the term \(J(\nu, T_{ex})/[J(\nu, T_{ex}) - J(\nu, T_{bg})]\) must be

\(^2\) See http://spec.jpl.nasa.gov/ftp/pub/catalog/catform.html.
\(^3\) See http://www.ph1.uni-koeln.de/vorhersagen/.
\(^4\) See http://physics.nist.gov/cgi-bin/micro/table5/start.pl.
\(^5\) All spectra are available at http://tanatos.asc.rssi.ru/~kalensky/scan.html.
First, the optical depths of the observed lines were determined. To estimate column densities of these species, we constructed the following iterative approach:

1. determine "initial guesses" of $T_{\text{rot}}$ and $N$ from equation (2).
2. calculate of $[J(v, T_{\text{rot}})]/[J(v, T_{\text{rot}}) - J(v, T_{\text{bg}})]$ from the estimate of $T_{\text{rot}}$.
3. determine of the next estimate of $T_{\text{rot}}$ and $N$ using the calculated value of $[J(v, T_{\text{rot}})]/[J(v, T_{\text{rot}}) - J(v, T_{\text{bg}})]$.

Steps 2 and 3 were repeated until convergence was achieved. The calculated rotational temperatures and column densities are given in Table 2.

For $C_4H$ and $C_4H_2$, no rotational diagrams were constructed. To estimate column densities of these species, we assumed that the energy level populations are thermalized at a temperature taken from the literature and presented in Table 2. First, the optical depths of the observed lines were determined from the relation $\tau = T_R / [J(T_{\text{rot}}, v) - J(T_{\text{bg}}, v)]$, where $T_R$ is the main beam brightness temperature. Then, using the prescription from the section "Intensity Units and Conventions" taken into account. Therefore, we derived $N$ and $T_{\text{rot}}$ applying the following iterative approach:

- Fig. 1.—Plot of a 1 MHz portion of the C band spectrum. The horizontal axis is the rest frequency in MHz, and the vertical axis is the antenna temperature in K. The strong absorption line at the center is the $1_{10}-1_{11}$ transition of $H_2CO$. The positions of the hyperfine components are shown by vertical bars.

![Diagram](image-url)
Upper Limit to the Antenna Temperatures for Undetected Lines and Relevant Molecular Column Density Limits

| Molecule     | Frequency (MHz) | Transition | $|T_2|$ (K) | Upper Limit (K) | Column Density (cm$^{-2}$) | Reference for Frequency |
|--------------|----------------|------------|-----------|-----------------|---------------------------|------------------------|
| HC$_3$N      | 4067.2695$^d$  | $J = 7-6$  | 0.026     | 2.53$ 	imes 10^{12}$ JPL |
| HC$_3$N      | 5071.88851     | $J = 15-14$ | 0.027     | 1.01$ 	imes 10^{12}$ JPL |
|              | 5410.0103      | $J = 16-15$ | 0.012     | 2.41$ 	imes 10^{12}$ JPL |
|              | 8115.007       | $J = 24-23$ | 0.033     | 3.12$ 	imes 10^{12}$ JPL |
|              | 8791.257       | $J = 26-25$ | 0.042     | 1.29$ 	imes 10^{12}$ JPL |
|              | 9129.376       | $J = 27-26$ | 0.018     | 1.33$ 	imes 10^{12}$ JPL |
| HC$_3$N      | 5348.622       | $J = 25-24$ | 0.012     | 1.33$ 	imes 10^{12}$ Cologne |
|              | 5562.566       | $J = 26-25$ | 0.013     | 1.26$ 	imes 10^{12}$ Cologne |
| C$_6$D       | 8868.9005      | $N = 1-0, J = 1/2-1/2$ | 0.033     | 2.25$ 	imes 10^{14}$ Cologne |
| C$_5$O       | 5467.388       | $J = 2-1$  | 0.030     | 5.00$ 	imes 10^{12}$ JPL |
| C$_5$S       | 5912.1755      | $N_1 = 3-2_{11}$ | 0.027     | 1.11$ 	imes 10^{13}$ Cologne |
|              | 8868.7075      | $N_1 = 4_{3}$ | 0.033     | 1.04$ 	imes 10^{13}$ Cologne |
| C$_5$S       | 5536.222       | $J = 3-2$  | 0.029     | 4.43$ 	imes 10^{12}$ JPL |
|              | 9227.028       | $J = 5-4$  | 0.036     | 3.81$ 	imes 10^{12}$ JPL |
| C$_5$N       | 5607.1377$^d$  | $N = 2-1, J = 5/2-3/2$ | 0.032     | 1.86$ 	imes 10^{13}$ JPL |
| C$_5$H       | 4201$^*$       | $^{2}P_{1/2, J = 3/2-1/2}$ | 0.026     | 1.36$ 	imes 10^{14}$ Cologne |
| CH$_2$C$_2$H  | 4071.4935      | $J_e = 1_{0,0}$ | 0.030     | 3.54$ 	imes 10^{14}$ Lovas |
| CH$_2$NH     | 5289.813$^d$   | $1_{0,1}$ | 0.030     | 9.63$ 	imes 10^{14}$ Lovas |
| HCOOH        | 4916.312       | $2_{1,1}$ | 0.039     | 3.68$ 	imes 10^{14}$ Lovas |
| CH$_3$CO     | 5660.9476      | $5_{1,1}$ | 0.024     | 0.072 |
| H$_2$C$_2$O  | 4388.8011$^d$  | $1_{0}$ | 0.021     | Lovas |
| H$_2$CO      | 4593.0865$^d$  | $1_{11}$ | 0.072     | Lovas |

Note.—The limits are given at 3 $\sigma$ level.  
$^a$ Assuming a rotational temperature equal to 10 K.  
$^b$ JPL catalog, Cologne database, and Lovas line list.  
$^c$ HC$_3$N column density is presented in Table 2.  
$^d$ Blended hyperfine structure.  
$^e$ Line multiplet.
weakness of the lines of the $^{13}$C-substituted species did not allow us to reliably measure the isotopic abundance ratios, but the results seem to be in qualitative agreement with the previous results of Takano et al. (1998) obtained from the observations of the $J = 2-1$, 4-3, and 5-4 lines at higher frequencies; i.e., the HCC$^{13}$CN emission is the strongest, and the HC$^{13}$CCN and H$^{13}$CCCN emission is weaker by a factor of 1.3. The ratio of the HC$_3$N/HCC$^{13}$CN line intensities, 54 ± 15, is also in agreement with the ratio of HC$_3$N/HCC$^{13}$CN abundances of 55 found by Takano et al., indicating a small optical depth for the lines observed using Arecibo.

3.2. HC$_5$N

We detected $J = 2-1$ emission of HC$_5$N (Fig. 3). The ratio between the intensities of different hyperfine components corresponds to LTE with small optical depth. Combining our line intensity with the intensities of different lines of HC$_5$N published by Snell et al. (1981), in a rotational diagram (Fig. 4) we derive a HC$_5$N rotational temperature of 4.3 K, in agreement with, e.g., Bell et al. (1998), and a column density of $5.6 \times 10^{13}$ cm$^{-2}$.

3.3. HC$_7$N

We detected the $J = 5-4$, 7-6, and 8-7 lines were observed, and spectra are shown in Fig. 3. The rotation diagram (Fig. 4) was constructed assuming a HC$_7$N source size of $6'' \times 1.3$ (Bell et al. 1998) and yields a rotational temperature of 7.7 K and a HC$_7$N column density of $1 \times 10^{13}$ cm$^{-2}$.

3.4. HC$_9$N

We detected the $J = 15-14$ and 16-15 transitions of HC$_9$N and marginally detected the $J = 9-8$, 10-9, and 14-13 lines. The $J = 7-6$ line was not found because of the weakness of the rotational transition and its hyperfine splitting (Fig. 5). Rotational diagrams were constructed assuming a source size equal to $6'' \times 1.3$ (Fig. 4, top right panel) and $100'' \times 55''$, suggested by Bell et al. (1998) (Fig. 4, middle right panel). One can see that the best fit to our data is obtained for the former source size. Thus, we derived a rotational temperature equal to 8.4 K and a HC$_9$N column density equal to $2.7 \times 10^{13}$ cm$^{-2}$.

Our results on cyanopolyne rotational temperatures are in agreement with the previous results by Bell et al. (1998), who
found that the rotational temperatures of the cyanopolyynes increase with the number of heavy atoms over the range HC$_5$N to HC$_9$N and explained this effect in terms of less efficient radiative decay in the longer cyanopolyyne chains.

### 3.5. Other Detected Molecules

An unexpected result is the weakness of the tentatively detected $N_J = 3_2 - 2_2$ line of CCS at 5402.6 MHz relative to the 1–0 line of C$_3$S at 5780.8 MHz (Fig. 6). The CCS abundance is higher by an order of magnitude (Fuente et al. 1990), and usually CCS lines are much stronger than C$_3$S lines at approximately the same frequencies (e.g., Dickens et al. 2001). The CCS line is intrinsically weaker than the C$_3$S line ($S_{3_2}/C_{22}^2 = 13.76$ for the C$_3$S line and only 6.71 for the CCS line). The relevant rotational diagram (Fig. 4) yields a rotational temperature of 5.7 K and a CCS column density of $3.4 \times 10^{12}$ cm$^{-2}$, which is in good agreement with that derived by Fuente et al. (1990). We derived the C$_3$S column density from LVG calculations, assuming $T_{\text{kin}} = 10$ K and $n_{\text{H}_2} = 3 \times 10^4$ cm$^{-3}$ (Pratap et al. 1997). Our value, $3 \times 10^{12}$ cm$^{-2}$, is in good agreement with that derived by Fuente et al. (1990). Thus, the weakness of the $3_2 - 2_2$ line of CCS is a consequence of its intrinsic weakness, the high location of its energy levels ($E/k = 10.84$ K for the $N_J = 3_2$ CCS level), and the fairly low rotational temperature of CCS.

We detected a strong $N = 1 - 0$, $J = 3/2 - 1/2$, $F = 2 - 1$ transition of C$_4$H (Fig. 2), already observed in TMC-1 by Bell et al. (1982, 1983). The Arecibo line is narrow because of the weakness of the 6.06 km s$^{-1}$ component toward the observed position. Since this component is fairly strong in the 1–0 line of HC$_3$N, our data suggest that there is a difference between the small-scale ($\sim 30''$) distributions of HC$_3$N and C$_4$H. Note that the same C$_4$H line observed with a much larger 3.4 beam (see Fig. 2 in Bell et al. 1982) is broader, having a width of $\sim 0.4$ km s$^{-1}$, which is typical of TMC-1.

We believe that the detection of the 1$_{01} - 0_{00}$ para-C$_4$H$_2$ line is real, since the C$_4$H$_2$ column density (derived from the line intensity under the assumptions that the C$_4$H$_2$ rotational temperature is 4.2 K and the ortho-to-para ratio is 4.2; Kawaguchi et al. 1991) is equal to $4.6 \times 10^{12}$ cm$^{-2}$, which is comparable to, but somewhat smaller than, the value of $7.5 \times 10^{12}$ cm$^{-2}$ derived by Kawaguchi et al. (1991).

The 1$_{10} - 1_{11}$ H$_2$CO line, detected using Arecibo (Fig. 1; Table 1), is rather similar but not identical to that observed previously by, e.g., Henkel et al. (1981) with a 2'6 beam. The relative intensities of hyperfine components yielded an optical depth of the main component of 1.6 and a line-excitation temperature of 1.2 K. No 1$_{10} - 1_{11}$ H$_{13}$CO and H$_2$C$^{18}$O lines were detected. We estimate lower limits to the ratios of the 1$_{10}$ level populations for H$_2$CO/H$_{13}$CO and H$_2$CO/H$_2$C$^{18}$O, assuming equal excitation temperatures for the 1$_{10} - 1_{11}$ transition of all isotopic species, of 24 and 76, which are below the $^{13}$C/12C and $^{18}$O/16O abundance ratios by factors of approximately 3 and 6, respectively. Thus, the nondetection of the 1$_{10} - 1_{11}$ H$_2$CO and H$_2$C$^{18}$O lines does not contradict the known values of the $^{13}$C/12C and $^{18}$O/16O abundance ratios.

### 3.6. Undetected Lines

Table 3 presents the upper limits to the antenna temperatures of observed but undetected lines, together with the relevant column-density limits. The column-density limits...
Fig. 4.—Rotation diagrams. The lines detected at Arecibo are denoted by stars, while the squares represent the lines taken from the literature. Two different diagrams for HC$_3$N were constructed assuming different source sizes: 6$^\prime$ $\times$ 1$^\prime$.3 (top right panel), and 1$^\prime$.7 $\times$ 0$^\prime$.9 (middle right panel). For each diagram, the horizontal axis is $E_u/k$, and the vertical axis is $\log (3kW/(8\pi^2\nu_0^{3/2}S_0^{1/2}))$ (see § 3).
Fig. 5.—Various HC$_3$N lines. The rotational transition is indicated in the upper right corner of each spectrum. The vertical lines indicate the positions of the hyperfine components. A minus sign after the species name means that the line was not detected. A question mark after the species name denotes a marginal detection. The axes are the same as in Fig. 3.
were calculated from equation (1), under the assumption that
the line populations are thermalized at 10 K. Most of the
molecular species from Table 3 have already been found in
TMC-1 at higher frequencies. Comparison of the published
column densities with the upper limits in Table 3 shows that
an increase in sensitivity by a factor of 2–5 could lead to the
detection of a much larger number of molecular lines. Thus,
molecular observations at low frequencies (4–10 GHz) may
be useful for studying dark clouds if the sensitivity (at 3
level) is about 5–10 mK or better.

We did not estimate H$_{13}^{12}$CO and H$_{2}^{18}$CO column densities
because of well-known strong deviations from LTE of the
level populations of these species. Note that some other mol-
ocules may remain undetected in dark clouds because of
excitation particularities rather than low abundances. For in-
fstance, CH$_{2}$NH was not detected in TMC-1 and L134 by
Dickens et al. (1997); they suggested that it may be an exci-
tation effect, since the observed transitions have critical den-
sities of about $10^6$ cm$^{-3}$, which is well below the density of
TMC-1. Our nondetection of the $1_{10}-1_{11}$ CH$_{2}$NH emission
line is probably a result of the $1_{10}-1_{11}$ transition at 167.4 GHz
($E_{low} = 2.135$ cm$^{-1}$), which can radiatively depopulate the $1_{10}$
level at the moderate densities found in TMC-1.

4. SUMMARY

The results of the lowest frequency spectral survey carried
out toward a dark cloud, studying TMC-1 in the 4–6 GHz
range using the Arecibo radio telescope, and those from
sensitive observations at selected frequencies in C and X
bands can be summarized as follows:

1. A number of molecular lines were detected. The majority
of the detected lines belong to the cyanopolyynes HC$_5$N,
HC$_7$N, and HC$_9$N.

2. The rotational temperatures of the detected molecules fall
in the range 4–9 K. Cyanopolyene column densities vary from
$5 \times 10^{13}$ cm$^{-2}$ for HC$_5$N to $2.7 \times 10^{12}$ cm$^{-2}$ for HC$_9$N.

3. Molecular observations at low frequencies (4–10 GHz)
can be useful for studying dark clouds, but to be really effec-
tive, the sensitivity must be increased by a factor of 2–3. To
date, observations at $\sim 10$ GHz have been more fruitful than
those at lower frequencies.

The National Astronomy and Ionosphere Center is operated
by Cornell University under a cooperative agreement with the
National Science Foundation. We are grateful to the staff of
the Arecibo Observatory and especially Jeff Hagen, Mike
Nolan, Phil Perillat, Chris Salter, and Arun Venkataraman for
help during the observations and useful discussions. We thank
the anonymous referee for important comments. S. V. K.’s
visit to Arecibo was supported by the NAIC Director’s Office.
The work was partly supported by the Russian Foundation for
Basic Research (grant 01-02-16902).

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