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Chapter V

# DETECTION OF $CH_3OH$ J = 5 → 4 LINES AROUND 242 GHZ FROM OMC-1

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**SUMMARY**

Sixteen methanol lines have been detected at a frequency of 242 GHz from OMC-1. They correspond to the J=5→4 Δk=0 transitions of $CH_3OH$ A and E. With the assumption of a 30" diameter methanol source in OMC-1 the observed brightness temperatures can be reproduced with a thermal excitation model using one temperature, $T_{exc}$ = 90 K and using a column density of $N(CH_3OH) = 5\times10^{16}$ $cm^{-2}$. All lines appear to be optically thin. Collisional excitation of the J=5 levels requires gas densities of $n(H_2) > 4\times10^6$ $cm^{-3}$. Some of the detected methanol lines are also observed at a position 2' south of OMC-1 and in DR21, M17(SW) and W3OH.

**Key words:** Interstellar molecules - Orion nebula - radio lines

## 1. INTRODUCTION

Methanol ($CH_3OH$) has already been observed in about 35 transitions towards Orion Molecular Cloud - 1 (OMC-1). Most lines seem to be consistent with thermal excitation at one temperature, $T_{exc} \approx 90$ K. However some transitions have intensities that vary in time (Barrett, Ho and Martin, 1975) and extremely narrow, multiple component velocity features (Hills et al., 1975) characteristic for maser emission. Recently using the Hat Creek Interferometer Matsakis et al. (1980) have mapped OMC-1 in to $CH_3OH$ maser transitions. They resolved the source into 10 components with different Doppler velocities separated by at most 30".

At a frequency of 242 GHz we detected 16 methanol lines produced by the $J=5\rightarrow4$ $\Delta k=0$ transitions of $CH_3OH$ A and E (see Fig.2). These lines originate from levels with upper level energies ranging from 26 to 87 $cm^{-1}$ above the ground state. Seven of these lines were observed before by Loren, Mundy and Erickson (1981).

## 2. OBSERVATIONS

The observations were carried out in October 1980 with the 3.8 m diameter U.K. Infrared Telescope and NASA's 3 m Infrared Telescope Facility, both located on top of Mauna Kea, Hawaii. Our heterodyne receiver system has been described elsewhere, Lidholm and de Graauw (1979). It had ambient temperature Schottky diode mixers and a carcinotron local oscillator. The system noise temperature (4000 K, single-sideband) was calibrated against an ambient and against a hot load. The antenna beam widths and the optical efficiences of the telescope-receiver combinations were measured by scanning across Jupiter and the Moon; for UKIRT we obtained 90" and 55%, and for IRTF 110" and 50%. The telescope beam was position-switched over 30' at 100 seconds intervals. The 1 MHz and 250 kHz 256 channel filterbanks were operated in series. The atmospheric tranparency was determined from sky dips to be about 80%.

Observations were made mainly towards OMC-1 [$\alpha(1950) = 5^h 32^m 47^s$, $\delta(1950) = 5° 24' 21"$] and at a position 2' south of it. We also made a few observations towards DR21, M 17(SW) and W3OH.

## 3. RESULTS AND DISCUSSION

Identification of the methanol lines was based on the frequencies given by Lees (1973) and Pickett et al. (1981). Fig.1 shows the lines observed towards OMC-1 obtained with UKIRT. The vertical bars indicate the positions of the 16 transitions which are labeled as in the energy level diagram (Fig.2) and listed in Table 1. The relative strengths of the bars correspond to the relative line intensities calculated later on. The antenna temparatures are corrected for atmospheric attenuation and telescope losses but not for beam dilution. The full line widths at half maximum are approximately 4 km $s^{-1}$ in agreement with other methanol observations. Thw dotted curve represents the theoretical spectrum calculated by adopting Gaussian profiles for the individual transitions. The feature at $\Delta\nu = -31$ MHz ( $\nu =$ 241774.3 MHz) is probably due to the $11_{0,11} \rightarrow 10_{0,10}$ transition of HNCO as suggested by an unknown referee.

In Table 1 we summarize the relevant data of the J=5→4 $\Delta k=0$ (A,E) transitions together with the observed and calculated peak antenna temperatures $T_A^*$ . The spontaneous radiative transition probabilities $A_{ul}$ and the energies of the lower state $E_l$ have been taken or calculated from Lees (1973) and Lees et al. (1973).

We predict antenna temperatures by supposing that the $CH_3OH$ energy levels are populated according to one excitation temperature $T_{exc}$. Then the peak antenna temperature, $T_A^*$ , is calculated to be

$$T_A^* = \left( \frac{\Theta_s}{\Theta_A} \right)^2 T_{exc} \left\{1 - \exp(-\tau_{lu})\right\} \qquad (1)$$

where $\Theta_A$ and $\Theta_s$ are the angular diameters of the antenna beam and the methanol emitting region, respectively and $\tau_{lu}$ is the line centre optical depth given by

$$\tau_{lu} = \frac{A_{ul}\, c^3}{4\pi\, \nu_{ul}^3} \left(\frac{\ln 2}{\pi}\right)^{1/2} \frac{N_l}{\Delta V} \frac{g_u}{g_l} \left\{1 - \exp\left(\frac{-h\nu_{ul}}{k\, T_{exc}}\right)\right\} . \qquad (2)$$

The quantities $g_u$ and $g_l$ are the statistical weights of the upper and lower levels, respectively, $\Delta V$ is the full line width at half maximum and $N_l$ is the column density in the lower level l. $N_l$ is related to the total $CH_3OH$ column density according to

$$N_l = \frac{g_l\, N(CH_3OH)}{2\, Q_i} \exp\left(\frac{-hE_l}{kT_{exc}}\right) \qquad (3)$$

Table 1: Properties of $CH_3OH$ transitions observed towards OMC-1

| Number | Transition | $\nu_{ul}$ (GHz) | $A_{ul}$ ($10^{-5}$ $s^{-1}$) | $E_l$ ($cm^{-1}$) | $T_A^*$ (K) obs. | $T_A^*$ (K) calc. |
|---|---|---|---|---|---|---|
| 1 | $5_0 \rightarrow 4_0$ E | 241.7002 | 5.85 | 19.77 | 3.8 | 3.8 |
| 2 | $5_{-1} \rightarrow 4_{-1}$ E | 241.7672 | 5.62 | 14.52 | 3.4 | 3.9 |
| 3 | $5_0 \rightarrow 4_0$ $A^+$ | 241.7914 | 5.86 | 16.13 | 4.5 | 5.0 |
| 4 | $5_4 \rightarrow 4_4$ $A^+$ | 241.8065 | 2.11 | 71.98 | 1.6 | 1.8 |
| 5 | $5_4 \rightarrow 4_4$ $A^-$ | 241.8065 | 2.11 | 71.98 | | |
| 6 | $5_{-4} \rightarrow 4_{-4}$ E | 241.8133 | 2.11 | 70.53 | 1.3 | 0.8 |
| 7 | $5_4 \rightarrow 4_4$ E | 241.8296 | 2.11 | 77.44 | blend | 0.7 |
| 8 | $5_3 \rightarrow 4_3$ $A^+$ | 241.8330 | 3.75 | 50.75 | 3.0 | 3.9 |
| 9 | $5_3 \rightarrow 4_3$ $A^-$ | 241.8330 | 3.75 | 50.75 | | |
| 10 | $5_2 \rightarrow 4_2$ $A^-$ | 241.8423 | 4.92 | 42.34 | 2.8 | 3.1 |
| 11 | $5_3 \rightarrow 4_{-3}$ E | 241.8436 | 3.75 | 43.81 | | 1.8 |
| 12 | $5_{-3} \rightarrow 4_{-3}$ E | 241.8524 | 3.75 | 54.23 | 1.9 | 1.6 |
| 13 | $5_1 \rightarrow 4_1$ E | 241.8791 | 5.63 | 25.28 | 3.3 | 3.3 |
| 14 | $5_2 \rightarrow 4_2$ $A^+$ | 241.8877 | 4.92 | 42.34 | 3.6 | 3.1 |
| 15 | $5_{-2} \rightarrow 4_{-2}$ E | 241.9041 | 4.93 | 28.65 | 4.0 | 5.0 |
| 16 | $5_2 \rightarrow 4_2$ E | 241.9044 | 4.93 | 26.11 | | |

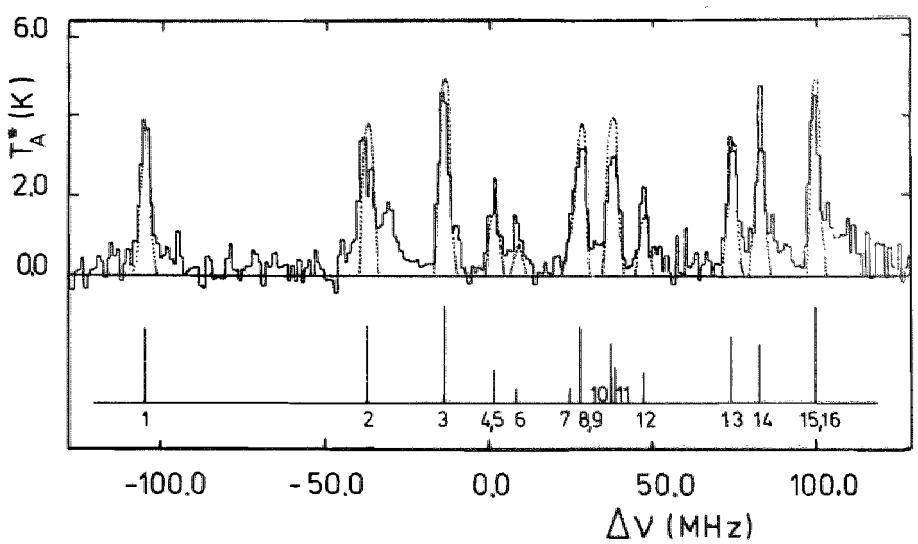


**Fig.1.** $CH_3OH$ J=5→4 Δk=0 lines measured at the Kleinmann-Low position in OMC-1. The antenna temperatures $T_A^*$ are corrected for telescope efficiency and atmospheric attenuation. The zero-point at the frequency scale is at $\nu_0$ = 241.8053 GHz. The transitions are indicated by the vertical bars and are labeled according Table 1 and Fig.2. The theoretical fit to the observed spectrum is represented by the dotted curve.

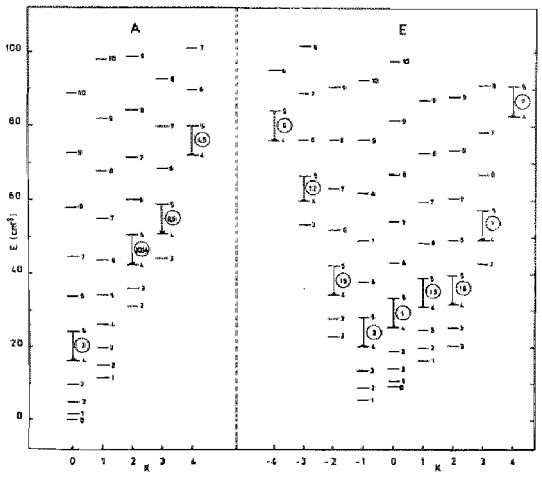


**Fig.2.** Energy level diagram of $CH_3OH$ A and E species. The detected transitions are indicated by arrows and their labels refer to Table 1.

Table 2: Peak antenna temperatures of the $CH_3OH$ $5_0 \rightarrow 4_0$ $A^+$ transition in several sources.

| Object | Telescope | $T_A^*$ in K |
|---|---|---|
| OMC-1 | UKIRT, 3.8 m | 4.5 |
| OMC-1 2' S | ,, | 1.4 |
| DR21 | ,, | 0.7 |
| M17(SW) | ,, | 1.4 |
| OMC-1 | IRTF, 3.0 m | 2.8 |
| W3OH | ,, | 0.6 |

where $E_l$ is the energy of level l and $Q_i$ is the rotational partition function for methanol A or E species. $Q_i$ is calculated according the prescription of Townes and Schawlow (1955) or is taken from Lees (1973). The factor 2 in Eq.(3) is included because the $CH_3OH$ A and E species are strictly separated with approximately equal numbers of molecules in each species.

To evaluate Eq.(1) numerically for OMC-1 a value for $\Theta_s$, the angular source diameter of the methanol emitting region, had to be assumed. The difference in antenna temperatures we have obtained using different telescopes (see Table 2) can be explained by beam dilution effects if $\Theta_s$ = 30" is adopted for OMC-1. This size agrees with the upper limit estimated by Hills et al. (1975) and with the assumption that the non-maser lines originate from the region in between the maser spots observed by Matsakis et al. (1980).

The antenna temperatures $T_a$(calc.) given in Table 1 are calculated by inserting $T_{exc}$ = 90 K, $N(CH_3OH) = 5\times10^{16}$ $cm^{-2}$, $\Delta V$ = 4 km $s^{-1}$ and $\Theta_s$ = 30" in the Eqs.(1-3). Within the errors of the observed antenna temparatures (±0.8 K) we find a good agreement between the observed and calculated line intensities. This agreement between predicted and observed spectra is also illustrated in Fig.1 where the dotted curve represents the calculated profiles. Using the same values for $T_{exc}$, $N(CH_3OH)$, $\Delta V$ and $\Theta_s$ we have also calculated peak line intensities for methanol

transitions observed by others (Barrett et al., 1971; Kutner et al., 1973; Lovas et al., 1976; Gottlieb et al., 1979; Jennings and Fox, 1979; Matsakis et al., 1980). The agreement between predicted and observed antenna temperatures is again reasonably good. The estimated uncertainties are $T_{exc} = 90 \pm 20$ K and $N(CH_3OH) = [5\ (-3,+2)]\times10^{16}$ $cm^{-2}$. This result for $T_{exc}$ is not affected by the assumed value of $\theta_s$ because it is predominantly determined by the relative line strengths. Since all transitions appear to be optically thin, the assumption that the diameter of the methanol emitting region is comparable with the telescope beam width results in a decrease of $N(CH_3OH)$ by about one order of magnitude.

Comparison of our peak antenna temperatures with those reported by Loren, Mundy and Erickson (1981) shows that the relative line strengths are in good agreement with each other. However our absolute intensities are a factor 3 larger. It is difficult to explain these differences in antenna temperatures. It may be caused by beam profile effects. Beam dilution effects can be excluded because the used telescopes have comparable beam widths at 242 GHz. It might be that the $T_A^*$'s given by Loren, Mundy and Erickson are not corected for antenna efficiency (which is given to be ~50%). An other possible explanation may be that the J=5+4 $\Delta k=0$ line intensities are variable on a time scale < 0.5 yr. Such a time variability has been observed for some cm transitions of methanol (Barrett, Ho and Martin, 1975; Hills et al., 1975) and for the $5_{-1}\rightarrow4_0$ E transition at 84.52 GHz (Tucker and Kutner; cited by Barrett, Ho and Martin, 1975). Further support for time variability comes from an unknown referee who communicated that $CH_3OH$ J=5+4 observations with the Bell Telephone $7^m$ antenna ($\theta_A$ ~ 40") give peak line intensities of about 2.7 K. On the other hand such a variability requires a variation of $T_{exc}$ and/or $N(CH_3OH)$, in disagreement with our fit to other mm transitions of $CH_3OH$ which have been observed over a period of one decade. In addition a variation of $T_{exc}$ had to affect the relative line strengths because the reported transitions originate from levels with different energies above the ground state. If no variation is present the Bell Telephone data contradict our estimate that the methanol emitting region is small compared to our telescope beam width.

In addition to the observations in the direction of OMC-1 we have positive detections towards several other objects in the $5_0\rightarrow4_0$ E, $5_{-1}\rightarrow4_{-1}$ E and $5_0\rightarrow4_0$ $A^+$ transitions. These lines originate from the lowest and most easily excited J=5 levels. In

Table 2 we summarize our results for the strongest line, the $CH_3OH$ $5_0 \rightarrow 4_0$ $A^+$ transition. The non-detection of the J=5→4 lines originating from higher energy levels imply excitation temperatures $\lesssim$ 25 K for these sources. The fact that we only detect lines originating from the lowest J=5 levels at a position 2' south of OMC-1 further supports our assumption that the warm ($T_{exc}$ = 90 K) methanol emitting region in OMC-1 had to be small compared with our telescope beam width (90"). This warm methanol core might be surrounded by a cooler and probably less dense envelope in which methanol molecules are less excited.

Since most of the mm methanol lines from the central position of OMC-1 show no significant departures from LTE we suppose that the corresponding energy levels are thermalized. A lower limit to the $H_2$ density can then be derived from the thermalization condition $\beta_{ul} \lesssim \varepsilon_{ul}$ where $\beta_{ul}$ is the so called escape probability (cf. de Jong et al., 1975)

$$\beta_{ul} = \frac{1 - \exp(-\tau_{ul})}{\tau_{ul}} \qquad (4)$$

and $\varepsilon_{ul}$ defines the probability that a molecule in level u is deexcited to level l by collisions, $\varepsilon_{ul} = C_{ul}/(C_{ul} + A_{ul})$. For the transitions originating from the highest J=5 levels we calculate an optical depth of about $\tau \approx 0.1$. Adopting a kinetic cross section $\sigma = 10^{15}$ cm$^2$ for $CH_3OH$-$H_2$ collisions (cf. Lees, 1973) and a thermal velocity of $(\frac{8kT}{\pi m})^{1/2} \approx 1$ km s$^{-1}$ we then find $n(H_2) \gtrsim 4\times10^6$ cm$^{-3}$ which agrees with previous estimates from $CH_3OH$ (Barrett et al., 1971; Kutner et al., 1973) and with gas densities derived from $HC_3N$ observations (Morris et al., 1977). This density corresponds to a mass of $M \gtrsim 40\ M_\odot$ for the warm methanol emitting region in OMC-1 if we adopt a distance of 500 pc. However $H_2CO$, HCN and $HCO^+$ observations imply gas densities which are one order of magnitude less (Evans et al., 1975; Huggins et al., 1979).

One possible explanation for the discrepancy in derived densities is that the assumed collisional cross section is too small. But it is difficult to understand how this estimate could be increased significantly. For example, close coupling calculations of thermal collisions with $H_2$ or He yield rate coefficients of about $1\times10^{-10}$ cm$^3$ s$^{-1}$ for OCS and $HC_3N$ and rate coefficients which are about a factor of 2 smaller for CO, CS and $H_2CO$ (Green and Chapman, 1978; Green et al., 1978).

A more likely explanation is that the emission of the $CH_3OH$

lines originates from a high density core or from several high density clumps, while the $H_2CO$, HCN and $HCO^+$ observations come predominantly from a surrounding less dense region. This explanation is supported by the fact that emission maps of these molecules are more extended (about 5' in diameter) than the region where the brightest methanol lines comes from.

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