THE ASTROPHYSICAL JOURNAL, 168:L101–L106, 1971 September 15

DETECTION OF METHYL ALCOHOL IN ORION AT A WAVELENGTH OF ~1 CENTIMETER

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Received 1971 June 14

ABSTRACT

Five transitions of CH_3OH, corresponding to the $J = 4, 5, 6, 7$, and 8 rotational levels, at frequencies of approximately 25 GHz, have been detected in Orion A. The source of emission is less than 1 arc minute in angular size and appears to be coincident with the infrared nebula. Although departures from LTE are evident in the line intensities, if the emission originates in the infrared nebula then a temperature of ~90° K, a column density of $\sim 5 \times 10^{16}$ CH_3OH molecules per cm^2, and a CH_3OH density of 0.25 molecules per cm^3 are indicated. Collisional excitation requires a total gas density of $\sim 2 \times 10^6$ cm^{-3} and a total mass of gas in excess of 20 $M_\odot$.

I. INTRODUCTION

The molecular structure of methyl alcohol (CH_3OH), also known as methanol and wood alcohol, is that of an asymmetric rotor capable of internal rotation; therefore, the molecule has energy levels which give rise to many microwave lines. In particular, the $\Delta J = 0$ lines between 17 and 40 GHz have been studied by Hughes, Good, and Coles (1951), for example, and the lines involving $\Delta J = \pm 1$ between 90 and 200 GHz have been studied by Lees and Baker (1968). More recently the studies have been extended to 830 MHz in support of the detection of CH_3OH in the galactic center (Ball *et al.* 1970). The transitions in the 20–30 GHz range belong to that group of energy levels classified as E_1 of the C_3 symmetry group (Lin and Swalen 1959; Lees and Baker 1968) and may be characterized by the selection rule $\Delta J = 0$, $K = 2 \rightarrow 1$, $\tau = 1 \rightarrow 2$, where J is the total rotational quantum number, K is the component of J along the "symmetry" axis—the C–O axis—of the molecule, and the quantum number τ relates to the tunneling of the hydroxyl group from one potential minimum to another about the symmetry axis.

Our detection of CH_3OH lines at ~25 GHz was fortuitous. During an unsuccessful search for the $J = 1 \rightarrow 0$ transition of nitrous oxide (N_2O) at 25,123.13 MHz we detected a line in Orion A whose radial velocity, relative to the local standard of rest, was -11.5 km s^{-1} if it was assumed to be N_2O. This velocity should be contrasted with those of all other molecular velocities in Orion A of 5–20 km s^{-1}. We noted that the $J = 7$, $\Delta J = 0$, $\Delta K = 1$ line of CH_3OH had a rest frequency of 25,124.88 MHz. If the line was in reality this transition, the radial velocity would be 8.5 km s^{-1}, in excellent agreement with other molecular velocities in Orion A. Fortunately, a conclusive test was possible by observing the $J = 6$, $\Delta J = 0$, $\Delta K = 1$ transition of CH_3OH at a frequency of 25,018.14 MHz. This line was also detected, thereby confirming that both lines were due to CH_3OH. Subsequently, three other lines were also detected, the parameters of which are given in Table 1.

II. OBSERVATIONS

Observations were made during 1971 April and May at the Haystack Observatory in Westford, Massachusetts. The 37-m antenna has a beamwidth of 1′.3 at 25 GHz. The rms error in antenna pointing is 10″, but because an offset feed horn was used the absolute positions may contain systematic errors up to 30″. The aperture efficiency of the antenna is approximately 0.23 including the radome loss of about 2.1 db, giving a ratio of

TABLE 1

PROPERTIES OF OBSERVED CH_3OH LINES

J	ν_0 (MHz)	A_{ij} (s^{-1})	$\Delta T_A(\nu)$ (°K)	$\Delta\nu$ (kHz)
4	24,933.47	8.40×10^{-8}	1.0 ± 0.2	<200
5	24,959.08	8.74×10^{-8}	1.1 ± 0.2	<200
6	25,018.14	8.98×10^{-8}	1.7 ± 0.2	150 ± 25
7	25,124.88	9.21×10^{-8}	1.5 ± 0.2	150 ± 25
8	25,294.41	9.48×10^{-8}	0.7 ± 0.2	<200

flux to antenna temperature of 15 f.u. per °K at 45° elevation where a zenith atmospheric attenuation of 6 percent has been included. All observations were made with linear polarization. The mixer radiometer had a single-sideband noise temperature ranging from 1900° to 2900° K, depending on the observing frequency. The local oscillator was derived from the hydrogen maser used as the observatory time standard. The spacing of the lines and the flexibility of the equipment enabled us to observe different lines in the upper and lower sidebands so that two or more lines could be observed simultaneously. Thus, the $J = 6$ and 7, $J = 2$, 4, and 6, and $J = 6$ and 8 lines could be observed in this manner. This removes many uncertainties, such as atmospheric absorption, in the determination of relative line intensities. Most observations were made with a 6-MHz bandwidth and 167-kHz resolution. Data were taken on and off the source and the difference spectra presented. Typically, 10 minutes were spent in each position.

The CH_3OH emission was detected from $J = 4$, 5, 6, 7, and 8, $\Delta J = 0$, $K = 2 \rightarrow 1$, transitions as shown in Table 1 and Figure 1. The emission appears centered on $\alpha(1950) = 05^h32^m48^s$ and $\delta(1950) = -5°24'20''$. The angular extent of the $J = 6$ and 7 lines was investigated by observing a grid of points surrounding the peak position and was found to be less than our beamwidth. The $J = 6$ and 7 lines were also observed with a frequency resolution of $\sim$50 kHz and were found to have full widths of 150 ± 25 kHz. Attempts were made to observe the $J = 2$, 3, and 9 lines without success: upper limits are 0.4° K for the $J = 2$ and 9 lines, and 2° K for $J = 3$ (because the observations were made in poor weather).

A number of other sources were searched for the CH_3OH emission at the $J = 7$ line. The results were negative, and the parameters of the search are given in Table 2. The velocity ranges given are for the $J = 7$ transition of CH_3OH, but can be converted to the $J = 1 \rightarrow 0$ transition of N_2O by subtracting 19.5 km s^{-1}.

III. DISCUSSION

The structure of CH_3OH is such that the transitions of the E_1 group which have $\Delta J = 0$, $K = 2 \rightarrow 1$, and $\tau = 1 \rightarrow 2$ occur at frequencies between 16 and 31 GHz for J-values between 2 and 30, with many concentrated near 25 GHz. This allows the study of many rotational levels of CH_3OH with a common receiving system, thereby giving reliable intensity ratios between the various J-states. This provides a valuable probe of the state of excitation of the CH_3OH molecule.

The spectral antenna temperature response $\Delta T_A(\nu)$ due to a resonance transition can be written as

$$\Delta T_A(\nu) = \eta(T_{ex} - T_c)[1 - \exp(-\tau_\nu)] , \quad (1)$$

where η is a factor which includes the antenna efficiency and the fact that the source is smaller than the antenna beamwidth, T_{ex} is the excitation temperature of the CH_3OH,

1971ApJ...168L.101B

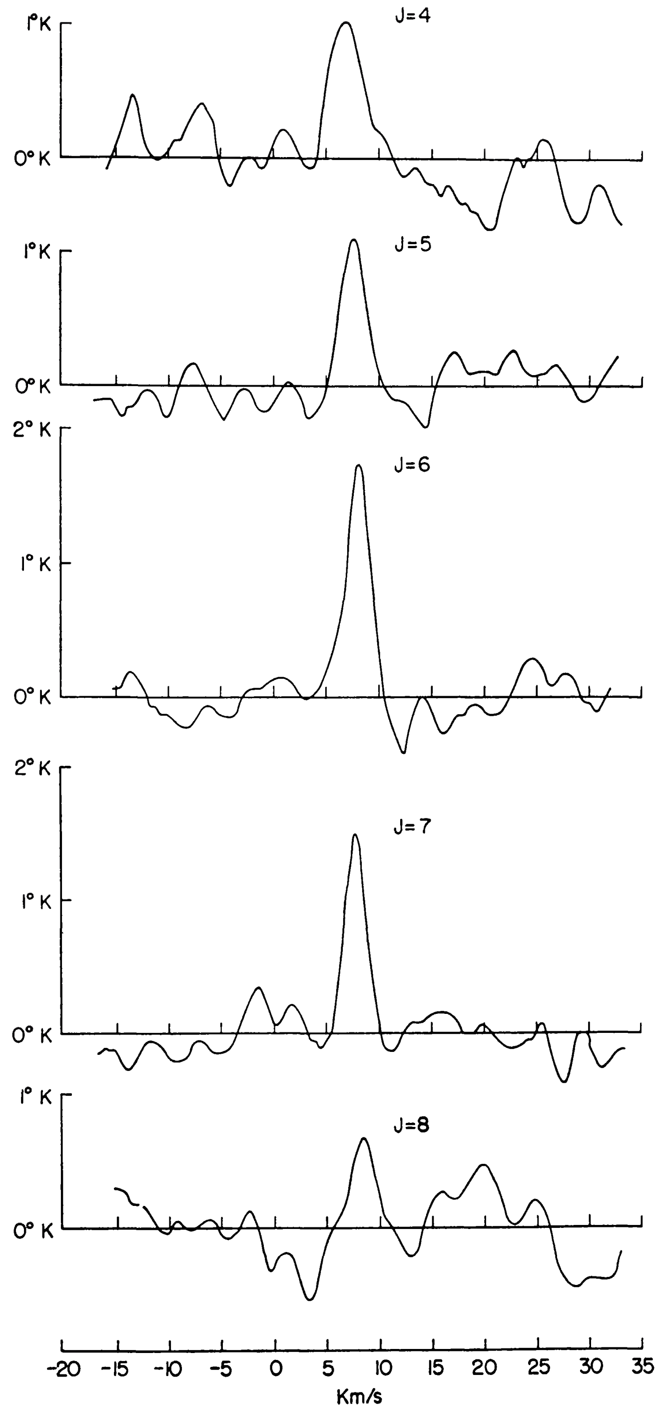

FIG. 1.—Observed spectra of the $J = 4, 5, 6, 7$, and 8, $\Delta J = 0$, $K = 2 \rightarrow 1$ transitions of CH_3OH in the Orion A infrared nebula. The frequency resolution is 167 kHz or 2 km s^{-1}. The vertical axes have been multiplied by a factor of 2 because of superheterodyne detection.

TABLE 2

NEGATIVE RESULTS OF CH_3OH SURVEY

Object	α(1950)	δ(1950)	Velocity Range Searched (km s^{-1})	Peak-To-Peak Noise (°K) Single Sideband
Cloud 127.7............	$02^h04^m31^s$	75°55′07″	−21 to + 59	1.0
W3....................	02 21 51	61 52 12	−61 to + 19	2.0
W3 OH..............	02 23 17	61 38 54	−66 to + 14	1.0
Cloud 2...............	04 38 32	25 18 23	−21 to + 59	1.0
IRC 50137............	05 07 20	52 48 48	−21 to + 59	1.0
VY CMa..............	07 20 53	−25 40 24	−48 to + 32	0.8
IRC+10216...........	09 45 18	13 30 36	−53 to + 27	1.0
CIT−6...............	10 13 12	30 49 24	−40 to + 40	1.0
RX Boo...............	14 21 58	25 55 54	−54 to + 26	0.8
Sgr A..................	17 42 28	−28 58 30	−21 to + 59	0.6
Sgr B2................	17 44 11	−28 23 48	+44 to +129	0.4
	17 44 11	−28 22 30	+25 to +105	0.6
R Aql.................	19 03 58	08 09 06	+ 8 to + 88	1.0
W49 (N)..............	19 07 50	09 01 20	−40 to + 40	0.8
W51..................	19 21 27	14 24 30	+34 to +114	0.8
NML Cyg.............	20 44 34	39 55 54	−59 to + 21	1.0
Cloud 114.............	22 35 47	74 58 28	−21 to + 59	1.0
Cas A.................	23 21 12	58 32 40	−61 to + 19	1.0

T_c is the brightness temperature of all radiation originating beyond the line source, and τ_ν is the optical depth. The optical depth is given by

$$\tau_\nu = \frac{hc^2 A_{ij} f(\nu)}{8\pi k T_{\text{ex}} \nu} \int n_{J,K} dl \,, \tag{2}$$

where A_{ij} is the transition probability and is tabulated in Table 1, $n_{J,K}$ is the number density in the *upper* level of the transition, and $f(\nu)$ is a line-shape function which, for a Doppler-broadened line, is given by

$$f(\nu) = \frac{2}{\Delta\nu}\left(\frac{\ln 2}{\pi}\right)^{1/2} \exp\left[(-4 \ln 2)\left(\frac{\nu - \nu_0}{\Delta\nu}\right)^2\right] , \tag{3}$$

where $\Delta\nu$ is the full width at half-maximum of the line. If LTE is assumed, then $T_{\text{ex}} = T$, the kinetic temperature, and $n_{J,K}$ can be related to the total number of CH_3OH molecules n_T by the usual relation

$$n_{J,K} = \tfrac{1}{4} n_T \left[\sum_{J=0}^{\infty} \sum_{K=0}^{J} g_K (2J + 1) \exp(-E_{K,\tau,J/kT})\right]^{-1} \times g_K(2J + 1) \exp(-E_{K,\tau,J/kT}) \,, \tag{4}$$

where the sums are taken only over the E_1 series of energy levels, $g_K = 2$ for $K \neq 0$ and $g_K = 1$ for $K = 0$. The energy of the K, τ, J level in the ground vibrational state is given by

$$E_{K,\tau,J} = E_{K,\tau} + a[J(J + 1) - K^2] + bK^2 \,; \tag{5}$$

and $E_{K,\tau}$ is tabulated by Ivash and Dennison (1953) or Burkhard and Dennison (1959), $a = 0.8066$ cm^{-1}, and $b = 4.2544$ cm^{-1}.

The detection of five CH_3OH transitions provides a critical test of whether or not the levels are populated in thermal equilibrium at a temperature T. The observed intensities, given in Table 1, require that $\tau_5 < \tau_7 < \tau_6$, which in turn requires that the kinetic temperature T be between 82° and 100° K. However, these values for T imply that the $J = 4$ and $J = 8$ transitions should be stronger than observed. Thus a true thermal equilibrium is not attained, but the departures from thermal equilibrium do not appear great. Indeed, departures from LTE are to be expected because the molecule has components of its dipole moment both parallel and perpendicular to its symmetry axis; thus many transitions are allowed which serve to empty the rotational levels relatively quickly. For example, the radiative lifetime of the $J = 7$, $K = 2$ level is 2.81×10^3 s, and that of the $J = 7$, $K = 1$ level is only 640 s.

Our observations can only place an upper limit on the angular size of the emitting region of approximately 1 arc minute. Furthermore, we cannot distinguish whether the source is coincident with the infrared nebula (Kleinmann and Low 1967), the infrared point source (Becklin and Neugebauer 1967), or the OH sources (Raimond and Eliasson 1967), as they are all within 1 arc minute of each other. If subsequent observations reveal that the CH_3OH emission originates from point sources, typical of the OH and H_2O, then it must be concluded that the CH_3OH is populated in a nonthermal manner and is another maser source. However, the existence of five lines with intensities within a factor of 2 of those to be expected from LTE considerations seems to argue against a maser phenomenon in this case.

It is interesting to speculate that the CH_3OH emission actually originates in the infrared nebula discovered by Kleinmann and Low (1967). This speculation is given some measure of credence by the fact that the infrared flux at 22 μ suggests a temperature of $\sim$70° K whereas the CH_3OH observations suggest a temperature of $\sim$90° K. Kleinmann and Low find that the infrared nebula is greater than 30″ in size. If this is taken as representative of the CH_3OH emitting region, then equations (1)–(5) can be solved for the column density of CH_3OH molecules. Adopting $\eta = 0.10$, $T_{ex} = T = 90°$ K, $T_c = 3°$ K, we find

$$\int n_T dl \simeq 5 \times 10^{16} \text{ molecules cm}^{-2} .$$

Typical optical depths are in the range 0.08–0.20. Given that the nebula is 500 pc distant, then its linear size is $\sim 2 \times 10^{17}$ cm, which in turn implies a CH_3OH density of 0.25 molecules cm^{-3} if a uniform distribution is assumed. Needless to say, this is a large density by molecular standards.

A limit on the total gas density can be derived from the fact that the CH_3OH transitions appear to be in approximate LTE. For this to occur, the collisions must be more frequent than the radiative transitions in an optically thin medium, or $R_{ij} = n_{H_2} \sigma v > (1/T)$, where T is a typical radiative lifetime of a level, n_{H_2} is the total gas density, and σ is the cross-section for collisional excitation. Because of the high densities involved, the electron density is expected to be small and electron collisions have been neglected. Taking $T \simeq 2.8 \times 10^3$ s, $\sigma = 10^{-15}$ cm ^{2} (the geometrical cross-section), and v as 10^5 cm s^{-1} appropriate for H_2 at 90° K, one finds

$$n_{H_2} > 2 \times 10^6 \text{ cm}^{-3} .$$

This value, coupled with the previously determined number density of CH_3OH molecules, gives a density ratio of

$$\frac{n_{CH_3OH}}{n_H} < 5 \times 10^{-8} ,$$

a result quite consistent with current ideas about molecular abundances relative to atomic hydrogen. The determination of the H_2 density allows the total mass of gas in the nebula to be computed, the result being $> 20\ M_\odot$. This value can be compared with a lower limit deduced by Hartmann (1967) of 12 $M_\odot$. In fact, Hartmann concludes that the total mass of gas should be considerably greater, between 10^2 and 10^3 $M_\odot$. Similar results are given by Harper and Low (1971) for other infrared sources in H II regions. Thus our lower limit on the total mass of gas is consistent with estimates arrived at from analysis of totally different data.

The infrared nebula in Orion appears to be intimately associated with several molecules detected recently by their radio spectra, all at a velocity of 8–8.5 km^{-1}. Thaddeus *et al.* (1971) have studied CH_2O, Penzias *et al.* (1971) have studied CS, Wilson *et al.* (1970) have studied CO, and HCN has been studied by Snyder and Buhl (1971). In all these cases, however, the line emission was found to occur over a region of the sky appreciably larger than the infrared nebula, typically 3 arc minutes or more, whereas our CH_3OH observations appear to originate from a region less than 1 arc minute in size. Another difference is that our derived total gas density is a factor of 10 greater than those derived from the CH_2O and CS observations, although all conclude that the microwave transitions are collisionally excited. This difference is attributed to the fact that the CH_3OH lines arise from more highly excited energy levels than the other molecules and hence need a greater gas density to maintain a detectable population in these levels. It is tempting to speculate that the more complex molecules are formed in the central regions of the infrared nebula where the density is significantly higher. Subsequent microwave observations of other molecules may bear this out. In any event, the CH_3OH molecule is particularly attractive for probing the physical conditions of sources like the Orion infrared nebula because the $\Delta J = 0$ transitions for different J's cluster near 25 GHz and permit observation by a common receiving system. As an example, the $J = 4$, $K = 2$ level is $\sim$31 cm^{-1} above the E_1 ground state and the $J = 8$, $K = 2$ level is $\sim$76 cm^{-1} above the ground state, yet the $J = 4$ and $J = 8$, $\Delta J = 0$, $K = 2 \rightarrow 1$, transitions are within 360 MHz of each other.

We would like to express our appreciation to K-Y Lo for assistance with the observations and computations, and to the staff of the Haystack Observatory for technical support. Haystack Observatory is operated by the Northeast Radio Observatory Corporation for the Massachusetts Institute of Technology with support of the National Science Foundation (grant GP-25865). The authors were supported in part by the National Science Foundation (grant GP-20769) and by the National Aeronautics and Space Administration (grant NGL-22-009-016).

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