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NEW INTERSTELLAR METHANOL LINES

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ABSTRACT

Interstellar methanol lines at $\lambda = 2$ mm, produced by the $J = 3 \rightarrow 2$, $\Delta K = 0$ transitions, have been observed in Ori A, Sgr A, Sgr B2 and DR 21(OH). The Ori A source appears to be less than 1′ in extent, with a methanol excitation temperature of $\sim 90°$ K and a column density of $\sim 4 \times 10^{15}$ cm^{-2}.
Subject heading: molecules, interstellar

Methanol has now been observed at over 20 wavelengths and is apparently one of the most abundant interstellar polyatomic molecules. We have detected at a wavelength of 2 mm a new series of methanol lines, produced by the $J = 3 \rightarrow 2$, $\Delta K = 0$ transitions (fig. 1), which in several respects are among the most useful probes yet found for the investigation of very dense regions. These lines appear first of all to be fairly common, having been detected in all four sources observed; they are highly sensitive to excitation conditions since they arise from levels of widely different energies; yet they lie within a frequency interval of only 40 MHz (table 1) and so can be observed simultaneously with existing multichannel receivers. This is a particularly valuable property from a practical standpoint since it permits accurate measurement of intensity ratios, and hence excitation temperatures.

Our observations were made with the NRAO[1] 36-foot (11-m) telescope. The half-power beamwidth was 60″, and the beam efficiency 0.6; spectral resolution was provided by a 50-channel filter bank with filters 1.2 MHz wide, spaced 1.2 MHz apart. Flat baselines were obtained by frequency switching at 10 Hz while simultaneously beam switching once per minute. The lines observed in the center of the Ori A molecular cloud are shown in figure 2. Some structure apparently exists in this source: 1′ south the lines were only marginally detected, but 2′ south they reappeared. Lines were also observed in Sgr B2, Sgr A and DR 21(OH), at locations of 2-mm formaldehyde emission (Thaddeus *et al.* 1971; Kutner 1972). A summary of the observational data is given in table 1.

It is in the Ori A molecular cloud that the 2-mm methanol lines, because of their good signal-to-noise and narrow width, provide the most revealing insight into physical conditions. Observations of millimeter-wave molecular lines have furnished strong evidence that the density in this source is extremely high ($\gtrsim 10^5$ cm^{-3}) by interstellar standards. With the exception of CO, which is so abundant and easily excited that it is seen over a wide area, such lines in Orion originate in a small source several arc minutes (~ 0.5 pc) in size, centered on the Kleinmann-Low infrared nebula, Becklin's infrared star, and the maser point sources of OH and H_2 emission.

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[1] Operated by Associated Universities, Inc., under contract with the National Science Foundation.

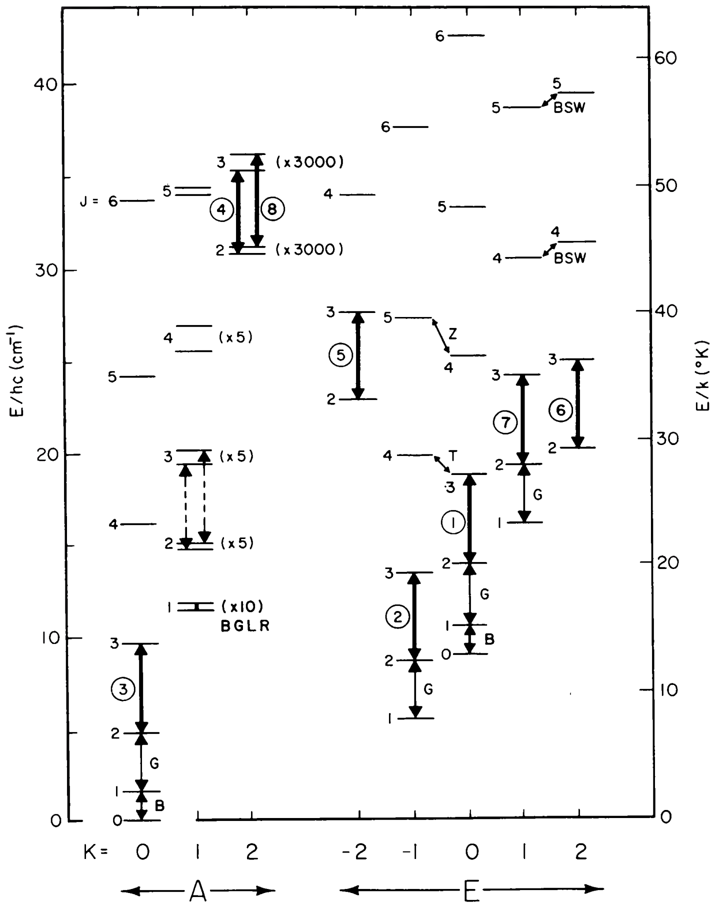

FIG. 1.—Lower rotational energy levels of methanol. The encircled numbers indicate the observed 2-mm transitions (see table 1); doublet splittings are magnified by the numbers in parentheses. Other observed interstellar methanol transitions are also shown: B = Barrett *et al.* 1972); G = Gottlieb 1972; BGLR = Ball *et al.* 1970; T = Turner *et al.* 1972; Z = Zuckerman *et al.* 1972; BSW = Barrett *et al.* 1971.

TABLE 1

THE $J = 3 \rightarrow 2$, $\Delta K = 0$ METHANOL LINES

		ANTENNA TEMPERATURES (° K)				
		Ori A				
Line	REST FREQUENCY* (MHz)	KL Neb.	2′ S	DR 21 (OH)	Sgr A	Sgr B2
...	143,865.79					
1	145,093.75	1.25	0.4	0.3		
2	145,097.47	1.45	0.9	0.7	0.8†	2.2†
3	145,103.23	1.35	1.5	1.1		
4	145,124.41 }					
5	145,126.37 }	1.45	0.6	0.5		
6	145,126.37 }					1.7‡
7	145,131.88 }	1.25	0.6	0.3		
8	145,133.46 }					
...	146,368.30					

* Lees *et al.* 1973. † Blend of lines 1–3. ‡ Blend of lines 4–8.

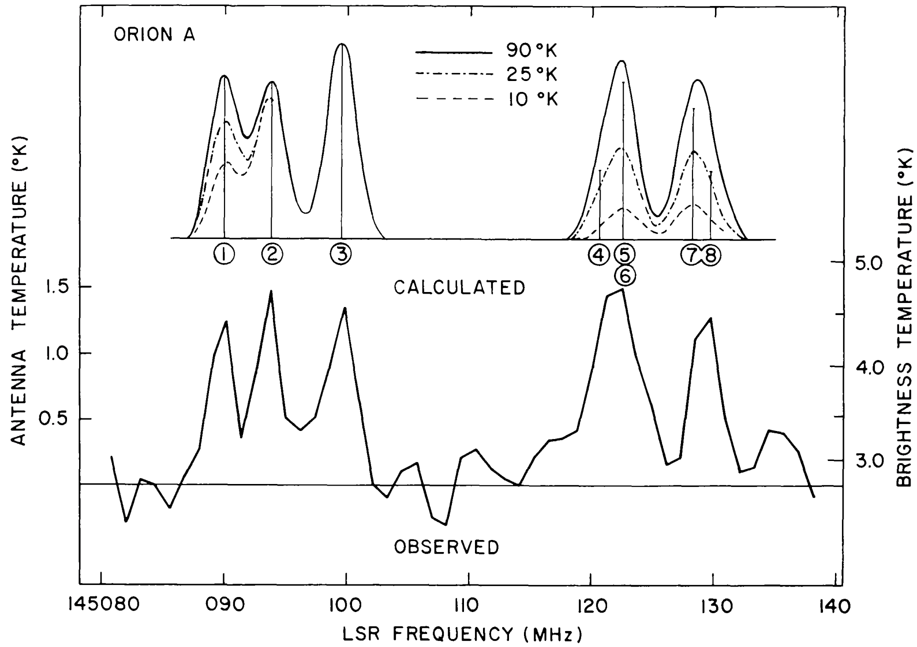

FIG. 2.—The observed 2-mm methanol lines in the Kleinmann-Low Nebula [$\alpha(1950) = 5^h32^m46.9^s$, $\delta(1950) = -5°24'26''$]. The frequency of the lines corresponds to an LSR velocity of $+7.5$ km s^{-1}. Above are theoretical spectra calculated for optically thin lines and rotational thermal equilibrium. The vertical lines indicate relative intensities for 90° K excitation.

As figure 2 shows, the relative intensities of the 2-mm methanol lines in the center of the Ori A molecular cloud are remarkably well accounted for by the simplest possible model of line formation: optically thin lines, produced by levels in rotational equilibrium. The excitation temperature T_{ex} is apparently about 90° K. A higher temperature cannot be entirely excluded by our observations, since above 90° K the relative intensities of the 2-mm lines are rather insensitive to T_{ex}, but it would conflict seriously with the observations of the 1-cm, $K = 2 \rightarrow 1$ lines (Barrett, Schwartz, and Waters 1971). For a 90° K excitation temperature the 2-mm lines yield a methanol column density (averaged over the 1′ beam) of

$$N_{CH_3OH} \approx 4 \times 10^{15}\ \mathrm{cm}^{-2}, \quad (1)$$

in agreement with Barrett *et al.* (1971), and only a factor of 2 less than the best estimates of the column density of HCN.[1] Methanol is evidently then one of the most abundant interstellar polyatomics so far discovered, and in view of the uncertainties in the excitation it may even in fact be the most abundant.

Numerical experiments which we have done on excitation of methanol by H_2 impact, with various model cross-sections, indicate that while a number of the lower-frequency transitions, in particular the 1-cm ones, are subject to pumping, the excitation temperatures of the 2-mm transitions rise together, monotonically as a function of density, from the background radiation temperature to the kinetic temperature. Quasi-equilibrium of the 2-mm transitions at temperatures below T_{kin} is therefore possible: for example, if the kinetic temperature were several hundred degrees, a total density in

[1] The unidentified line U169.3 (Wilson *et al.* 1972) is now almost certainly the 10_1–$10_0(E)$ methanol line, since at the excitation temperature and column density we derive, the predicted intensity of this line is almost exactly that observed.

the range 10^6–10^7 would produce the observed 90° K excitation temperature. However, if T_{ex} is close to T_{kin}, a total (presumably H_2) density of almost 10^8 cm^{-3} is required.

Our limited mapping in Orion indicates that the peak methanol emission source may be less than 1 arc minute in diameter. If we assume the source to be a homogeneous cloud which does not fill our beam, then a lower limit on the source size can be obtained by noting that

$$\frac{\Omega_s}{\Omega_a} \geqslant \frac{T_A}{\eta T_{ex}} \approx 1/36, \tag{2}$$

where Ω_a and Ω_s are the solid angles of the main antenna beam and of the source and η is the beam efficiency; the equality holds if the lines are optically thick. The source must therefore be greater than 10″ (~ 0.02 pc) in diameter, which suggests that the emission comes from a region about the size of the infrared nebula (~ 30″). A density then of 10^8 corresponds to a total mass of 1000 $M_\odot$, at the upper end of the range of masses considered reasonable for this object (Hartmann 1967; Kleinmann and Low 1967).

These observations therefore provide strong evidence for the existence of a dense (10^7–10^8 cm^{-3}), hot ($T_{kin} > 90°$ K) core in the Ori A molecular cloud. The structure we observe seems to indicate that there may exist other condensations as well, though the KL nebula is certainly the most prominent. The small source and high excitation temperature are sufficient to explain why Barrett *et al.* (1972) do not detect the $J = 1 \rightarrow 1$–0 lines in Ori A, while detecting them in Sgr B2—a more extended source which has lower excitation temperatures.

Finally, these new methanol lines demonstrate forcefully a proposition which so far has been largely assumed in the analysis of millimeter molecular emission lines in Ori A: that, at least in the central core, the excitation temperatures of such transitions are at least several tens of degrees, and that weak lines are the result of low optical depth.

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