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THE DETECTION OF THE 4_{-1}–3_0 E TRANSITION OF METHANOL AT 36.2 GHz TOWARD HOT H II REGIONS

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ABSTRACT

Using Haystack Observatory at 36.169240 GHz, we have detected the 4_{-1}–3_0 E transition of methanol toward 26 H II regions. The strong emission lines have narrow velocity components, thus exhibiting some of the characteristics of maser emission, as well as broader features which are assumed to be thermal in origin. The methanol emission preferably occurs in molecular clouds associated with hot H II regions and has not been detected in cold dark cloud regions or late-type stellar sources. The characteristics of the emission are discussed.

Subject headings: interstellar: molecules — line identifications — nebulae: H II regions

I. INTRODUCTION

Maser emission in the J_2–J_1 (J = 4–8) series of E-type methanol was detected initially in Orion K-L by Barrett, Schwartz, and Waters (1971). This has remained the sole source of detected methanol maser emission until fairly recently when the cloud associated with the H II region W3(OH) was shown to exhibit strong maser emission in the 9_2–10_1 A^+ and 2_1–3_0 E transitions (Wilson *et al.* 1984, 1985). The maser emission which is characterized by line widths of 0.3–2 km s^{-1} is shown to be superposed on the 23 GHz continuum and intermingled with the OH maser emission mapped by Reid *et al.* (1980; also see Menten *et al.* 1985). Morimoto, Ohishi, and Kanzawa (1985) have claimed to have discovered maser emission in the 4_{-1}–3_0 E and 7_0–6_1 A^+ lines toward Sgr B2 and three other galactic sources; however, these methanol lines have very different characteristics from those of the other OH, H_2O, and CH_3OH maser sources. The emission is extended, has line widths of 10–20 km s^{-1}, and does not apparently arise from clouds associated with star-forming regions or stellar envelopes. In order to investigate this phenomenon further we have searched 53 Galactic sources including molecular clouds associated with compact H II regions, dark clouds, and late-type stellar sources displaying SiO and OH maser emission, for the 4_{-1}–3_0 E transition of methanol. We have detected this transition toward 26 Galactic H II regions but not in dark clouds or late-type stars. Narrow emission suggestive of maser action was detected in six sources.

II. OBSERVATIONS

The 53 molecular clouds associated with Galactic H II regions, dark clouds, and late-type stars were observed using the Haystack Observatory 120 ft antenna in Westford, Massachusetts, in 1987 June, July, and December and 1988 April. The antenna was equipped with a 35.5–49 GHz maser preamplifier receiver having a system temperature of $\sim$130 K at the rest frequency of 36.169240 GHz of the 4_{-1}–3_0 E line of methanol. The 1024 channel auto correlator provided a channel width of 0.5 km s^{-1} at the 20 MHz bandwidth which gives a velocity coverage of 166 km s^{-1} and a width of 0.3 km s^{-1} at the 13 MHz bandwidth. The antenna has an aperture efficiency of 0.14 (19 Jy/K) and a beamwidth of 56″ at this frequency. The sources are observed using the total power mode having a scan duration of 3 minutes. The results presented here represent a 30 minute on-source integration time. The data was corrected for both gain and atmospheric variations.

III. RESULTS

The sources observed are presented in Table 1 and Table 2. Emission was detected toward 26 Galactic H II regions and are listed in Table 1 where the uncertainties are the 1 σ errors of the Gaussian fits and the nondetections are given in Table 2. In Figure 1 the spectra for the detections are shown. Individual sources are discussed below.

a) Sgr A-G

Sgr A-G is a continuum source close to the Galactic center source (Ho *et al.* 1985) and displays the most intense detection of CH_3OH in the 4_{-1}–3_0 transition of our sample. The shape of the profile is similar to that seen in other molecules but its velocity width of 12 $\pm$ 0.4 km s^{-1} is narrower than that seen for NH_3, HNCO, ^{13}CO, $C^{18}O$ (Armstrong and Barrett 1985), and SiO (Haschick and Ho 1989). The narrower than usual velocity width of this line suggests that this feature may represent a cloud or clouds with an inverted population which may be partially amplifying the background radio continuum. A five-point, half-beamwidth map of this source (Fig. 2) shows that the profile changes shape on a small spatial scale, and this may indicate that compact features partially comprise the spectrum. At the position of Sgr A-F (2′ North of Sgr A-G) Szczepanski *et al.* (1989) have indeed detected three or four narrow spikes superposed on the broader emission profile.

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b) *Sgr B2*

This source was initially detected in this transition by Morimoto, Ohishi, and Kanzawa (1985), who detected strong emission at a position 40″ to the northwest. They ascribe the intense emission to maser action although the source is extended by ~90″. In a five-point half-beamwidth map we find evidence for a narrower component at 70 km s^{-1} superposed on the broader (22 km s^{-1} wide) emission.

c) *Orion A and Orion S*

The profile for Orion A given in Figure 1 shows a narrow, intense feature (2 km s^{-1} wide) having a weaker blueshifted plateau or wing extending by ~10 km s^{-1} from the 8 km s^{-1} feature. This weak high-velocity outflow is also indicated in the formaldehyde observations of Bastien *et al.* (1985).

The source Orion S lying 1′.5 south of the Orion A position has been detected and mapped in ammonia (Batrla *et al.* 1983), SO_2 (Irvine, Good, and Schloerb 1983), silicon monoxide SiO ($v = 0$, $J = 2 \rightarrow 1$; Ziurys and Friberg 1987), H_2CO (Johnston *et al.* 1983); also, SiO ($v = 0$, $J = 1 \rightarrow 0$) has been detected at this position (Haschick and Ho 1988). The velocities of the present detection of methanol and silicon monoxide ($v = 0$, $J = 1 \rightarrow 0$) agree but the line width is 6 km s^{-1} for the SiO and 3.3 ± 0.2 km s^{-1} for the methanol. If we assume that the 6 km s^{-1} represents the thermal width of the line, the narrower width of the methanol may be an indication of the nonthermal behavior of the 4_{-1}–3_0 transition of methanol. This is also possibly true for Orion A where the methanol feature is 4 times stronger than that for Orion S and the width of 1.8 ± 0.03 km s^{-1} is less than that of the ridge component of ~ 4 km s^{-1} as seen in other molecules (Welch 1988).

d) *W75S/W75N*

The profile for W7S is unusual in that we have a narrow spike at 0.4 km s^{-1} having a velocity width of 0.6 km s^{-1} superposed on a weaker broader feature centered at −3.3 km s^{-1} having a width of 4 km s^{-1}. This situation is similar to what is seen for the 5_{-1}–4_0 *E* transition at 84.5 GHz in this source (Menten *et al.* 1988), in which case we have a narrow spike feature protruding from a broad plateau of thermal emission. The broad thermal emission is concentrated in a compact clump which is offset from the maser position in both transitions.

In W75N only a single component is present in the line of width 3 km s^{-1} and centered at 9.5 km s^{-1}, which is the cloud velocity.

e) *NGC 2071*

This source has a profile similar to that seen in W75S with two narrower features of 0.6 and 1.5 km s^{-1} in width on top of a broader plateau component extending from 5 to 15 km s^{-1}. The two narrow features in Figure 1 are blended but at higher velocity resolutions, are seen to be well resolved.

TABLE 1

DETECTIONS OF THE 4_{-1}–3_0 *E* TRANSITIONS OF METHANOL

	COORDINATES				
SOURCE	R.A. (1950)	Decl. (1950)	T_{mb}[a] (K)	V_{LSR} (km s^{-1})	ΔV (km s^{-1})
W3 (OH)	$2^h23^m17^s.3$	61°38′58″	1.3 ± 0.1	−46.5 ± 0.1	2.1 ± 0.2
Orion A	5 32 47..0	−5 24 23	13.6 ± 0.2	7.8 ± 0.05	1.8 ± 0.03
Orion S	5 32 44.8	−5 26 0	1.5 ± 0.1	6.9 ± 0.1	3.3 ± 0.2
OMC 2	5 32 59.9	−5 11 29	5.0 ± 0.4	11.2 ± 0.02	0.45 ± 0.04
S235	5 37 31.8	35 40 18	3.4 ± 0.3	−16.6 ± 0.04	0.9 ± 0.1
NGC 2024	5 39 11.4	−1 55 59	1.0 ± 0.3	10.5 ± 0.2	1.2 ± 0.4
NGC 2071	5 44 30.0	0 20 40	8.6 ± 0.4	14.6 ± 0.02	0.6 ± 0.04
NGC 2071	...	...	5.8 ± 0.2	16.2 ± 0.06	1.2 ± 0.2
G188.9+0.9	6 5 54.0	21 39 9	1.2 ± 0.2	3.5 ± 0.2	2.6 ± 0.4
NGC 2264	6 38 24.0	9 32 0	6.7 ± 0.2	7.3 ± 0.02	0.6 ± 0.05
NGC 2264	...	...	1.1	8.5	5.1
NGC 2264G	6 38 28.0	9 32 12	2.3 ± 0.2	7.5 ± 0.1	3.6 ± 0.3
NGC 6334F	17 17 32.3	−35 44 4.0	5.5 ± 0.5	−8.7 ± 0.1	3.8 ± 0.3
NGC 6334F	...	...	5.7 ± 0.4	−4.6 ± 0.1	2.1 ± 0.2
Sgr A-G	17 42 27.3	−29 4 35.8	17.8 ± 0.2	11.5 ± 0.06	7.4 ± 0.2
Sgr A-G	...	...	6.7 ± 0.2	2.8 ± 0.2	9.3 ± 0.4
Sgr B2	17 44 10.6	−28 22 5.0	21.7 ± 0.4	70.4 ± 0.2	6.8 ± 0.4
Sgr B2	...	...	13.9 ± 0.2	62.6 ± 0.2	22.4 ± 0.3
G10.6−0.4	18 7 30.5	−19 56 28.4	8.6 ± 0.5	−6.0 ± 0.03	1.0 ± 0.1
W33A	18 11 44.5	−17 52 56	1.6 ± 0.2	36.2 ± 0.3	4.6 ± 0.7
G30.8−0.1	18 45 11.0	−1 57 57	11.0 ± 0.2	98.5 ± 0.04	5.5 ± 0.1
G34.3+0.2	18 50 46.2	1 11 12	2.1 ± 0.1	57.8 ± 0.3	5.1 ± 0.6
W48	18 59 13.8	1 9 13	(0.3)	44.2	7.3
G43.8−0.1	19 09 31.2	9 30 51	(0.3)	43.0	4.7
W51 N	19 21 26.2	14 25 13	0.8 ± 0.3	59.8 ± 0.1	2.8 ± 0.2
W51 M	19 21 36.2	14 24 43	4.4 ± 0.1	55.2 ± 0.1	6.8 ± 0.2
ON 1	20 08 9.9	31 22 42	1.7 ± 0.2	11.0 ± 0.1	2.4 ± 0.3
W75 N	20 36 50.4	42 27 1	2.8 ± 0.1	9.5 ± 0.4	2.9 ± 0.5
W75 S	20 37 13.8	42 12 13	7.0 ± 0.4	0.4 ± 0.04	0.56 ± 0.1
W75 S	...	...	1.9 ± 0.2	−3.3 ± 0.15	3.9 ± 0.4
NGC 7538IR	23 11 36.7	61 11 49	2.3 ± 0.3	−57.4 ± 0.3	3.7 ± 0.7
NGC 7538S	23 11 36.1	61 10 33	4.4 ± 0.3	−55.9 ± 0.1	2.8 ± 0.2

[a] $T_{mb} = T_{A/0.18}$.

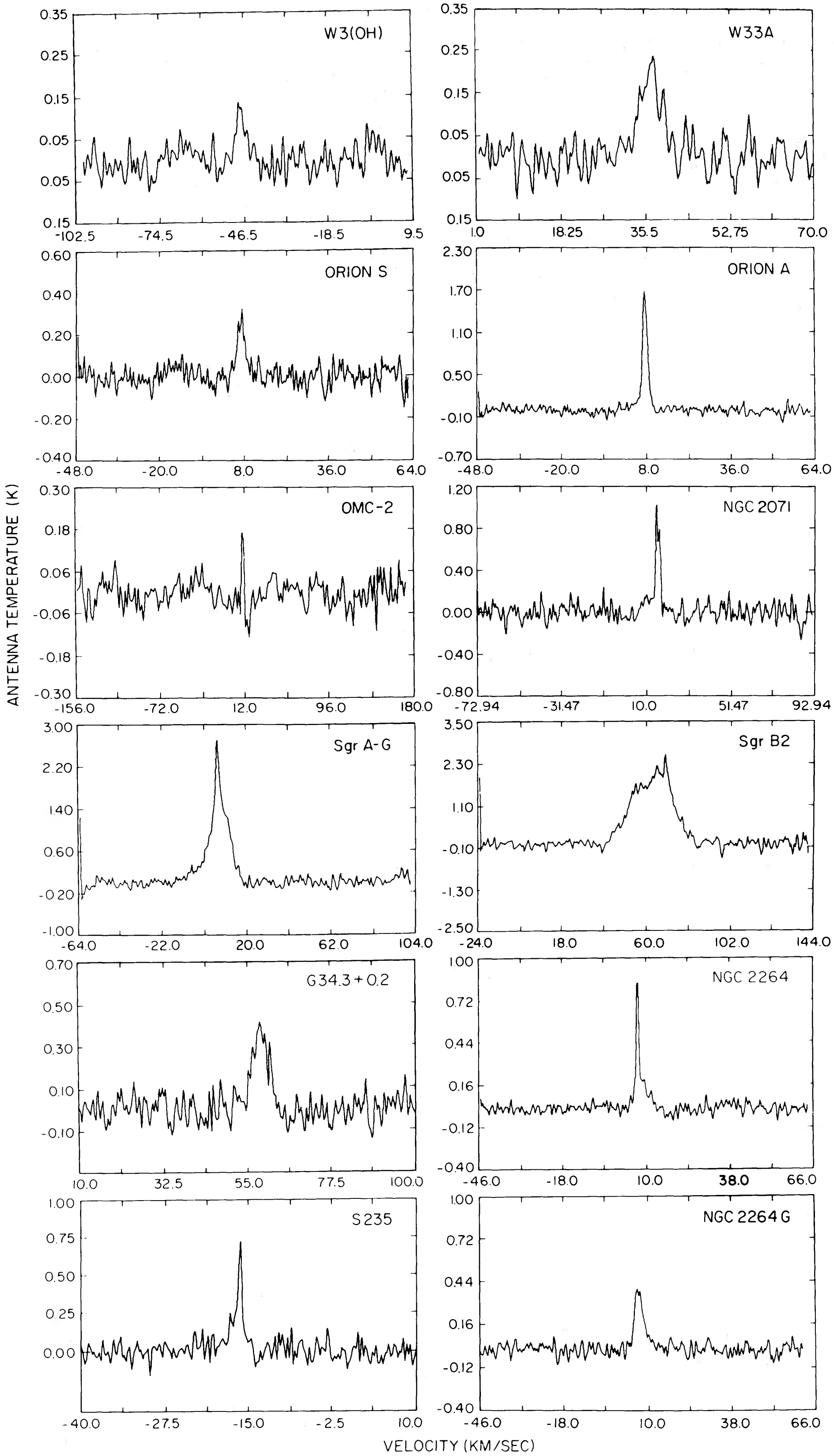

FIG. 1*a*

FIG. 1.—(*a*) Spectra of the 4_{-1}–3_0 *E* transition of methanol in the detected sources. The bandwidths used were 20 MHz and 13 MHz, giving resolutions of 0.5 and 0.3 km s^{-1}, respectively. The integration time was 30 minutes per spectrum. (*b*) Same as for (*a*).

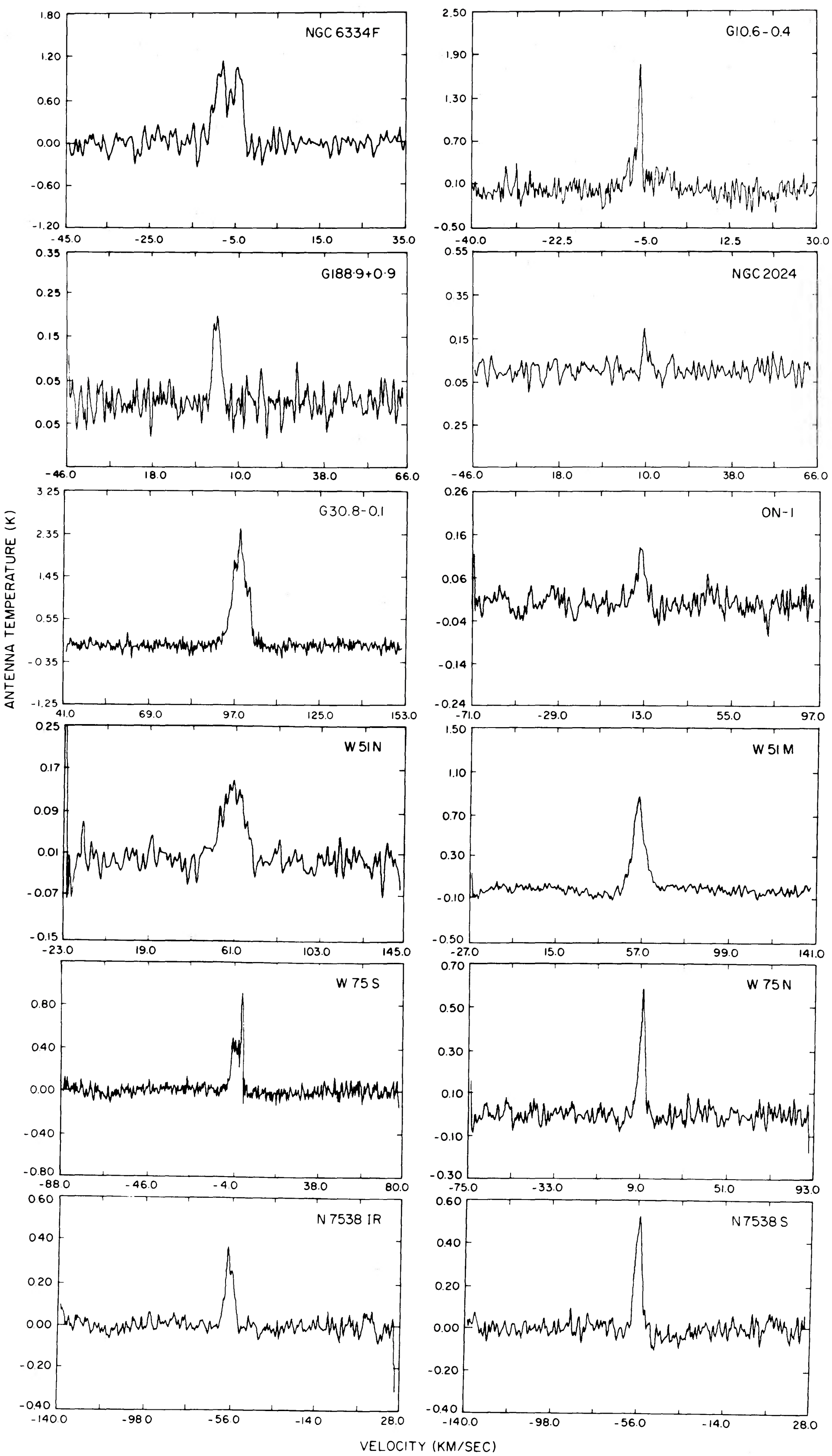
NGC 6334F
G10.6-0.4
G188.9+0.9
NGC 2024
G30.8-0.1
ON-1
W 51 N
W 51 M
W 75 S
W 75 N
N 7538 IR
N 7538 S
ANTENNA TEMPERATURE (K)
VELOCITY (KM/SEC)

FIG. 1*b*

TABLE 2

NONDETECTION OF THE 4_{-1}–3_0 *E* TRANSITION OF METHANOL

Source	Coordinates R.A. (1950)	Decl. (1950)	V_{LSR} (km s^{-1})	ΔT_{mb}[a] (K)
S187 IRS	01^h19^m58^s.0	61°33′03″	−15	1.5
HH 7-11	03 25 58.0	31 05 45	8	0.5
L1551 IR	04 28 40.0	18 01 52	6	0.5
TMC 1 (NH3)	04 38 20.0	25 42 00	5.9	0.5
Orion (3N)	05 32 47.0	−5 21 23	8	2.0
GGD 4	05 37 21.8	23 49 24	−2	0.5
Mon R2	06 05 22.0	−6 22 25	10	0.8
GGD 12	06 08 25.7	−6 10 49.5	−8	2.0
S255	06 10 01.0	18 00 00	7.2	0.8
VY CMa	07 20 55.0	−25 40 11	20.0	2.5
OH 0739	07 40 0	−14 36 00	0	0.5
R Leo	09 44 52.0	11 39 42	0	0.8
IRC 10216	09 45 14.8	13 30 39	−26	1.0
WHY Dra	13 46 12.2	−28 07 03	39	0.8
L134N	15 51 32.7	−02 42 51	2.4	1.5
L183	15 52 35.7	−7 40 54	2.5	0.5
IR 18383	18 38 32.3	−05 12 00	17	1.0
W49N	19 07 49.8	09 01 17	6	0.8
B335	19 34 34.0	7 27 00	8.2	0.5
K3-50	19 59 50.1	33 24 18	−24	3.0
ON 2	20 19 51.8	37 17 01	−1	1.0
DR 21	20 37 13.0	42 08 50	−2	0.5
NGC 7027	21 05 9.4	42 02 03	0	0.8
S128	21 30 33.6	55 40 11	−75	0.5
S140	22 17 41.2	63 03 43	−7	1.5
Cep A	22 54 23.4	61 45 54	−10	1.5
Cas A	23 21 10.6	58 33 06	−20	0.3

[a] 3 σ upper limit.

f) *W51M/W51N*

W51N is 5 times weaker than W51M, and it has a velocity width which is twice as wide. W51M is found to be slightly extended by ∼40″, and no estimation of any extension in W51N was made.

g) *NGC 2264/NGC 2264G*

This is another case similar to W75S and NGC 2071 where a narrow emission feature is superposed on a broader plateau of emission. The narrow feature is found to have a width of 0.6 km s^{-1} and the weaker plateau a width of 5.1 km s^{-1} In Figure 1 a spectrum of NGC 2264G which is at a position offset by 60″ in R.A. and 12″ in decl. from the maser position and close to the peak of the NH_3 map of Krügel *et al.* (1987), shows a broad feature 3.6 km s^{-1} wide, and is presumably simply the thermal emission from this region.

IV. DISCUSSION

a) *Maser versus Thermal Emission*

The results presented in Table 1 and Figure 1 show that the line profiles exhibit a wide range of widths and intensities and that most of the sources display one single feature. In some cases multiple narrow features occur together with a broader, weaker plateau feature. These characteristics perhaps indicate the presence of both thermal and maser emission in these sources.

The three sources W75S, NGC 2264, and NGC 2071 are particular examples of this phenomenon. Menten *et al.* (1988) detected a narrow maser emission spike superposed on a broad

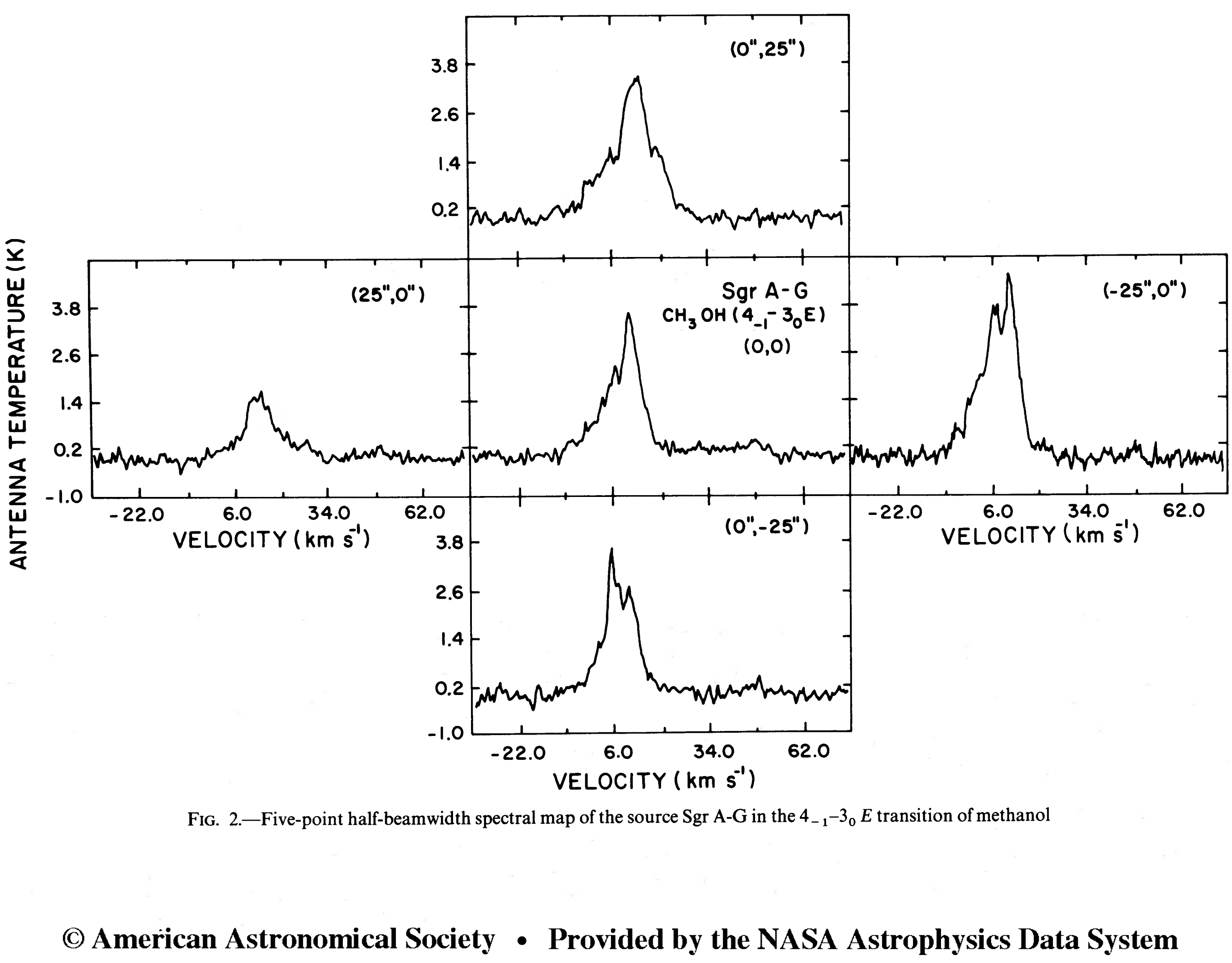

FIG. 2.—Five-point half-beamwidth spectral map of the source Sgr A-G in the 4_{-1}–3_0 *E* transition of methanol

feature in the 5_{-1}–4_0 *E* line at 84.5 GHz toward W75S. This maser feature is pointlike to their 28" beam. They find the broad thermal emission to be concentrated in a compact clump which is offset from the maser position. An identical situation pertains to the 4_{-1}–3_0 *E* transition: the velocities of the maser spikes agree in the two transitions, and the broad thermal emission is found to be also offset in position from the maser spike.

The three sources OMC 2, G10.6−0.4 and S235 also show narrow emission features less than 1 km s^{-1} in width and are presumed to be possible maser sources. A VLBI measurement of the size of the sources is needed to help determine their thermal or nonthermal nature.

It is known that collisions of helium or ground-state H_2 with CH_3OH favor final states with the same *k* value as the initial state (Lees and Haque 1974). In *E*-type methanol this leads to an overpopulation of the $k = -1$ ladder relative to the $k = 0$ or -2 ladders (Walmsley *et al.* 1988). Thus, one expects collisions to lead to inversions of the 5_{-1} to 4_0 and the 4_{-1} to 3_0 transitions. The ground state for the *E* species of methanol is the 1_{-1} energy level. Morimoto, Ohishi, and Kansawa (1985) have made a statistical equilibrium calculation of the 121 lowest levels of CH_3OH for both the *E* and *A* transitions and find that for $T_K = 80$ K and $n(H_2) \sim 10^4$ cm^{-3}, collisional excitation is effective in populating high lying levels and maser action occurs. For lower temperatures, $\sim$40 K, population inversion occurs but no transition had sufficient brightness temperatures to explain their observations. For the case of W75 S we may be seeing a situation where the narrow maser line is produced when hot gas is pumped by collisions and the thermal gas, being offset from the heating IR source, is colder and shows no maser action. In NGC 2264, we find an analogous situation where the narrow maser spike occurs at a position close to the IR source and a broader thermal line is detected (NGC 2264G) at a position close to the molecular cloud peak.

b) Source Characteristics

The 4_{-1} to 3_0 *E* transition of methanol has been detected toward 26 out of a sample of 40 H II regions searched. Thus 65% of the star formation regions showed either thermal or maser methanol emission. Recently Batrla *et al.* (1987) have detected very strong maser emission for the 2_0–3_{-1} *E* transition of methanol at 12.2 GHz. They detected maser emission in 46% of the star-formation regions searched, with most of the remaining sources showing absorption or emission. This may be compared to the 24% detection rate by Norris *et al.* (1987) of 106 southern star formation regions searched in this same transition. Koo *et al.* (1988) have detected only 14% of the 78 nonstellar H_2O maser sources searched at 12.2 GHz. The latter have shown no emission or absorption in type I OH/IR stars.

Although the presence of 12.2 GHz methanol masers does not show a strong correlation with H_2O maser sources (14%), the sample at 36.2 GHz in Table 1 almost exclusively have associated type I OH and H_2O maser emission. No accurate positions have been measured for the 36.2 GHz masers; thus, no direct association may be made with the other objects in the region. However, from the observed associations with OH and H_2O masers we may infer that the conditions necessary for the pumping of type I OH and H_2O masers are necessary for the methanol molecule as well. There are also notable examples of H_2O maser sources (e.g., W49N) which have no associated methanol emission at 36.2 GHz, implying that the Methanol masers require more restrictive conditions than either OH or H_2O.

c) Dark Clouds

The energy level of the 3_0 state of *E* type methanol is listed by Lees *et al.* (1973) as 13.313 cm^{-1}. The equivalent temperature of this state would be 19.1 K, and since dark clouds have a kinetic temperature of only 10 K we may have anticipated the result obtained that this 4_{-1}–3_0 *E* transition does not readily show any emission in dark clouds. For molecular clouds associated with H II regions the kinetic temperatures are usually greater than 20 K and thus the ease with which thermal emission is detected in these sources.

V. CONCLUSIONS

In a survey of 53 molecular clouds associated with H II regions, dark clouds, and stellar sources we have detected 26 examples of Methanol emission in the 4_{-1}–3_0 *E* transition. There is evidence for both thermal emission and possible narrow 0.5 km s^{-1} wide maser spikes. Narrow maser spikes were detected in six sources. In several sources the emission is broad, 2–10 km s^{-1}, extended, and strong. This emission may be considered to be mostly thermal in excitation although low gain amplification of the background continuum may also produce broader lines. The maser action is attributed to collisional excitation of hot high-density gas with possible amplification of the background radio continuum.

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