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THE DISCOVERY OF A NEW, VERY STRONG, AND WIDESPREAD INTERSTELLAR METHANOL MASER LINE

KARL M. MENTEN
Harvard-Smithsonian Center for Astrophysics, 60 Garden Street, Cambridge, MA 02138
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ABSTRACT

We report the first detection of very strong maser emission in the 6.6 GHz $5_1 \rightarrow 6_0\,A^+$ transition of methanol toward a large number of star-forming regions. Essentially all 6.6 GHz maser sources found are associated with interstellar OH masers. Toward a number of sources, the 6.6 GHz emission has flux densities of several thousand Jy, exceeding that of any known OH maser. Since all known masers in the 12 GHz $2_0 \rightarrow 3_{-1}E$ transition observationally accessible to us have been found to have 6.6 GHz counterparts, the latter line is undoubtedly a Class II methanol maser transition. In all cases the 6.6 GHz luminosity exceeds the 12 GHz luminosity, often by large factors. Toward Class I methanol maser regions, the 6.6 GHz line is observed in absorption, as has been predicted by pumping models for this variety of sources.

Subject headings: interstellar: molecules — masers — nebulae: H II regions — radio sources: lines — stars: formation

1. INTRODUCTION

Over the last few years, numerous centimeter- and millimeter-wave transitions of interstellar methanol (CH_3OH) have been found to show maser emission toward star-forming regions. All known methanol masers can be divided in two classes (Batrla et al. 1987; Menten 1991): Class I sources are found offset from compact H II regions and OH maser centers and may arise when mass outflows interact with ambient high-density material (Plambeck & Menten 1990). In contrast, Class II methanol masers appear projected against the continuum emission of ultracompact H II regions over an extent that is similar to that of the OH masers associated with these sources (Menten et al. 1988a, b; Norris et al. 1988). Both Class I and Class II sources show maser emission in various transitions, but none of the transitions that is masing in Class I sources is masing in Class II sources and vice versa.[1]

The excitation of most Class I methanol maser transitions is, at least qualitatively, easy to understand (Menten 1991). As first discussed by Lees (1973), one expects in the case of the E-symmetry species over a range of physical conditions an overpopulation of the lower levels of the $k = -1$ energy ladder relative to its neighboring ladders. This leads to the $5_{-1} \rightarrow 4_0\,E$ and $4_{-1} \rightarrow 3_0\,E$ masers at 84 and 36 GHz, respectively, as well as to enhanced absorption ("overcooling") in the 12 GHz $2_0 \rightarrow 3_{-1}E$ line. Analogously, the $K = 0$ ladder of A-type methanol is overpopulated, leading to the known $8_0 \rightarrow 7_1 A^+$ and $7_0 \rightarrow 6_1 A^+$ masers at 95 and 44 GHz. The lowest frequency transition that has its *lower* level in the $K = 0$ ladder is the $5_1 \rightarrow 6_0\,A^+$ transition near 6.6 GHz. In analogy with the 12 GHz $2_0 \rightarrow 3_{-1}E$ line, Menten (1991) predicted enhanced absorption in this transition toward Class I maser sources.

In this *Letter* we report the first observations of the CH_3OH $5_1 \rightarrow 6_0\,A^+$ transition in the interstellar medium. In addition to Class I methanol maser sources, we also searched for the line toward Class II regions. The excitation of Class II methanol masers is poorly understood, and there seems to be no reliable way to predict maser action in any transition for these sources. Of course, *if* a centimeter-wave methanol transition *is* inverted by some process in a Class II region, this may lead to strong maser emission, because in these sources the methanol-emitting region appears frequently, if not always, projected against ultracompact H II regions whose continuum emission is optically thick at lower radio frequencies and can in principle be amplified by the masers. The strongest and most widespread Class II maser transition detected in the past is the 12 GHz $2_0 \rightarrow 3_{-1}E$ line, the same transition that shows *absorption* toward Class I sources. Maser emission in this line has been reported toward 45 sources (Batrla et al. 1987; Norris et al. 1987; Koo et al. 1988; Kemball, Gaylard, & Nicolson 1988). Motivated by the example of the 12 GHz line, we observed the 6.6 GHz transition toward the 26 of the 12 GHz sources that were observationally accessible to us and toward a large sample of other H II region/OH maser sources.

2. OBSERVATIONS

The observations were made between 1991 May 31 and June 3 with the 140 foot (43 m) telescope of the NRAO[2] in Green Bank, WV. An upconverter maser receiver ($T_{sys} \approx 50$–70 K) was operated at 6668.518 MHz, the rest frequency of the CH_3OH $5_1 \rightarrow 6_0\,A^+$ transition. We believe that the quoted value of the line frequency is accurate to within 5 kHz and describe its derivation in § 3. The line emission was analyzed with an autocorrelator split into two parts of 512 channels each. The autocorrelator modules were used with bandwidths of 0.625 and 5 MHz, with resulting velocity resolutions of 0.055 and 0.44 km s^{-1} per channel, respectively. The calibration was obtained by inserting a pulsed noise signal for half the duty cycle. This signal was measured relative to a hot and cold standard. The flux density scale was checked by continuum measurements of extragalactic calibrator sources and is thought to be accurate to 10%. The beam size is 5′.

[1] Class I and II CH_3OH masers were previously called Class A and B, respectively. As suggested by Menten (1991), we use the new notation which avoids the confusion with the A- and E-symmetry species of CH_3OH.

[2] The National Radio Astronomy Observatory is operated by Associated Universities, Inc., under contract with the National Science Foundation.

3. RESULTS AND DISCUSSION

We searched for the $5_1 \rightarrow 6_0 A^+$ transition toward 123 molecular cloud regions, most of which show evidence for recent or ongoing high-mass star formation in the form of H_2O, or OH masers, and/or ultracompact H II regions. We detect emission in 80 regions, absorption in five, and both emission and absorption in three regions. Table 1 summarizes our detections. For several sources, offset measurements at half-beam spacing were made around the nominal pointing position and the emission appeared unresolved at our resolution.

In all cases, almost certainly maser emission is observed. This is clear from (1) the high brightness temperatures exceeding 1000 K toward several sources; (2) the complicated spectra observed toward many sources, which resemble OH maser spectra; and (3) the narrow line widths of unblended emission features (0.3–0.5 km s^{-1}). The extremely high flux densities of several thousand Jy observed toward a number of sources make the CH_3OH $5_1 \rightarrow 6_0 A^+$ transition the second strongest centimeter-wave maser line detected so far in the interstellar medium, with only the 22 GHz H_2O transition showing stronger emission toward a few sources. Spectra taken toward a selection of regions are shown in Figure 1. All observed spectra and detailed information on our observations will be presented in a further publication.

The 6.6 GHz transition is undoubtedly a Class II methanol

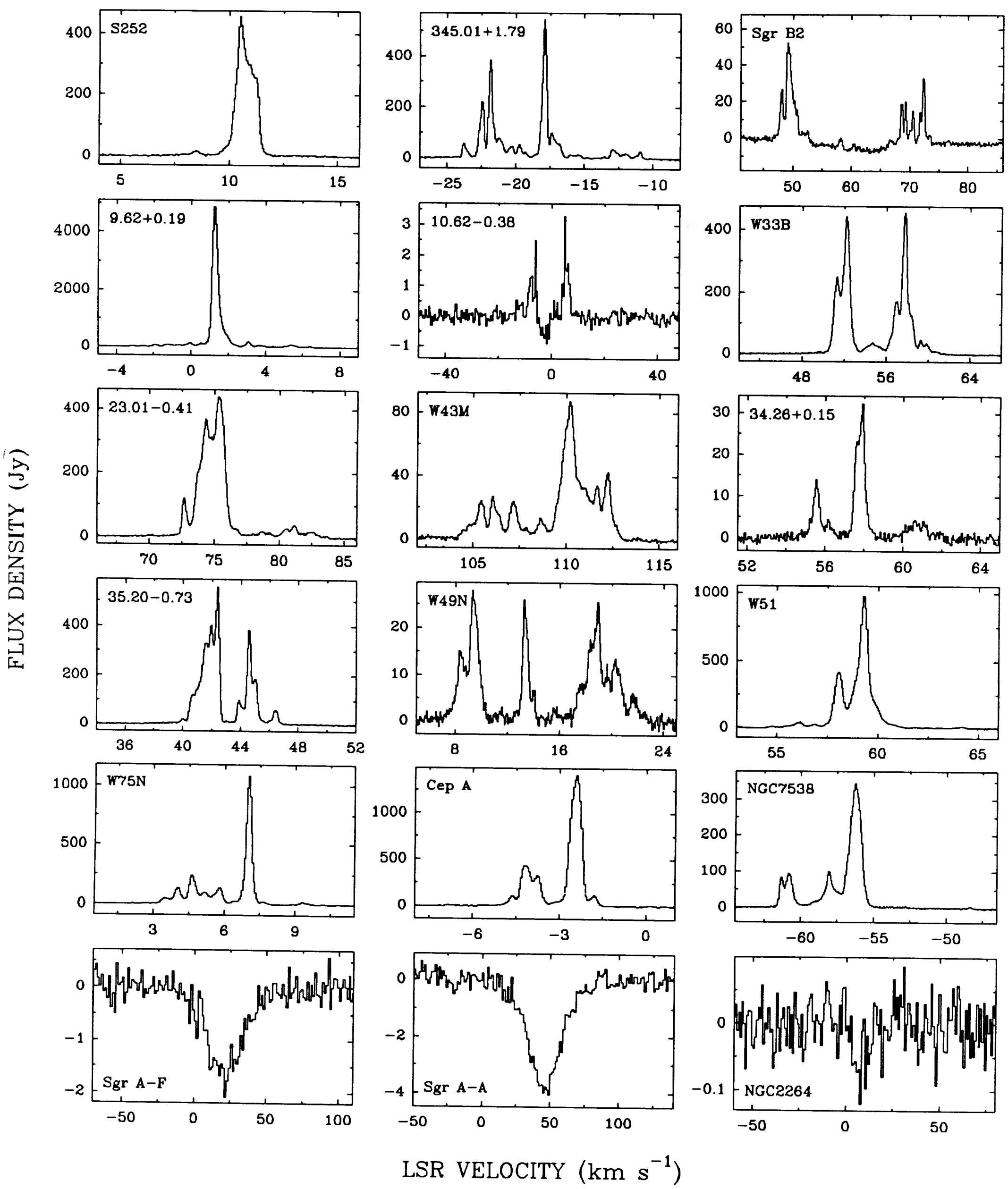

FIG. 1.—Spectra of the 6.6 GHz $5_1 \rightarrow 6_0 A^+$ transition of methanol toward selected star-forming regions. The velocity resolution is 0.055 km s^{-1} for all spectra, except for Sgr B2 (0.11 km s^{-1}), G10.62−0.38 (0.44 km s^{-1}), NGC 2264 (0.88 km s^{-1}), and Sgr A-A and -F (1.32 km s^{-1}). Note that in the case of Sgr B2 the broad absorption underlying the maser emission extends over a higher velocity range (43–92 km s^{-1}) than shown here.

TABLE 1

SOURCES DETECTED IN THE $5_1 \rightarrow 6_0\ A^+$ TRANSITION OF CH_3OH

Source	α_{1950}	δ_{1950}	S_{peak} (Jy)	v_{LSR}-range (km s^{-1})	Source	α_{1950}	δ_{1950}	S_{peak} (Jy)	v_{LSR}-range (km s^{-1})
W3(OH)[a]	$02^h23^m16^s.4$	61°38′57″	3880	−48,−41	M17[a,c]	$18^h17^m31^s.8$	−16°13′00″	49	21,24
S231[b,c]	05 35 51.3	35 44 16	208	−17,−10	16.59−0.06	18 18 20.3	−14 33 18	22	56,65
173.59+02.44	05 36 06.4	35 29 21	5	−14,−13	18.46−0.01	18 21 48.0	−12 53 02	28	46,50
Mon R2	06 05 20.0	−06 22 40	160	9,14	19.48+0.16	18 23 10.3	−11 54 31	24	13,28
S252A[b]	06 05 36.5	20 39 34	18	3,6	20.24+0.08	18 24 55.8	−11 16 24	112	69,76
S252[a,b]	06 05 53.7	21 39 09	457	8,12	20.08−0.13	18 25 23.0	−11 30 46	4	43,44
S255[c]	06 10 01.0	18 00 44	61	3,6	21.88+0.02[a]	18 28 16.1	−09 51 01	14	20,22
S269[a]	06 11 46.5	13 50 39	134	13,20	22.44−0.18	18 30 01.0	−09 27 00	24	24,39
NGC2264[b,c]	06 38 24.9	09 32 28	−0.07[d]	∼ 8	23.43−0.19	18 31 55.8	−08 34 17	85	95,108
345.01+1.79[a,b]	16 53 21.0	−40 09 40	544	−25,−10	23.01−0.41	18 31 56.7	−09 03 18	439	70,84
344.58−0.02	16 59 27.1	−41 37 42	3	∼ 2	24.33+0.11	18 32 32.3	−07 38 24	3[d]	107,120
345.51+0.35	17 00 54.7	−40 39 59	171	−23,−12	W42[c]	18 33 30.6	−07 15 07	89	106,115
345.00−0.22[a]	17 01 40.2	−41 25 00	148	−32,−20	27.35−0.20	18 39 16.0	−05 06 35	12[d]	96,103
345.70−0.09	17 03 21.5	−40 47 01	−1.2[d]	−22,−8	28.21−0.05	18 40 21.6	−04 16 26	2[d]	95,105
350.11+0.09	17 16 02.3	−37 07 00	43	−76,−61	28.83−0.25	18 42 12.4	−03 49 08	85	80,93
NGC6334-B	17 16 34.5	−35 54 44	13	−12,−2	29.95−0.02[a,c]	18 43 27.1	−02 42 36	229	95,105
RCW122	17 16 39.7	−38 54 17	98	−18,−2	30.82+0.28	18 44 00.5	−01 48 29	4[d]	82,109
NGC6334-C[b]	17 16 56.5	−35 51 58	−2.8[d]	−6,3	30.22−0.15	18 44 24.0	−02 32 00	11	103,114
NGC6334-F[a,c]	17 17 32.3	−35 44 04	3910	−15,1?	30.60−0.06	18 44 45.0	−02 09 15	5[d]	40,90?
351.78−0.54	17 23 20.9	−36 06 46	246	0,3	30.70−0.06	18 44 58.9	−02 04 27	125	85,92
354.61+0.48[a]	17 27 00.0	−33 11 38	191	−26,−14	30.79−0.06	18 45 08.8	−01 59 12	25[d]	88,110
353.41−0.36[a]	17 27 06.6	−34 39 20	96	−23,−18	30.82−0.06[a,c]	18 45 11.0	−01 57 57	21	90,110
355.34+0.15	17 30 12.0	−32 45 54	15	9,21	W43M[a]	18 45 36.8	−01 29 12	87	104,114
359.14+0.03	17 40 14.6	−29 38 12	18	5,0	32.74−0.07	18 48 46.0	−00 15 28	46	28,40
359.43−0.10	17 41 28.3	−29 27 04	29	−53,−45	33.13−0.09	18 49 33.6	00 04 25	10	72,110?
Sgr A−F[b,c]	17 42 27.4	−29 02 18	−1.7[d]	−13,54	34.26+0.15	18 50 46.2	01 11 12	32	55,62
359.62−0.25	17 42 30.0	−29 22 31	39	14,25	35.03+0.35[a]	18 51 30.3	01 57 30	50	44,46
Sgr A−A[b,c]	17 42 41.3	−28 58 18	−3.8[d]	11,84	35.19−0.74[c]	18 55 40.8	01 36 30	107	27,34
Sgr B2[a,c]	17 44 10.7	−28 22 17	53[e]	46,77	35.20−0.73[a]	18 59 13.8	01 09 20	556	39,47
0.54−0.85[a]	17 47 04.1	−28 54 01	86	8,20	40.62−0.14	19 03 34.9	06 41 55	14	30,37
2.14+0.01	17 47 29.0	−27 05 01	11	55,63	W49N[a]	19 07 49.9	09 01 14	28	−2,23
3.91−0.01	17 51 35.6	−25 34 19	2?	∼ 18	43.80−0.13	19 09 30.8	09 30 47	152	39,44
9.62+0.19[a]	18 03 16.0	−20 32 01	4870	4,7	45.07+0.13	19 11 00.4	10 45 43	42	57,59
8.67−0.37[a,c]	18 03 18.9	−21 37 59	117	38,45	45.47+0.13	19 11 47.5	11 07 14	15[d]	57,75
W31(1)[a]	18 05 40.5	−19 52 23	823	57,85	45.47+0.05	19 12 04.4	11 04 11	3[d]	55,60
10.62−0.38[a,c]	18 07 30.5	−19 56 28	4[e]	−10,8	W51[a,c]	19 21 24.4	14 24 48	979	48,76
12.89+0.49[a]	18 08 56.4	−17 32 14	75	32,41	V645 Cyg	19 41 04.2	23 36 42	103	15,28
12.03−0.04	18 09 07.4	−18 32 39	98	105,112	ON1[c]	20 08 10.0	31 22 40	91	−1,16
11.91−0.15	18 09 18.1	−18 42 25	77	39,45	ON2[c]	20 19 50.5	37 16 30	54	−11,3
12.22−0.12	18 09 45.0	−18 25 10	23	16,31	W75N[c]	20 36 50.4	42 27 23	1080	0,13
W33B[a]	18 10 59.3	−18 02 40	456	49,62	DR21(OH)[c]	20 37 13.8	42 12 13	13	−7,8
11.94−0.62[b,c]	18 11 04.4	−18 54 20	46	30,44	W75S(3)[c]	20 37 16.7	42 15 15	39	−7,5
W33[c]	18 11 15.7	−17 56 53	5[e]	31,41	Cep A[a]	22 54 19.2	61 45 47	1420	−6,−1
W33A[a]	18 11 44.2	−17 52 58	327	35,41	NGC7538[a,c]	23 11 36.6	61 11 50	346	−62,−54

NOTE.—Peak flux densities as determined from 0.055 km s^{-1} resolution data are given, except where noted, and the lowest and highest LSR velocities at which a signal is detected are listed. See Menten 1991 for the CH_3OH maser references mentioned in the following notes.

[a] Source also shows CH_3OH maser emission in the 12 GHz $2_0 \rightarrow 3_{-1}E$ transition.

[b] Source with no reported OH maser emission.

[c] Known Class I CH_3OH maser source.

[d] Line parameters determined from 0.44 km s^{-1} resolution data.

[e] Spectrum also shows absorption.

maser transition: We have observed all known Class II regions, i.e., sources with maser emission in the 12 GHz $2_0 \rightarrow 3_{-1}E$ transition, that were reported in the literature and have declinations greater than −42° and detect 6.6 GHz masers toward all of them. For all of these, the 6.6 GHz photon luminosity, $L_{6.6}$, is greater, and in many cases much greater, than the 12 GHz photon luminosity, L_{12}, if both lines are equally beamed; in the case of W51, $L_{6.6} = 4 \times 10^{46}\ s^{-1}$ (assuming isotropic emission), so that $L_{6.6} > 200L_{12}$. The 6.6 GHz spectra are in general richer than the 12 GHz spectra, showing a greater number of strong features. Toward all sources, the velocity range observed for the 6.6 GHz maser

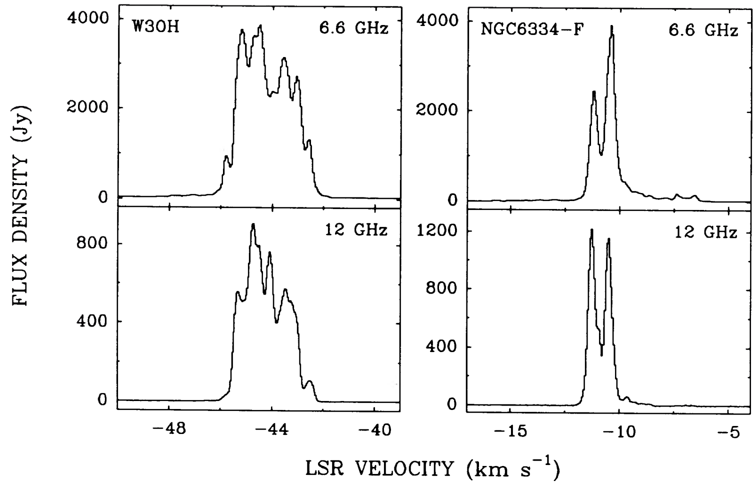

FIG. 2.—Spectra of the 6.6 GHz $5_1 \rightarrow 6_0 A^+$ and 12 GHz $2_0 \rightarrow 3_{-1}E$ transitions of methanol toward the prototypical Class II methanol maser sources W3(OH) (*left*) and NGC 6334-F (*right*). Velocity resolutions are 0.055 km s^{-1} for both 6.6 GHz spectra and 0.038 and 0.060 km s^{-1} for the 12 GHz spectra of W3(OH) and NGC 6334-F, respectively.

emission is greater than or comparable to the velocity range over which 12 GHz masers are observed. In some cases individual velocity components of the 12 GHz line appear also to be present in the 6.6 GHz spectra, although with different relative intensities. This is demonstrated in Figure 2 for the prototype Class II methanol maser sources W3(OH) and NGC 6334-F. The existence of 6.6 GHz counterparts to 12 GHz maser features found toward a number of sources was used to determine 6668.518 MHz as the rest frequency of the $5_1 \rightarrow 6_0 A^+$ line to very high accuracy, which is limited by the 3 kHz uncertainty of the frequency measured for the 12 GHz line (Gaines, Casleton, & Kukolich 1974). Anderson, De Lucia, & Herbst (1990), based on their theoretical analysis of the methanol spectrum, predict a frequency of 6668.421 MHz, with a formal uncertainty of 27 kHz.

The previously noted close relationship of Class II CH_3OH and OH masers is further reinforced by our observations: Our sample contains 98 interstellar OH maser sources and $5_1 \rightarrow 6_0 A^+$ emission is detected toward 78 of them, with CH_3OH and OH masers covering comparable velocity ranges. In particular, we observed all 63 OH maser regions in the Galactic longitude range 359° through 0° to 50° that were measured during the 18 cm OH surveys of Caswell & Haynes (1983a, b). We detect the $5_1 \rightarrow 6_0 A^+$ transition toward 48 of these sources. This high detection rate is all the more remarkable if we note that our typical rms noise level ($\approx$0.4 Jy) is 5 times higher than that of the OH observations. Toward $\approx$60% of the sources in this sample, the peak intensity observed in the 6.6 GHz methanol spectra is higher than that of the strongest OH hyperfine transition.

We detect absorption in the $5_1 \rightarrow 6_0 A^+$ transition toward NGC 2264, G10.62−0.38, Sgr B2, and toward the Galactic center sources Sgr A-A and Sgr A-F, which are all known to contain Class I methanol masers (Haschick, Menten, & Baan 1989) and also show absorption in the 12 GHz $2_0 \rightarrow 3_{-1}E$ transition (Batrla et al. 1987; Menten et al. 1991). In addition to the broad absorption, G10.62−0.38 and Sgr B2 also exhibit maser emission in both the 6.6 and the 12 GHz transitions. This almost certainly means that regions giving rise to Class II maser emission, i.e., ultracompact H II regions, on the one hand, and Class I masers, accompanied by 6.6 and 12 GHz absorption, on the other, are both within the large beamwidth.

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