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The discovery of methanol masers at 107 GHz

I.E. Val'tts[1], **A.M. Dzura**[1], **S.V. Kalenskii**[1], **V.I. Slysh**[1], **R.S. Booth**[2], **and A. Winnberg**[2]

[1] Astro Space Center of Lebedev Physical Institute, Profsoyuznaya 84/32, 117810 Moscow, Russia
[2] Onsala Space Observatory, S-439 92 Onsala, Sweden

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Abstract. A new methanol maser line at 107 GHz was discovered in five galactic sources. All of them are known Class II methanol masers. Toward Class I methanol maser sources, the 107-GHz line was found in absorption, or as rather weak quasi-thermal emission sources. The detection of these new methanol masers supports an assumption that the level population inversion is due to overpopulation of some K ladders relative to neighbouring ladders.

Key words: line: profiles – masers – molecular processes – ISM: molecules – radio lines: ISM

1. Introduction

Methanol (CH_3OH) masers are observed in transitions between energy levels located in different K ladders. It seems that two types of pumping mechanisms create unequal population of the ladders. Thus, in E-methanol the $K = -1$ ladder is overpopulated relative to the $K = 0$ or $K = -2$ ladders in Class I masers (Menten 1991a). This leads to maser emission between the ladders in such transitions as $4_{-1} - 3_0E$ at 36.1 GHz or $5_{-1} - 4_0E$ at 84.5 GHz, or to enhanced absorption in the transition $2_2 - 3_{-1}E$ at 12.1 GHz. DR 21 (OH) is a typical Class I source. Similarly, in A-methanol the $K = 0$ ladder is overpopulated relative to the $K = 1$ ladder in Class I masers leading to maser emission in the transitions $7_0 - 6_1A^+$ at 44 GHz, $8_0 - 7_1A^+$ at 95.1 GHz, $9_0 - 8_1A^+$ at 146.6 GHz and to absorption in the transition $5_1 - 6_0A^+$ at 6.7 GHz. In Class II masers the situation is reversed: the $K = -1$ ladder in E-methanol is underpopulated relative to the $K = 0$ or $K = -2$ ladders leading to masers in the transitions $2_0 - 3_{-1}E$ at 12 GHz and in $7_{-2} - 8_{-1}E$ at 37.7 GHz; in A-methanol the $K = 0$ ladder is underpopulated relative to the $K = 1$ ladder with maser emission in the $5_1 - 6_0A^+$ transition at 6.7 GHz. A typical Class II source is W 3 (OH). With these simple rules, one can predict new maser transitions. For example, masers are expected in A-methanol transitions similar to the $5_1 - 6_0A^+$ transition: $4_1 - 5_0A^+$ at 57 GHz, $3_1 - 4_0A^+$ at 107 GHz, $2_1 - 3_0A^+$ at 156.6 GHz and $1_1 - 2_0A^+$ at 205.8 GHz. The line at 107 GHz was first observed by Goldsmith et al. (1983); it was also present in spectral scans of Sgr B2 (Cummins et al. 1986) and in Sgr B2 and Ori KL (Turner 1991): It was very weak in Sgr B2 and rather strong in Ori KL but in both sources the emission apparently is thermal.

In order to search for masers, observations of the $3_1 - 4_0A^+$ transition of methanol at 107 GHz were made towards a number of galactic sources.

2. Observations

The observations were carried out in the period from May 17 to 22, 1993, using the radome-enclosed 20-m millimetre-wave telescope of Onsala Space Observatory. The rest frequency of the transition $3_1 - 4_0A^+$ has been measured in the laboratory and is found to be 107.01385 GHz (Lees & Baker 1968). At this frequency the aperture efficiency is 45% and the half-power beamwidth is $35''$. The pointing accuracy is $3''$ rms. The observations were performed in a dual-beam switching mode with the beam separation $11'$ and a switch frequency of 2 Hz. A cryogenically cooled low-noise SIS mixer was used in the receiver. The single side-band receiver noise temperature was 80 K, and the system noise temperature, corrected for atmospheric absorption, rearward spillover and radome losses, varied during observations between 100 and 500 K depending on weather conditions and elevation of the telescope. The data were calibrated using the standard chopper-wheel method of Kutner & Ulich (1981). One Kelvin of antenna temperature corresponds to 19.5 Jy. Assuming a gaussian illumination of the dish, one Kelvin of main-beam brightness temperature corresponds to 11.4 Jy. The uncertainty of the absolute flux density scale is estimated to be 2.5 Jy (rms). The backend was a 64-MHz wide 256-channel filter spectrometer with a frequency resolution of 250 kHz (velocity resolution 0.7 km s^{-1}, at 107 GHz).

3. Results

Methanol emission was detected in 17 known Class II methanol maser sources. Spectra of the emission line sources are shown in Fig. 1, and gaussian parameters of the lines are given in Table 1.

Send offprint requests to: A. Winnberg

Table 1. CH_3OH $3_1 - 4_0A^+$ emission line parameters with their 1ρ statistical errors

Source	α_{1950}			δ_{1950}			V_{LSR}	ΔV	S	$\int S_{107}dV$
	(h)	(m)	(s)	(°)	(′)	(″)	(km s^{-1})	(km s^{-1})	(Jy)	(Jy km s^{-1})
W 3 (OH)	02	23	17.3	+61	38	58	−45.4(0.1)	4.3(0.2)	10.3(0.4)	46.8(3.0)
							−43.3(0.6)	0.8(0.1)	20.9(0.4)	23.4(1.7)
Ori S6	05	32	44.8	−05	26	00	6.6(0.1)	4.2(0.3)	4.5(0.4)	19.5(2.3)
Ori KL	05	32	47.0	−05	24	23	7.0(0.1)	9.2(0.3)	23.0(1.0)	226.0(12.0)
							7.6(0.02)	2.4(0.05)	64.2(1.2)	168.0(4.6)
OMC 2	05	32	59.8	−05	11	29	11.4(0.3)	2.0(0.6)	2.5(0.5)	6.0(2.2)
							14.2(0.6)	2.2(1.4)	1.3(0.4)	3.3(0.7)
S 252 ≡ G188.9+0.9	06	05	54.0	+21	39	09	10.6(0.04)	0.9(0.1)	10.1(1.0)	11.7(2.1)
G9.62+0.19	18	03	16.0	−20	32	01	−0.8(0.2)	3.8(0.6)	6.0(0.6)	23.4(4.5)
							4.5(0.5)	3.6(1.3)	2.7(0.8)	9.8(4.6)
W 31 (1)	18	05	40.5	−19	52	23	66.1(0.3)	8.8(0.9)	7.2(0.6)	68.0(8.8)
							75.7(0.6)	3.7(1.4)	2.7(0.8)	9.8(4.6)
G29.95-0.02	18	43	27.1	−02	42	36	97.7(0.4)	4.9(1.0)	2.9(0.6)	16.0(4.5)
G30.82+0.28	18	44	00.5	−01	48	29	102.7(0.2)	1.5(0.4)	3.7(0.8)	5.9(2.0)
W 48	18	59	13.8	+01	09	20	41.3(0.03)	2.2(0.1)	15.4(0.4)	37.0(1.6)
							45.0(0.04)	2.0(0.1)	11.9(0.4)	25.0(1.5)
W 51	19	21	24.4	+14	24	48	56.5(0.4)	6.3(1.0)	1.8(0.2)	12.0(2.4)
W 51 (e1/e2)	19	21	26.2	+14	24	43	55.6(0.05)	8.9(0.1)	16.2(0.2)	152.0(2.8)
W 51 (Met1)	19	21	26.2	+14	23	32	60.6(0.3)	1.9(0.7)	1.2(0.4)	2.0(1.5)
W 75 (N)	20	36	50.4	+42	27	23	8.4(0.3)	6.2(0.6)	2.9(0.2)	18.0(2.6)
DR 21 (OH)	20	37	13.8	+42	12	13	−5.7(0.4)	2.7(1.0)	2.0(1.2)	6.0(4.1)
							−2.3(0.7)	5.0(1.1)	3.9(0.4)	20.6(4.5)
Cep A	22	54	19.2	+61	45	47	−2.2(0.03)	1.0(0.1)	24.4(1.2)	31.0(2.6)
NGC 7538	23	11	36.7	+61	11	49	−59.2(0.1)	1.7(0.3)	10.1(1.2)	19.5(3.7)
							−56.3(0.1)	3.1(0.2)	17.4(1.8)	58.5(7.5)
NGC 7538 (IRS1)	23	11	37.7	+61	11	12	−57.8(0.4)	4.5(1.0)	1.6(0.4)	5.8(2.0)

Several sources show absorption: all of them are known Class I masers. Their parameters are given in Table 2 and their line profiles are shown in Fig. 2. Non-detected sources are listed in Table 3.

4. Notes on individual sources

4.1. Emission sources

W 3 (OH). This is a prototype Class II source, observed in many transitions. At 107 GHz its spectrum resembles the $9_2 - 10_1A^+$ (Wilson et al. 1984) and $6_2 - 5_3A^+$ (Haschick et al. 1989) profiles with a single strong feature at −43.3 km s^{-1}. A wider component at −45.4 km s^{-1} may result from a superposition of several weaker components which are better represented in $2_0 - 3_{-1}E$ and $5_1 - 6_0A^+$ spectra (Batrla et al. 1987; Menten 1991b).

Ori S6 and Ori KL. The profile of Ori KL is composed of 2 components: a narrow one at 7.6 km s^{-1} and a wide one at 7.0 km s^{-1}. Some indication of the presence of a broader plateau is seen in Fig. 1. This profile is typical for Ori KL in many methanol transitions and the line is believed to be quasi-thermal. Ori S6 is a methanol emission region at 102″ from Ori KL and its spectrum is similar to that of Ori KL.

OMC 2. This is a Class I methanol maser source (Haschick et al. 1990) and the weak line seen at 107 GHz is probably quasi-thermal.

S 252 ≡ G188.94+0.89. A Class II methanol maser is observed in the $2_{-1} - 3_0E$, $5_1 - 6_0A^+$, and $7_{-2} - 8_{-1}E$ transitions (Koo et al. 1988; Menten 1991b; Haschik et al. 1989). The profile at 107 GHz shows a single strong narrow line at the same radial velocity as in other transitions.

G9.62+0.19. This is the strongest $5_1 - 6_0A^+$ Class II maser (Menten 1991b) also observed in the $2_{-1} - 3_0E$ and $7_{-2} - 8_{-1}E$ transitions (Koo et al. 1988; Haschick et al. 1989). At 107 GHz there are two or more components within the velocity interval of other Class II lines, which are neither strong, nor narrow enough to be considered as masers.

W 31 (1). The widths of the two lines are so large that the excitation is probably thermal unless the lines are blends of several narrow components unresolved with the present velocity resolution.

G29.95-0.02. Toward this region both Class I and Class II methanol masers have been detected (Bachiller et al. 1990; Menten 1991b). At 107 GHz the profile consists of a weak broad

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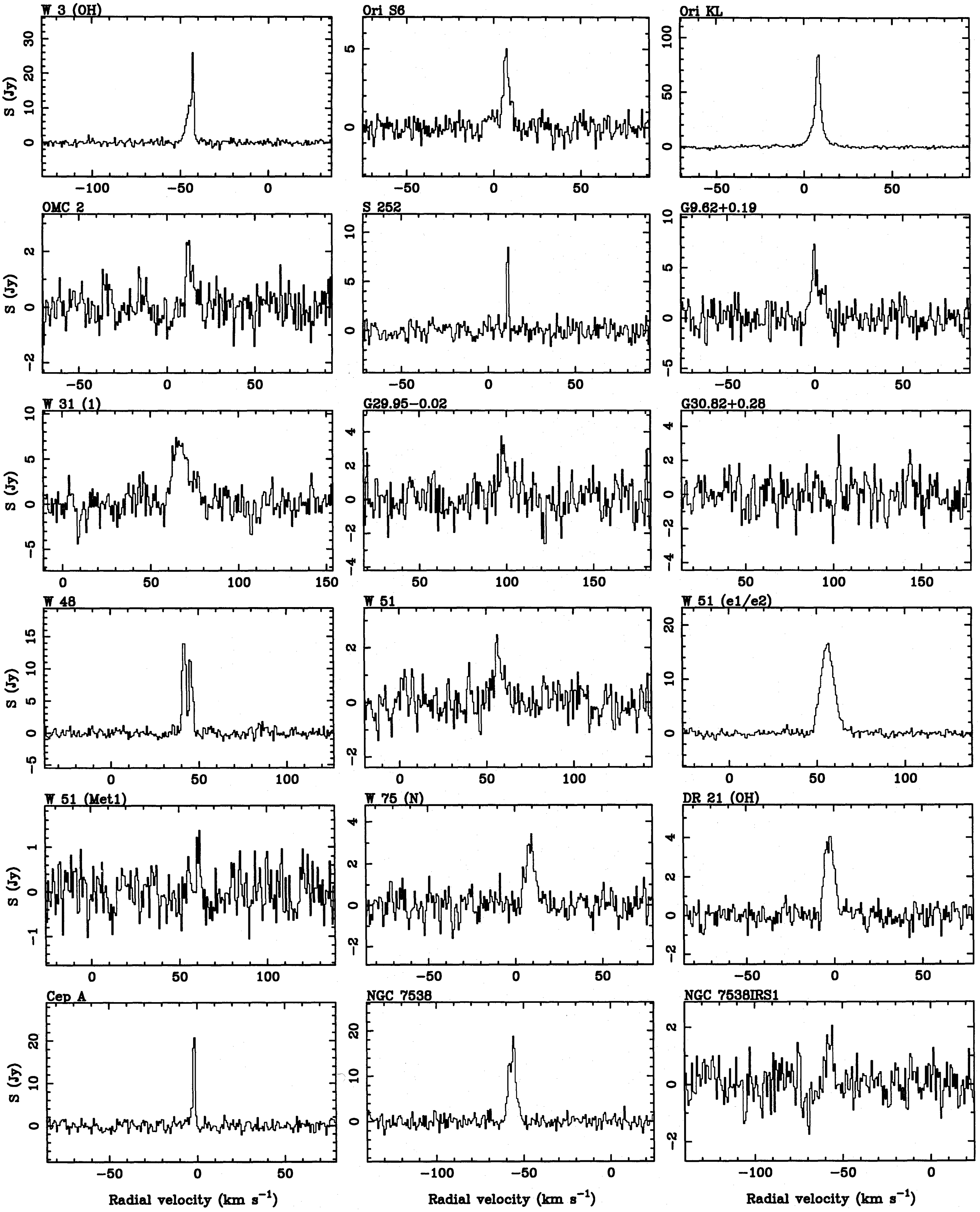

Fig. 1. Spectra of the $3_0 - 4_1 A^+$ 107-GHz emission of methanol. The velocity resolution is 0.7 km s^{-1}

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Table 2. CH_3OH $3_1 - 4_0A^+$ absorption line parameters with their 1ρ statistical errors

Source	α_{1950}			δ_{1950}			V_{LSR}	ΔV	T_A^*	$\int T_A^* dV$
	(h)	(m)	(s)	(°)	(′)	(″)	($km\,s^{-1}$)	($km\,s^{-1}$)	(K)	($K\,km\,s^{-1}$)
S 231	05	35	51.3	+35	44	16	−17.4(0.2)	3.0(0.6)	−0.08(0.01)	−0.25(0.03)
NGC 2264 (G)	06	38	28.0	+09	32	12	7.5(0.4)	2.8(0.9)	−0.08(0.02)	−0.2(0.08)
DR 21 (West)	20	37	07.6	+42	08	46	−8.0(0.5)	3.5(1.5)	−0.095(0.029)	−0.37(0.19)
W 75 (S3)	20	37	16.7	+42	15	15	−4.1(0.5)	4.2(1.2)	−0.06(0.01)	−0.2(0.06)

Table 3. CH_3OH $3_1 - 4_0A^+$ - non-detections

Source	α_{1950}			δ_{1950}			V_{LSR}
	(h)	(m)	(s)	(°)	(′)	(″)	($km\,s^{-1}$)
IC 1795	02	21	51.0	+61	52	10	−47.9
W 3 (3)	02	22	06.1	+61	50	40	−38.4
G173.59+2.44	05	36	06.4	+35	29	21	−13.5
Mon R2	06	05	20.0	−06	22	40	11.5
S 252 A	06	05	36.5	+20	39	34	4.5
S 269	06	11	46.5	+13	50	39	16.5
S 255	06	10	01.0	+18	00	44	11.2
NGC 2264	06	38	24.9	+09	32	28	7.2
G232.62+1.00	07	29	55.0	−16	51	47	23.0
S 33	15	57	15.7	−01	29	51	1.0
G8.67-0.36	18	03	18.9	−21	37	59	34.0
W 33 (A)	18	11	44.5	−17	52	56	36.2
G20.24+0.08	18	24	55.8	−11	16	24	72.5
G23.01-0.41	18	31	56.7	−09	03	18	77.0
W 42	18	33	30.6	−07	15	07	110.5
G30.70-0.06	18	44	58.9	−02	04	27	88.5
G35.19-0.74	18	55	40.8	+01	36	30	30.5
G43.80-0.13	19	09	30.8	+09	30	47	41.5
W 51 (Met5)	19	21	20.5	+14	24	12	66.7
W 51 (Met4)	19	21	25.6	+14	25	41	64.4
W 51 (Met3)	19	21	27.5	+14	23	52	56.6
W 51 (Met2)	19	21	28.8	+14	23	47	56.7
G64.9-0.9	20	07	31.1	+31	17	24	13.5
DR 21	20	37	12.6	+42	08	46	−3.8
S 117	20	56	58.7	+44	08	45	0.8
IC 1396 (N)	21	39	10.3	+58	02	29	−0.5
S 140	22	17	41.2	+63	03	43	−8.2
S 158	23	11	33.4	+61	14	17	−59.0
NGC 7538 (S)	23	11	36.1	+61	10	30	−55.6

line and therefore suggests thermal emission.

G30.82+0.28. This source shows a weak possible maser line with a probable narrow absorption at lower velocity. It is a weak maser at 6.7 GHz (Menten 1991b).

W 48. As in the $2_{-1} - 3_0E$ (Koo et al. 1988) and $5_1 - 6_0A^+$ (Menten 1991b) transitions the profile of this source at 107 GHz consists of 2 narrow lines separated by about 4 $km\,s^{-1}$. This is a well established Class II maser source.

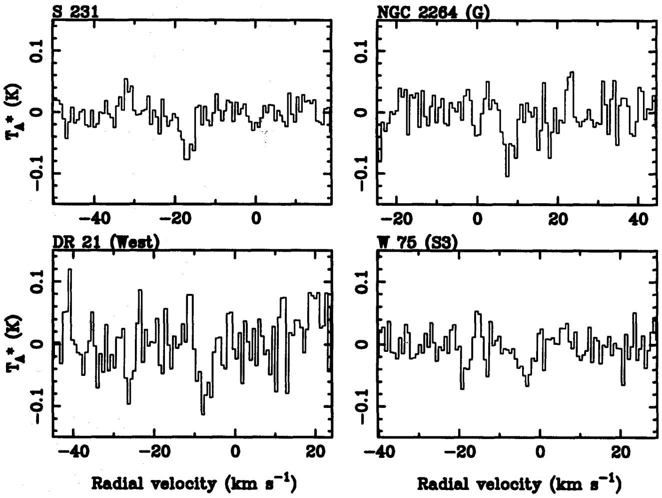

Fig. 2. Spectra of the $3_0 - 4_1A^+$ 107-GHz absorption of methanol. The velocity resolution is 0.7 $km\,s^{-1}$

W 51 (e1/e2). This is a very strong thermal methanol source seen in many transitions. At 107 GHz the profile is broad, consistent with thermal origin. The profile called W 51 was taken 27″ (less than one HPBW) from W 51 (e1/e2) and it could belong to the same source.

W 51 (Met1). This is a Class I methanol maser source (Haschick et al. 1990) 70″ to the south of W 51 (e1/e2). The 107-GHz line is rather weak (at the level of 3σ) and should be confirmed by further observations.

W 75 (N). Methanol maser emission from this source was found both in Class I (Haschick et al. 1990) and in Class II transitions (Menten 1991b). At 107 GHz the line is much wider than the other lines and the emission is probably thermal.

DR 21 (OH). The 107-GHz line is probably double and consists of 2 apparently thermal features. This is a strong Class I maser (Haschick et al. 1990). In the Class II $2_0 - 3_{-1}E$ transition it is observed in absorption (Batrla et al. 1987), but Menten (1991b) reports relatively weak emission in another Class II transition, $5_1 - 6_0A^+$ at 6.7 GHz.

Cep A. This is the strongest one of the sources in our sample with probable maser-amplified lines (see Section 5.2). It is a strong

Class II source at 12 GHz (Koo et al. 1988) and at 6.7 GHz (Menten 1991b) with no emission in the Class I transitions.

NGC 7538. The 107-GHz line may be represented by two gaussian features at radial velocities consistent with the radial velocity of Class II lines at 12 GHz (Batrla et al. 1987) and at 6.7 GHz (Menten 1991b). The width of the 107-GHz features is larger than those of the 12 or 6.7-GHz features, but not as large as in thermal sources. In the $J_2 - J_1 E$ (J=2, 3, 4,...) transitions, which show maser action toward Class I methanol maser sources, absorption was observed toward NGC 7538 (Menten et al. 1986). NGC 7538 (IRS1) is 38″, about one beam-width, away from the NGC 7538 position, and at 107 GHz a weak probably thermal line was observed here. The source is a Class I maser at 44 GHz (Bachiller et al. 1990).

4.2. Absorption sources

S 231. Both Class I (Bachiller et al. 1990) and Class II (Menten 1991b) maser lines are observed in this source. The radial velocity of the lines is within the limits of the 107-GHz absorption.

NGC 2264 (G). A source of probably thermal methanol emission at 36 GHz discovered by Haschick & Baan (1989) offset by 60″ from the Class I maser position. Weak absorption at 107 GHz is tentatively observed at the same radial velocity.

DR 21 (West). Weak 107-GHz absorption is tentatively observed at the position of the 44-GHz Class I methanol maser (Haschick et al. 1990) but at a slightly different radial velocity.

W 75 (S3). As in DR 21 (West) the 107-GHz absorption is tentatively seen at the position of the 44-GHz Class I maser (Bachiller et al. 1990), but a weak Class II maser was also found here by Menten (1991b) at 6.7 GHz. The radial velocity of the 107-GHz absorption feature is consistent with the radial velocity of the Class I and II masers.

5. Discussion

5.1. Rest frequency

The radial velocities of Ori KL and other well studied sources were found to be systematically higher than the velocities found from other spectral lines by 0.5 km s^{-1}. This may be due to a rest frequency error. If corrected by this amount the rest frequency should be equal to 107.01367 GHz, or 0.18 MHz lower than given by Lees & Baker (1968) and only 0.11 MHz lower than the value found by De Lucia et al. (1989) in their theoretical calculation. Velocities in Tables 1 and 2 were corrected by −0.5 km s^{-1}.

5.2. Methanol masers at 107 GHz

Among the emission sources listed in Table 1 at least five show intense narrow lines. In W 3 (OH), S 252, and Cep A the lines have uncorrected widths less than 1 km s^{-1}, and are barely resolved with the 0.7-km s^{-1} velocity resolution. Based on the narrowness of the lines and their relatively high intensity these three sources together with W 48 and NGC 7538, which have somewhat wider lines, can be regarded as maser sources. They are associated with the strongest 6.7-GHz emission sources belonging to Class II methanol masers (Menten 1991b). The new 107-GHz emission sources should be assigned also to Class II methanol masers.

The detection of 107-GHz methanol masers gives support to the assumption made in the Introduction that in Class II sources the $K = 1$ ladder of A-methanol is overpopulated relative to the $K = 0$ ladder, leading to population inversion of levels in transitions between $K = 1$ and $K = 0$ ladders. The other 107-GHz emission sources show weaker and wider lines. They are associated mostly with Class I emission sources radiating at 36 and 44 GHz, like OMC 2 and DR 21 (OH) (Haschick et al. 1989; Haschick et al. 1990).

Other strong Class I sources like DR 21 (West) or W 75 (S3) are associated with 107-GHz absorption. This can be understood if one assumes that in Class I sources the $K = 0$ ladder is overpopulated relative to the $K = 1$ ladder (in contrast to Class II sources), and the population inversion is changed to anti-inversion, i.e. $T_{\rm ex} < 2.7$ K. Sources with strong continuum background show enhanced absorption. The quasi-thermal emission observed in DR 21 (OH) and Ori KL may be caused by a quenching of non-equilibrium excitation processes.

The 107-GHz methanol masers are not as strong and widespread as the 6.7-GHz masers, although 107-GHz maser emission was detected toward several sources with strong 6.7-GHz masers. There are several interesting exceptions, however. The strongest 6.7-GHz maser, G9.62+0.19, with a flux density of 5000 Jy (Menten 1991b) was found to be rather weak at 107 GHz. Among non-detected sources there are quite strong 6.7-GHz masers like W 33 (A) or G23.01-0.41 with flux densities of 300 to 400 Jy. It is not clear why 107-GHz emission was not found in these strong 6.7-GHz masers. The 107-GHz emission arises in transitions between levels 3 and 4 which lay lower than levels 5 and 6 of the 6.7-GHz transition. One possible explanation might be that the physical conditions (temperature, density, radiation field) required to pump the two maser transitions are not the same in the two cases. The temperature and density adequate for the inversion of the $5_1 - 6_0A^+$ transition might be too high for inversion of the $3_1 - 4_0A^+$ transition. This might be the case for G9.62+0.19. It would be interesting to check this hypothesis by observing the intermediate transition $4_1 - 5_0A^+$ at 57 GHz. Unfortunately this frequency is heavily absorbed in the Earth's atmosphere, and it will be difficult to observe it from the ground.

6. Summary and conclusions

A new methanol maser was detected in five galactic sources in a transition between the $K = 0$ and $K = 1$ ladders at 107 GHz. It is similar to the much stronger 6.7-GHz masers discovered by Menten (1991b). The sources where the new maser line was observed are in general the same sources which are 6.7-GHz Class II line emitters. Class I methanol sources were observed in absorption or as weak quasi-thermal emission sources. The detection of the new methanol maser line supports an assumption that in interstellar methanol the whole K-ladders are over or under-populated relative to neighbouring ladders; depending on which ladder is overpopulated Class I or Class II masers are produced.

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