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Torsionally excited methanol at 44.9 GHz

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Abstract. Using the Haystack Observatory 37-m radio telescope we have undertaken a search for emission in the 2_0-3_1 E rotational transition of methanol in its first torsionally excited state ($v_t = 1$) at 44.9 GHz. We examined seven galactic sources – six strong emitters of Class II methanol maser lines and Orion KL, the only source where this line had been previously detected. We confirm (at a level of 5σ) the previous detection and report two new detections – a reliable (9σ) detection in W3(OH) and a marginal (3.5σ) detection in NGC 6334F. Upper limits for other sources are presented. Although we did not see obvious signatures of maser amplification in this transition in any source, arguments in favor of weak masing in W3(OH) are presented.

Key words. masers – ISM: molecules – ISM: individual objects: W3(OH), Orion KL, NGC 6334F – stars: formation

1. Introduction

Of the molecular species observed in interstellar space, methanol has by far the largest number of detected transitions, both in thermal and maser emission. Interstellar methanol masers are associated with regions of active star formation, and fall into two classes (Menten 1991a). Class I masers are normally seen apart from compact continuum sources, while Class II masers are found close to ultra-compact H II regions. The difference between the two classes is likely due to a difference in pumping mechanism: collisional excitation produces Class I masers while radiative excitation produces Class II masers (e.g., Cragg et al. 1992). Torsionally excited interstellar methanol was first detected by Lovas et al. (1982) who observed the 6_1-5_0 E, 1_0-2_1 E, 2_1-1_1 E, and 2_0-1_0 E rotational transitions of the first torsionally excited state ($v_t = 1$) towards the Orion Kleinmann-Low (KL) nebula. Later, other transitions between torsionally excited levels were detected by Menten et al. (1986b), with the 10_1-11_2 A^+, $v_t = 1$ transition probably being inverted in W3(OH). Sobolev & Deguchi (1994) suggested that pumping cycles through the first two torsionally excited states may play an important role in the pumping of the brightest Class II methanol masers at 6.7 GHz and 12 GHz. Such a model is able to explain the observed brightnesses at 6.7 GHz and 12 GHz as well as the ratio of their intensities. This model predicts weak maser emission in the 2_0-3_1 transition of the first torsionally excited state of E-type methanol at 44.9 GHz (Sobolev et al. 1997), although no obvious correlation between 44.9 GHz brightness and that of other known transitions was expected. Thus, observations of this transition may be a valuable test of the Class II methanol maser pumping model. The goal of this work is to search for 2_0-3_1 E, $v_t = 1$ emission towards some of the brightest known Class II masers. In addition, we reobserved this line in Orion KL, which is the only source where 44.9 GHz emission was previously detected (Saito et al. 1989).

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2. Observations

For our observations in June and July of 2000 we used the radome-enclosed 37-m telescope at the Haystack Observatory, Westford, MA. A 35.5−49 GHz tunable maser amplifier receiver was used at the 2_0-3_1 E, $v_t = 1$ rest frequency 44955.8±0.05 MHz (Tsunekawa et al. 1995) with typical system noise temperature between 150 K and 400 K. The notable exception is the low declination source NGC 6334F for which the system temperature was often as high as 700 K. All system temperatures are given on a corrected antenna temperature (T_A^*) scale. The backend was an autocorrelator operating with a bandwidth of 5.93 MHz split into 8192 channels. During postprocessing, each of 32 adjacent channels were averaged and then additional Hanning smoothing was applied, yielding 128 channels with a velocity resolution of 0.309 km s^{-1}. At 44.9 GHz, the beamwidth was 45 arcsec and the aperture efficiency was about 0.27. A corrected antenna temperature of 1 K corresponds to a flux density of 9.5 Jy. From observations of Jupiter and Venus we estimate that this calibration is accurate to about ±30%. The observations were carried out in the beam switching mode with a switching frequency of 10 Hz. The pointing accuracy was about 12″.

3. Results and individual sources

Our source list contains 7 sources, 6 known bright Class II methanol masers and Orion KL, which is a Class I methanol maser. In spite of the rather high noise level we detected 44.9 GHz emission towards W3(OH) (at a level of 9σ)[1] and Orion KL (5σ). For NGC 6334 we present a marginal detection (3.5σ). These three spectra are shown in Fig. 1. The other four sources brought no detections. Table 1 contains observed positions and velocities as well as achieved rms noise levels for all observed sources. The table also shows results of Gaussian fitting for the three sources with detected 44.9 GHz emission features. Fitting errors are given in parenthesis.

3.1. Orion KL

As mentioned above, Orion KL is the only source for which a detection of the $2_0{-}3_1$ E, $v_t = 1$ line at 44.9 GHz was previously reported (Saito et al. 1989). Our values for the linewidth and the peak flux density are in agreement with those observations within the errors of our measurement. The peak radial velocity of 6.5 km s^{-1} is typical for this region, e.g., emission of the hot core component (HC) peaks at velocities about 3–5 km s^{-1} and emission of the methanol emission core (MEC, located about 10″ south of our observed position) peaks at 7–8 km s^{-1} (Johansson et al. 1984; Menten et al. 1986b).

Wilson et al. (1989) found the peak of the $10_1{-}9_2$ A$^-$ methanol line emission at a velocity of about 8.0 km s^{-1}. They attributed the narrow component in the spectrum of this line to the MEC, and a broad and weak component to the HC. It should be mentioned that the $10_1{-}9_2$ A$^-$ line is formed via a transition between levels with energies 140 K above the ground, which is rather low in comparison to about 300 K for the levels of the torsionally excited transition studied here. Minh et al. (1993) mapped the $15_3{-}14_4$ A$^-$ line emission of methanol, originating from levels at 329 K above the ground. The map shows a source of elongated shape between the HC and the MEC, and peaks at the MEC, the radial velocity of the maximum being 7.5 km s^{-1}. The same velocity and position properties were observed for some torsionally excited lines seen towards Orion KL (Menten et al. 1986b). So, most of the $2_0{-}3_1$, $v_t = 1$ emission is probably associated with the MEC. The velocity difference of about 1 km s^{-1} may be attributed to fitting errors because the line may have

[1] The signal to noise ratio was determined as the quotient of the integrated flux density and its uncertainty, both given in the Col. 5 of Table 1.

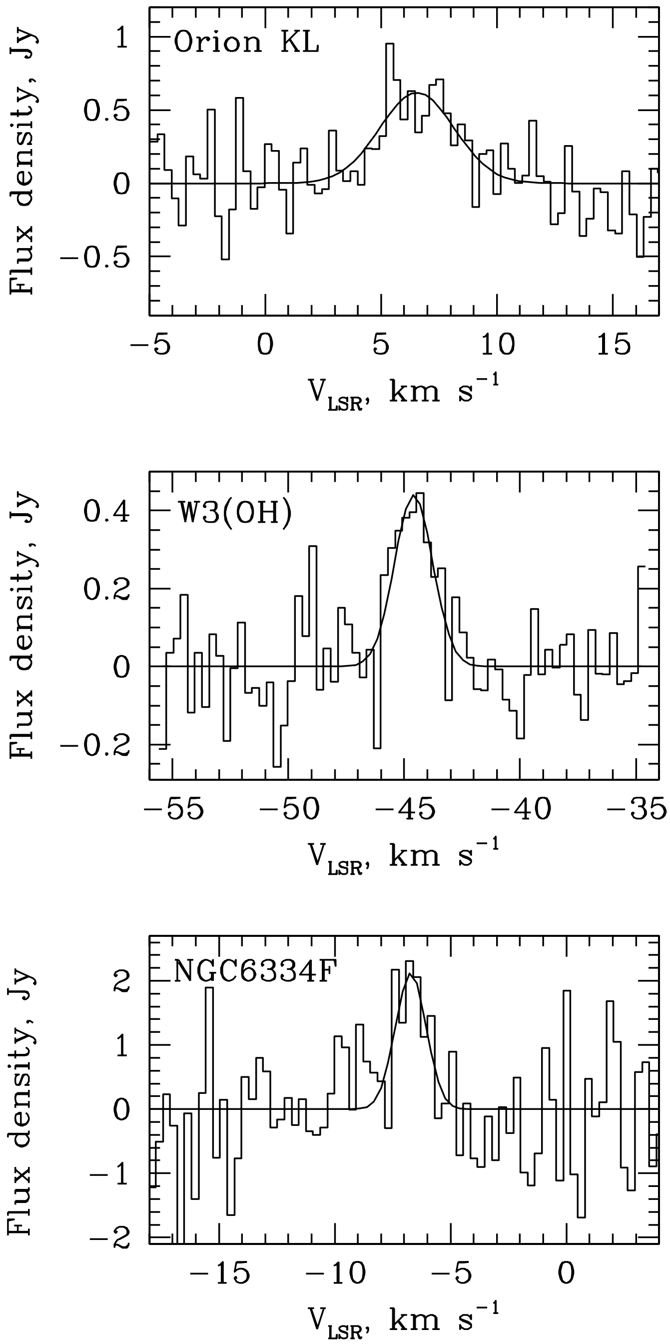

Fig. 1. Spectra of the sources detected at 44.9 GHz. Solid line represents Gaussian fit.

a complex non-Gaussian profile similar to that reported for other lines (Minh et al. 1993; Johansson et al. 1984), as well as to the 50 kHz uncertainty in the adopted rest frequency which corresponds to an uncertainty in velocity of about 0.33 km s^{-1}. If the 44.9 GHz emission comes from the MEC the flux density shown in Table 1 is slightly underestimated (we would detect about 90% of the total flux) because the position of the MEC is about $\frac{1}{4}$ of the beamwidth away from the beam center. Cragg et al. (2001) detected the $1_0{-}2_1$ E, $v_t = 1$ line at 93.1 GHz which belongs to the same $J_0-(J+1)_1$ E line series as the observed

Table 1. Sources observed at 44.9 GHz.

Source	α_{1950} (h m s)	δ_{1950} (° ′ ″)	$V_{\rm LSR}$ (km s^{-1})	$\int S(v)\,{\rm d}v$ (Jy km s^{-1})	S_ν (Jy)	Δv^a (km s^{-1})	1σ-rms (Jy)
Orion KL	05 32 46.9	−05 24 23	+6.5 (0.4)	2.5 (0.5)	0.6	3.8 (1.0)	0.3
S252	06 05 53.5	+21 39 02	+11				0.3
W3(OH)	02 23 16.5	+61 38 57	−44.6 (0.1)	0.9 (0.1)	0.4	1.9 (0.3)	0.1
NGC 6334F	17 17 32.3	−35 44 04	−6.7 (0.2)	3.5 (1.0)	2.1	1.6 (0.5)	0.9
9.62+0.19	18 03 16.0	−20 31 53	−0.7				0.3
W48	18 59 13.1	+01 09 07	+43				0.2
W75N	20 36 50.4	+42 27 23	+5				0.3

[a] Δv is the full width at half maximum (FWHM).

44.9 GHz transition. The peak velocity and the peak flux density were about 7.6 km s^{-1} and 3.5 Jy, respectively.

3.2. W3(OH)

Towards W3(OH) the $2_0{-}3_1$ E, $v_{\rm t}=1$ line has a peak at −44.6 km s^{-1}. Such a value allows us to associate this emission with the gas located in front of the ultra-compact H II region in W3(OH) rather than with the nearby (∼7″ apart) warmer region W3(H_2O) – the cluster of water vapor masers. According to Wilson et al. (1991) the gas around W3(OH) is responsible for emission at velocities greater than −45 km s^{-1} while W3(H_2O) shows a velocity of about −48 km s^{-1}. The $10_1{-}11_2$ A$^+$, $v_{\rm t}=1$ and $12_2{-}11_1$ A$^-$, $v_{\rm t}=1$ lines detected by Menten et al. (1986b) peak at a velocity of −44.0 km s^{-1} which also implies an association with W3(OH). The velocity of about −44.6 km s^{-1} falls in the range covered by masers in W3(OH), though weak masers in this source usually have the strongest spike at a velocity of −43.2 km s^{-1} (e.g., Sutton et al. 2001). The observed linewidth of the 44.9 GHz line in W3(OH) is about 1.9 km s^{-1} while broad and probably non-maser lines in this source usually have widths 2 or 3 times larger (e.g., Slysh et al. 1995; Kalenskii et al. 1997). However, torsionally excited lines detected by Menten et al. (1986b) near −44.6 km s^{-1} are as narrow as the 44.9 GHz line in our observations. This most probably reflects the fact that lines formed by transitions between levels with high excitation energy originate from a rather compact region (for example, near the exciting source) and, hence, the velocity dispersion is small in comparison to the majority of lines with considerably lower excitation energy.

3.3. NGC 6334F

NGC 6334F is a marginal detection: the peak flux density is only a factor of 2 higher than the rms noise in the spectrum (see Table 1). However, Menten & Batrla (1989) detected many non-maser lines including the torsionally excited $10_1{-}11_2$ A$^+$, $v_{\rm t}=1$ line at a velocity of about −6 km s^{-1}. This gives a hint that this feature can be real. The maser velocity of about −10.1 km s^{-1} is not present in our spectrum, so the line, if any, probably has a quasi-thermal origin. Towards this source Cragg et al. (2001) detected $1_0{-}2_1$ E, $v_{\rm t}=1$ emission at 93.1 GHz produced by a transition from the same $J_0-(J+1)_1$ E series as the 44.9 GHz line. The velocity was about −8 km s^{-1}, and the line was interpreted as quasi-thermal too.

4. Discussion

4.1. Is the 44.9 GHz emission in W3(OH) a low gain maser?

The weak 44.9 GHz line may represent either a thermal feature or a weak maser. It is possible to prove the low gain maser nature of the observed weak feature in W3(OH) by an analysis of the excitation temperature of the $2_1{-}3_0$ E transition of the ground torsional state at 19.9 GHz. The latter transition is important for two reasons. Firstly, rather strong maser emission was detected at 19.9 GHz towards W3(OH) (Wilson et al. 1985). Secondly, each level of the 44.9 GHz transition is connected by a strong allowed radiative transition with only one level of the 19.9 GHz transition and vice versa, while other transitions with a change of torsional quantum number are forbidden. These facts provide the basis for the following estimates.

The subsystem of the levels of the two transitions is given in Fig. 2, where arrows show allowed transitions. The levels 2_0, 3_1 of the first torsionally excited state and the levels 3_0, 2_1 of the ground torsional state are labeled a,b,c,d respectively. The formal definition of the excitation temperature corresponds to the following relation:

$$\frac{\nu_{\rm ab}}{T_{\rm ex,ab}}=\frac{\nu_{\rm ad}}{T_{\rm ex,ad}}-\frac{\nu_{\rm bc}}{T_{\rm ex,bc}}+\frac{\nu_{\rm dc}}{T_{\rm ex,dc}}, \tag{1}$$

where $T_{{\rm ex},ij}$ is the excitation temperature of the transition between two levels, i and j, and ν_{ij} is its frequency. From Fig. 2 it is obvious that

$$\nu_{\rm ab}=\nu_{\rm ad}+\nu_{\rm dc}-\nu_{\rm bc}. \tag{2}$$

Further, we are making the important assumption that both transitions with a change of torsional quantum number, ad and bc, have excitation temperatures equal to the

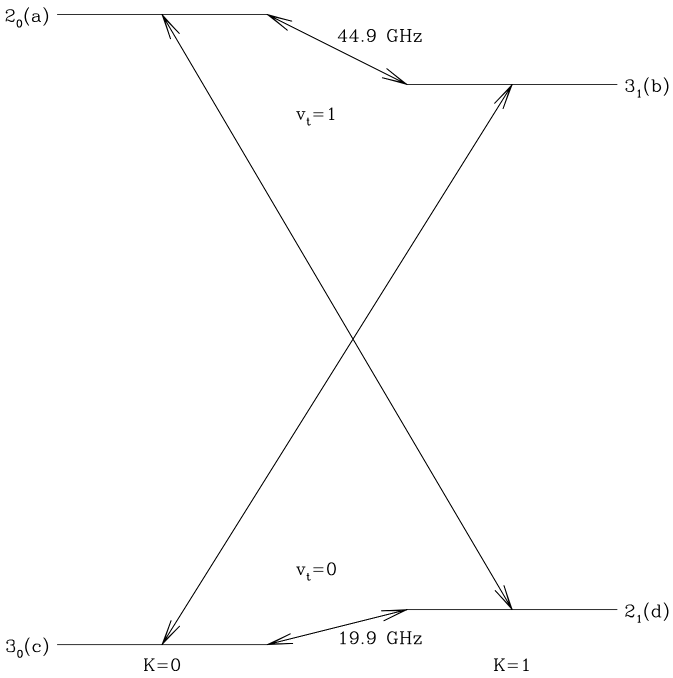

Fig. 2. Levels of 44.9 GHz and 19.9 GHz transitions. Arrows represent all allowed transitions (both upward and downward) between these levels.

temperature $T_{\rm R}$ of the external radiation field at the transition frequency of about 6×10^{12} Hz.

Methanol masers are generally assumed to be pumped by diluted emission of the hot dust (e.g., Sobolev & Deguchi 1994; Sutton et al. 2001). Hence, $T_{\rm R}$ can be derived from the dust temperature using guesses on dilution and dust opacity. The best fit model of Sutton et al. (2001) yields $T_{\rm R} \approx 83$ K while the brightness temperature at the ad frequency is 0.3 K higher than that at the bc one. In principle, such a difference helps inverting the 44.9 GHz transition (see considerations below). However, for the sake of simplicity this difference will be neglected.

The equality of excitation and radiation temperatures is expected when collisional rates for transitions between different torsional states are negligible and is confirmed by modeling (Ostrovskii, priv. comm.). So, such equality implies that for transitions ad and bc (see Fig. 2) the value of C/A is small compared to $B\overline{I}/A = W\tau_{\rm d}/(\exp{(h\nu/kT_{\rm d})} - 1)$ and $C/A \ll 1$. Here A and B are Einstein coefficients, C is the collisional transition rate and $\overline{I}$ represents the average intensity at the transition frequency ν. Further parameters of the dust layer responsible for pumping are the temperature $T_{\rm d}$, the dilution factor W and the optical depth $\tau_{\rm d}$. The experiments conducted by Lees & Haque (1974) in conjunction with a hard sphere approximation yield $C = 1.3 \times 10^{-4}$ s^{-1} for methanol collisions with para-H_2 at a hydrogen density of 10^6 cm^{-3} and a kinetic temperature of 100 K. The spontaneous emission rates for both transitions are about 0.2 s^{-1} (Mekhtiev et al. 1999), so, $C/A \approx 6.5 \times 10^{-4}$. Hence, for a dust temperature of 175 K, the collisions are negligible in comparison to induced transitions if $W\tau_{\rm d} \gg 2.7 \times 10^{-3}$. The best fit model of Sutton et al. (2001) has $W\tau_{\rm d} = 0.18$ ($W = 0.5$ and $\tau_{\rm d} = 0.36$ at a frequency around 6×10^{12} Hz). Note that collisional rates for transitions with a change of torsional quantum number are believed to be considerably lower than the values obtained using a hard sphere approximation due to a large energy separation of the levels (Umanskii 1979; Massey 1979), and this increases the prevalence of induced transitions.

It follows from (1) and (2) that

$$\frac{1}{T_{\rm ex,ab}} = \alpha \left(\frac{1-\alpha}{\alpha T_{\rm R}} + \frac{1}{T_{\rm ex,dc}} \right), \qquad (3)$$

where $\alpha = \nu_{\rm dc}/\nu_{\rm ab} > 0$ – the ratio of the frequencies. The small difference in ad and bc excitation temperatures (see above) results in an additional negative term Δ on the right side of (3), increasing the degree of 44.9 GHz inversion

$$\Delta = -\frac{\nu_{\rm ad}}{\nu_{\rm ab} T_{\rm R}} \left(\frac{\Delta T_{\rm R}}{T_{\rm R} + \Delta T_{\rm R}} \right) \approx \nu_{\rm ad} \left(1-\alpha\right) \frac{\rm d}{{\rm d}\nu} \frac{1}{T_{\rm R}}, \qquad (4)$$

where $\Delta T_{\rm R}$ is the difference between brightness temperatures of the radiation field at $\nu_{\rm ad}$ and $\nu_{\rm bc}$ (see Fig. 2 for level description). When the pumping radiation corresponds to black-body the correction equals to zero because the temperature of the radiation is constant. In the considered case of diluted radiation of the optically thin dust the value of Δ is negative because $\alpha < 1$ and the radiation temperature grows with frequency.

For the case with $\alpha < 1$ and $T_{\rm ex,dc} < 0$ the ab transition will be inverted if

$$-T_{\rm R} < \frac{1-\alpha}{\alpha} T_{\rm ex,dc} < 0. \qquad (5)$$

This expression is directly applicable to the case of the 44.9 GHz line in W3(OH) because α is about 0.44 and the 19.9 GHz transition is inverted. So, to show that the 44.9 GHz line is inverted in W3(OH) one can estimate the excitation temperature of the 19.9 GHz transition and compare it with the radiation temperature at frequencies around 6×10^{12} Hz.

The peak optical depth is determined by both the excitation temperature and the specific (divided by the line width) column density of molecules in the upper level of the considered transition. Assuming that the excitation temperature is constant throughout the source and the line profile is Gaussian, one obtains the following expression for the optical depth in the 19.9 GHz (dc) line center:

$$\tau_{\rm dc} = \frac{c^3 A_{\rm dc} \sqrt{\ln 2}}{4\pi^{3/2} \nu_{\rm dc}^3} \left(\exp\left(\frac{h\nu_{\rm dc}}{kT_{\rm ex,dc}} \right) - 1 \right) \left(\frac{N_{\rm d}}{\Delta V_{\rm dc}} \right), \qquad (6)$$

where $A_{\rm dc}$ is the spontaneous decay rate and $\Delta V_{\rm dc}$ is the full line width at half maximum (*FWHM*) for the 19.9 GHz transition, $N_{\rm d}$ is the column density of the molecules at the level d. Transformation of (6) provides us with the following dependence of the excitation temperature on τ_{dc} and the specific column density $(N_d/\Delta V_{dc})$

$$T_{ex,dc} = \frac{h\nu_{dc}}{k}\left[\ln\left(1-\beta\left(\frac{N_d}{\Delta V_{dc}}\right)^{-1}\right)\right]^{-1}, \quad (7)$$

where β denotes the critical specific column density of the molecules in the transition's upper level

$$\beta = -\frac{4\pi^{3/2}\nu_{dc}^3\tau_{dc}}{c^3 A_{dc}\sqrt{\ln 2}}. \quad (8)$$

When the specific column density is equal to β the case of maximum possible inversion is realized, i.e., there are no molecules in the lower level of the masing transition.

According to Wilson et al. (1985) the 19.9 GHz maser in W3(OH) amplifies the background emission by a factor of 100 at the peak velocity. At the velocity of the 44.9 GHz emission the flux density is about 5 times weaker, yielding the optical depth $\tau_{dc} \approx -3$. Adopting the spontaneous decay rate $A_{dc} = 1.66\times10^{-8}$ s^{-1} (Mekhtiev et al. 1999) and the rest frequency $\nu_{dc} = 19967.43$ MHz (Xu & Lovas 1997), one obtains $\beta = 1.4\times10^9$ cm^{-3} s.

The dependence (7) is almost linear for $(N_d/\Delta V_{dc}) \gg \beta$ and the condition (5) becomes

$$\left(\frac{1-\alpha}{\alpha}\right)\left(\frac{h\nu_{dc}}{k\beta}\right)\left(\frac{N_d}{\Delta V_{dc}}\right) < T_R. \quad (9)$$

This yields $(N_d/\Delta V_{dc}) < 9.2\times10^{10}$ cm^{-3} s for reasonable values of $T_R \approx 80$ K. The fraction of molecules populating the d level with respect to the total number of molecules (including both A and E species of methanol under the assumption of equal abundances) is estimated to be less than 3×10^{-3} (equilibrium value for a temperature of 175 K is about 5×10^{-4} and the value of the best fit model of Sutton et al. 2001 is about 1.5×10^{-4}), giving the condition in terms of the full specific column density $(N/\Delta V_{dc}) < 3\times10^{13}$ cm^{-3} s. Wilson et al. (1985) report a linewidth $\Delta V_{dc} < 1$ km s^{-1} for the 19.9 GHz feature at a velocity near that of the 44.9 GHz line in W3(OH). Therefore the transition at 44.9 GHz is inverted if the line at 19.9 GHz originates from a region with a methanol column density $N < 3\times10^{18}$ cm^{-2}.

Published estimates of the total column density of methanol (N) in W3(OH) are well below this limit. Using the 96 GHz emission line data Kalenskii et al. (1997) estimated N to be about 6.7×10^{15} cm^{-2}. Analysis of the 25 GHz absorption line data by Menten et al. (1986a) provides $N \approx 5.8\times10^{16}$ cm^{-2} under the assumption that all relevant excitation temperatures are equal to the estimate of the rotational temperature $T_{rot} = 73$ K. The best fit model of Sutton et al. (2001) corresponds to $N \approx 4\times10^{16}$ cm^{-2}. So, the line detected at 44.9 GHz towards W3(OH) is likely to be a low gain maser. However, our method does not allow us to determine the value of optical depth and, hence, it cannot be used to predict 44.9 GHz line intensities on the basis of observed masers at 19.9 GHz. Further, the small difference in ad and bc excitation temperatures occurring due to the difference in the brightness temperatures at the respective transition frequencies (see above) can provide an inversion of the 44.9 GHz even in the case when the associated 19.9 GHz maser is weak or absent. The gain difference as well as the difference in brightness of amplified or pumping emission between maser spots is very influential. Hence, the 44.9 GHz emission in W3(OH) may be associated with a weaker 19.9 GHz feature while the brightest 19.9 GHz feature has no 44.9 GHz counterpart.

The estimates of the 44.9 GHz optical depth using a single line are very rough and arbitrary. However, the optical depth can be estimated from the flux ratio under assumptions that the background amplification dominates in the 44.9 GHz maser output and that the continuum and the line sources in W3(OH) have the same diameter. The value of the line flux $F_l = 0.4$ Jy is small compared to the continuum flux $F_c = 3$ Jy (Wilson et al. 1991). So, the value of the optical depth is about $\tau \approx -F_l/F_c \approx -0.13$.

4.2. Non-detections of masers

Except for W3(OH), no reliable emission has been detected towards other bright Class II methanol masers. The marginal detection in NGC 6334F is at a velocity near -6.7 km s^{-1}, which is different from the typical maser velocity of -10.1 km s^{-1} and gives an argument in favor of its non-maser nature. It was shown that the inversion of the 44.9 GHz transition is expected, if the transition at 19.9 GHz is masing. Strong 19.9 GHz masers have been detected both in W3(OH) (Wilson et al. 1985) and NGC 6334F (Menten & Batrla 1989). However, in our spectrum there is not any hint of 44.9 GHz emission at the velocity of the 19.9 GHz maser in NGC 6334F. This can be explained by poor sensitivity of our NGC 6334F data. Other possibilities are the smaller (by absolute value) optical depth and the smaller brightness of background emission in comparison to W3(OH).

4.3. Application to other lines

In the case of a rather strong maser in the ground state transition the method described above can be used to predict the inversion of transitions between the levels of the first torsionally excited state with the same quantum numbers K (see Fig. 2) and close quantum numbers J (ΔJ $= 0, \pm1$). Therefore, we can consider the $1_0{-}2_1$ E, $v_t = 1$ transition at 93.1 GHz as ab instead of the $2_0{-}3_1$ E, $v_t = 1$ transition at 44.9 GHz. In this case $\alpha \approx 0.21$ and the relation (9) requires a methanol column density $N < 10^{18}$ cm^{-2} on the 93.1 GHz line inversion, which is about half an order of magnitude less then that for the 44.9 GHz line. However, the estimates of the column density cited above satisfy the relation as well. Therefore, the transition at 93.1 GHz seems also to be inverted in W3(OH). As was mentioned already, the inversion of the line can not be considered as an indication of observable masers, because the actual gain and, hence, observed brightness may be arbitrary. Information on the 93.1 GHz line in W3(OH) is not published at present.

The strongest methanol masers were found in the $5_1{-}6_0$ A$^+$ transition at 6.7 GHz (Menten 1991b) and the $2_0{-}3_{-1}$ E transition at 12.2 GHz (Batrla et al. 1987). However, corresponding lines of the first torsionally excited state have very high frequencies (about 10^{12} Hz) and very low α. So, the described method is not applicable. The situation for the bulk of known Class II maser transitions is similar, both for the A and E species of methanol.

Important exceptions, besides the $2_1{-}3_0$ E transition at 19.9 GHz, are the masers in the $9_2{-}10_1$ A$^+$ transition at 23.1 GHz and the $8_2{-}9_1$ A$^-$ transition at 28.9 GHz detected by Wilson et al. (1984, 1993). Corresponding transitions in the first torsional state are $8_1{-}9_2$ A$^+$ at 118 GHz, $9_1{-}10_2$ A$^+$ at 69.6 GHz, $10_1{-}11_2$ A$^+$ at 20.9 GHz, $7_1{-}8_2$ A$^-$ at 169 GHz, $8_1{-}9_2$ A$^-$ at 121 GHz and $9_1{-}10_2$ A$^-$ at 73.8 GHz. However, ground state masers at 23.1 GHz and 28.9 GHz are usually weaker than the 19.9 GHz maser and for most of the mentioned torsional transitions the value of α is smaller than that in the case of the 44.9 GHz line. So, the tendency of these torsional transitions to be inverted in the sources with maser emission at 23.1 GHz or 28.9 GHz is less pronounced.

Regarding the $10_1{-}11_2$ A$^+$, $v_\mathrm{t} = 1$ transition at 20.9 GHz, Menten et al. (1986b) observed this transition and concluded that it is probably inverted in W3(OH). The method described here cannot be directly applied to this transition because α is greater than 1.

4.4. Thermal nature of 44.9 GHz emission in Orion KL

Orion KL is a Class I methanol maser source and displays no maser emission at 19.9 GHz (Wilson et al. 1985) as is common for this class of objects. We cannot draw any conclusion on 44.9 GHz inversion in this case. Menten et al. (1986b) performed a Boltzmann analysis using a rotational diagram method (Johansson et al. 1984) for a number of methanol lines observed towards Orion KL including torsional excited lines. In general, the data were consistent with the assumption of LTE, yielding a rotation temperature of 139 K and a methanol column density of about 10^{17} cm^{-2} under the assumption that the source size is 30″. Our observations yield the integrated flux density $\int S(v)\ \mathrm{d}v = 2.5$ Jy km s^{-1} for Orion KL (see Table 1). Assuming $A = 3.78 \times 10^{-7}$ s^{-1} (Mekhtiev et al. 1999) for the 44.9 GHz transition, one obtains $\ln(N_\mathrm{u}/g_\mathrm{u}) = 29.0$, with a source size of 30″. In the latter equation N_u is the column density of the molecule in the upper level of the 44.9 GHz transition, and g_u is the statistical weight. The energy corresponding to the 44.9 GHz levels is about 300 K above the ground level and our data are in perfect agreement with the rotational diagram by Menten et al. (1986b). The $1_0{-}2_1$ E, $v_\mathrm{t} = 1$ line at 93.1 GHz detected by Cragg et al. (2001) belongs to the same $\mathrm{J}_0 - (\mathrm{J}+1)_1$ E line series as the observed 44.9 GHz transition and should show similar behavior. Cragg et al. (2001) find $\int S(v)\ \mathrm{d}v = 11.8$ Jy km s^{-1} for Orion KL. Along with $A = 3.74 \times 10^{-6}$ s^{-1} (Mekhtiev et al. 1999) and $E_\mathrm{u} \approx 291$ K for the 93.1 GHz transition this gives $\ln(N_\mathrm{u}/g_\mathrm{u}) = 28.8$ which is in agreement with the results of Menten et al. (1986b). Hence, both torsionally excited lines at 44.9 GHz and 93.1 GHz have a quasi-thermal nature in Orion KL.

5. Summary

We have observed the $2_0{-}3_1$ E, $v_\mathrm{t} = 1$ methanol line at 44.9 GHz towards six bright Class II methanol masers and Orion KL where this line was previously observed. We confirm (at a level of 5σ) the previous detection and report two new detections – a reliable (9σ) detection in W3(OH) and a marginal (3.5σ) detection in NGC 6334F. We show that this line may be a low gain maser in W3(OH) and probably has a quasi-thermal nature in NGC 6334F. The line in Orion KL has a quasi-thermal nature.

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