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Torsionally excited methanol in hot molecular cloud cores

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Summary. We report the detection of centimeter lines of torsionally excited methanol (CH_3OH) towards four galactic molecular cloud sources using the Effelsberg 100-m telescope. The $10_1 - 11_2A^+$ and $12_2 - 11_1A^-$ transitions from the first torsionally excited state, with excitation energies of $E/k \sim 450$ K, as well as the $10_1 - 9_2A^-$ and the $11_1 - 10_2A^+$ from the torsional ground state have been observed towards hot molecular cloud cores in the Orion-KL region, W3(OH), NGC 7538, and W51. The measured velocities and linewidths indicate that the methanol emission from Orion emerges from a distinct hot region in the southern ridge cloud, offset from the "hot core" observed e.g. in ammonia. To check this, five point maps were measured simultaneously in the torsionally excited $10_1 - 11_2A^+$ line and in the (6, 4) line of ammonia. From these data we find the methanol peak at a position $\sim 4''$ south of the hot core. In all of the observed sources deviations from LTE appear which are most pronounced if a strong compact continuum source is present such as towards W3(OH) and NGC 7538. Towards W3(OH), the $10_1 - 11_2A^+$ transition appears to be inverted. It is shown that for the sources observed, radiative and collisional excitation are both capable of populating the torsionally excited levels.

Key words: interstellar medium: abundances – molecules – radio lines: molecular

1. Introduction

Torsionally excited ($v_t = 1$) methanol was first detected towards the Orion Kleinmann-Low (KL) nebula by Lovas et al. (1982) who measured three E-type $v_t = 1$ transitions at frequencies in the range 93–100 GHz. This result was followed up by Hollis et al. (1983) who confirmed the line identifications and fit the column densities derived from both ground ($v_t = 0$) and excited state data to a Boltzmann relationship. Their data implied a rotation temperature of 90 K for the ground state transitions and 200 K for the $v_t = 1$ transitions. More recently, the results of the Onsala and Caltech spectral scans have become available (Johansson et al., 1984, Sutton et al., 1985). These confirmed that the methanol lines are formed in a hot compact region, which however is distinct from the "hot core" region seen in ammonia and many other nitrogen rich molecules (see e.g. Pauls et al., 1983; Hermsen et al., 1985). The ammonia hot core region has a mean L.S.R. velocity of 5–6 km s^{-1} as compared to 7–8 km s^{-1} for even the highly excited (200–400 cm^{-1}) methanol lines. The methanol lines appear to form in a portion of the ridge (spike) gas abutting upon Orion-KL. Presumably, these regions are heated by infrared sources in this complex.

The Orion-KL region is unlikely to be unique. Indeed, searches for methanol masers analogous to those found in Orion ($5_2 - 5_1E$, $6_2 - 6_1E$ etc.) have found several sources of narrow (0.5 km s^{-1}) line emission in regions of star formation (Menten et al., 1986). These observations show, however, that the $J_2 - J_1$ series of transitions of E-type methanol is not necessarily always inverted. Towards a number of sources, quasi-thermal emission is observed. Towards W3(OH) and NGC 7538 one observes these lines in absorption against the background continuum radiation of the compact H II region. The apparent rotation temperatures towards W3(OH) and NGC 7538 are of order 70–80 K and hence one is again observing relatively hot methanol clumps. In other lower frequency (~ 20 GHz) transitions by contrast, one observes maser emission towards W3(OH) and probably also towards NGC 7538 (Wilson et al., 1984, 1985; Menten et al., 1985). This presumably occurs because the transitions in question are b-type $\Delta k = \pm 1$ transitions, which are very sensitive to slight inbalances between the populations of the various k-ladders. For example, a slight overpopulation of, say, the E-type $k = 2$ ladder relative to $k = 1$ can cause inversion of the $J_2 - J_1$ series of lines while the inverse situation will produce enhanced absorption. Low frequency b-type CH_3OH transitions are consequently good tracers of small departures from local thermodynamic equilibrium (LTE). They are most sensitive to such departures when the methanol cloud is viewed against the background of a radio continuum source, since in this case the line intensity depends most sensitively on the CH_3OH optical depth.

With this in mind, we have made a study of two torsionally excited ($12_2 - 11_1A^-$ and $10_1 - 11_2A^+$) and two ground state ($10_1 - 9_2A^-$ and $11_1 - 10_2A^+$) transitions in the 20 – 24 GHz frequency interval using the Effelsberg 100-m telescope. Figure 1 gives an overview of the observed transitions which range up to an excitation of 480 K above ground. We have detected both $v_t = 1$ lines towards W3(OH), NGC 7538, and Orion and the $v_t = 1$, $10_1 - 11_2A^+$ line towards W51, and discuss conditions towards these three sources. The energies of both of the observed ground state lines lie only little above those of the highest $J_2 - J_1$ transitions of E-type methanol observed by Menten et al. (1986), and

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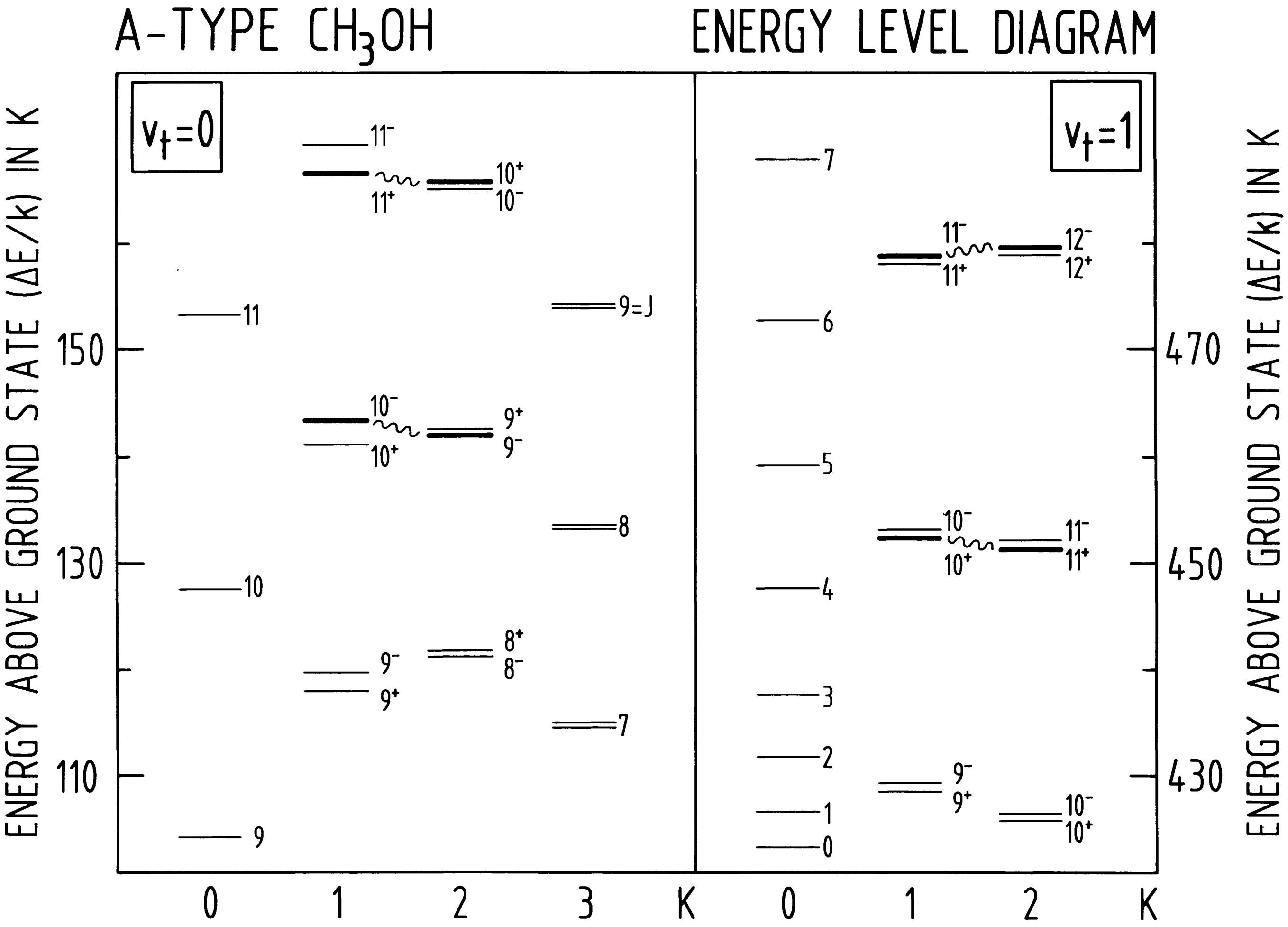

Fig. 1. Extracts from the level diagrams of A-type methanol in the torsional ground ($v_t = 0$) and the first torsionally excited ($v_t = 1$) state. The wavy lines indicate the transitions observed by us. For clarity reasons, the K-doublet splittings have been enlarged, except in the case of the $v_t = 0$, $K = 1$ stack

thus the properties of A- and E-type methanol of roughly equal excitation energies can be studied. Since A-type methanol does not interconvert with the E-species, a comparison of the data for both the A- and the E-species can yield information about the dominant excitation mechanism.

2. Observations

All observations were carried out using the Effelsberg 100-m telescope of the MPIfR. Details of the observed lines and observing dates are given in Table 1. A K-band maser receiver ($T_{sys} \sim$ 80–100 K) was used and the spectra were analysed using a 1024 channel autocorrelator. At a bandwidth of 12.5 MHz the velocity resolution was 0.17 km s^{-1} per channel. During the February 1986 observing session, the autocorrelator was split into two halves of 6.25 MHz bandwidth each, in order to measure the CH_3OH $v_t = 1$, $10_1 - 11_2A^+$ and the (6,4) line of NH_3 simultaneously. In this case the velocity resolution also was 0.17 km s^{-1} per channel. Some of the $10_1 - 9_2A^-$ spectra were taken with a bandwidth of 25 MHz, and, correspondingly, a resolution of 0.31 km s^{-1}. Continuum scans of W3(OH) and NGC 7027 were used to establish a main-beam brightness temperature scale, assuming flux densities for these sources of 3 Jy and 5.86 Jy, respectively. At 21 GHz one Jansky per beam corresponds to 1.4 K main-beam brightness temperature T_B, and the beam size is 44″. Uncertainties in the absolute calibration due to atmospheric effects and pointing errors should be smaller than 20%. Observed spectra are shown in Fig. 2–5 and Table 2 lists the derived line parameters.

Table 1. Details of observed CH_3OH transitions

v_t	Transition	ν (MHz)	E_l (cm^{-1})	Observing dates
0	$10_1 - 9_2A^-$	23444.82	98.80	Feb. 1984
0	$11_1 - 10_2A^+$	20171.07	114.96	Dec. 1984
1	$10_1 - 11_2A^+$	20970.65	313.67	Dec. 1984, Feb./July 1985, Feb. 1986
1	$12_2 - 11_1A^-$	21550.31	332.22	Dec. 1984

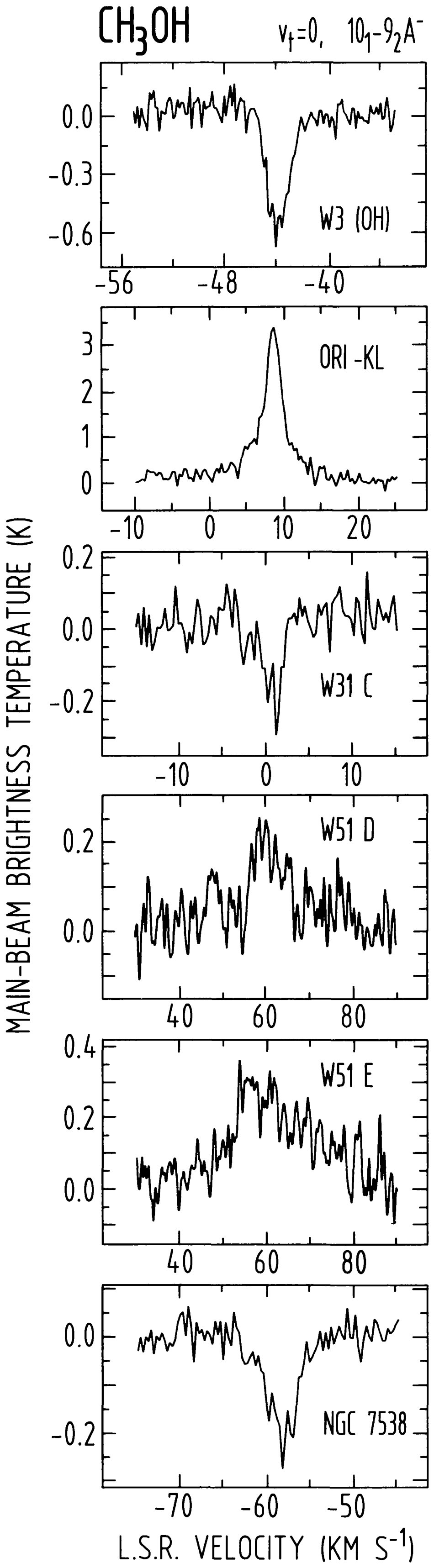

Fig. 2. Observed spectra of the $v_t = 0$, $10_1 - 9_2A^-$ line. The velocity resolution is $0.17\,\mathrm{km\,s^{-1}}$ for W3(OH) and NGC 7538, and $0.34\,\mathrm{km\,s^{-1}}$ for Ori-KL and W31C. The W51D and *E* spectra have been smoothed to a resolution of $0.5\,\mathrm{km\,s^{-1}}$.

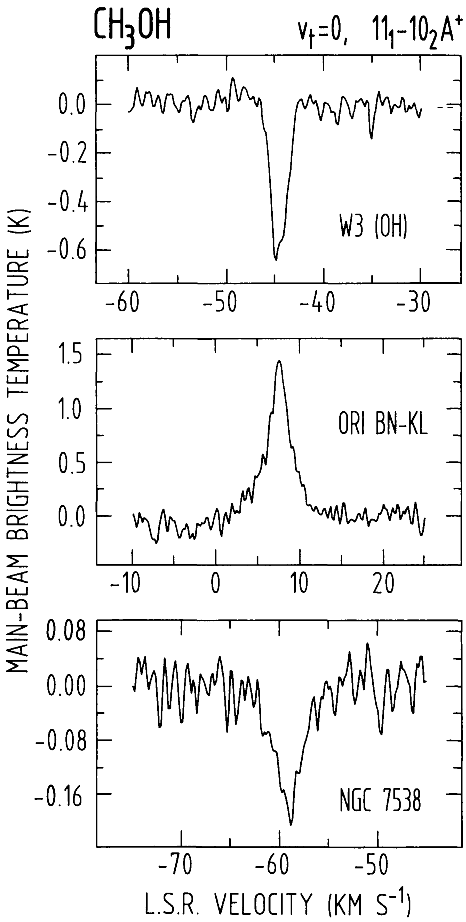

Fig. 3. Observed spectra of the $v_t = 0$, $11_1 - 10_2A^+$ line. The spectra have been Hanning-smoothed to an effective velocity resolution of $0.28\,\mathrm{km\,s^{-1}}$.

3. Results and discussion

3.1. *Orion-KL*

3.1.1. The methanol emission core (MEC)

Earlier work on lower energy lines has shown that the region in Orion-KL which shows the strongest CH_3OH emission is located between $\sim 10''$ and $20''$ south of our (0,0)-position ($\alpha_{1950} = 05^h32^m46\overset{s}{.}7$, $\delta_{1950} = -05°24'21''$) and thus south of BN-KL and IRc 2, and that its extent is $\lesssim 30''$ (Olofsson, 1984; Wilson et al., 1985). These estimates are in agreement with the values found from the 25 GHz data of Hills et al. (1975) for the broad feature in their spectra underlying the maser spikes. Interferometric measurements by Matsakis et al. (1980) have shown that the

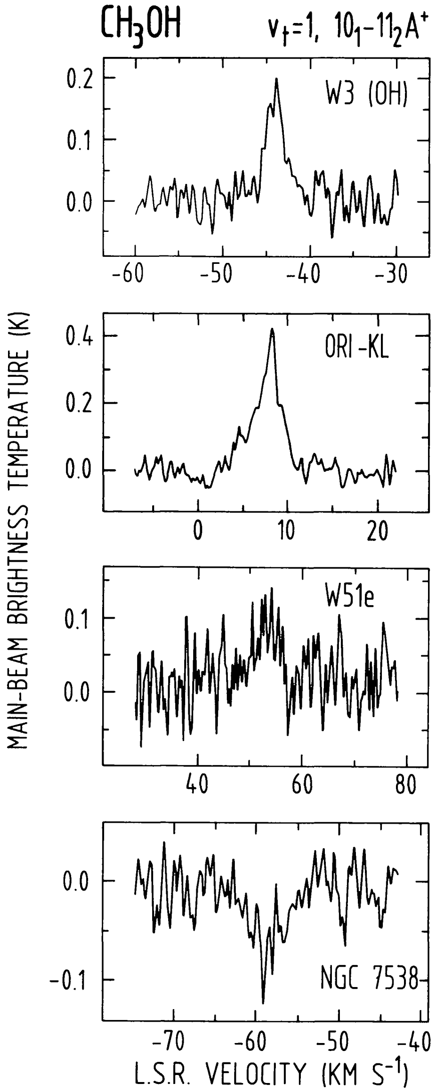

Fig. 4. Same as Fig. 3 for the $v_t = 1$, $10_1 - 11_2 A^+$ line

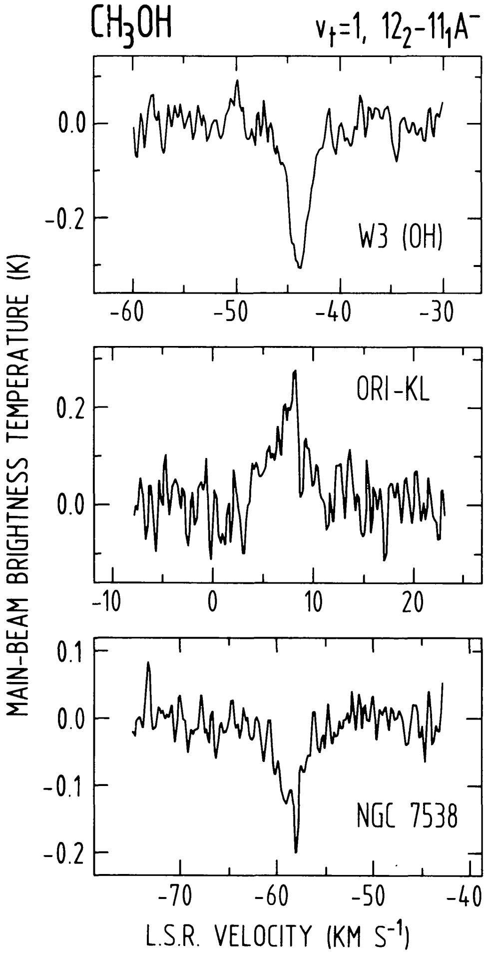

Fig. 5. Same as Fig. 3 for the $v_t = 1$, $12_2 - 11_1 A^-$ line

distribution of the intense 25 GHz masers is more widespread, although one component with an L.S.R. velocity of 7.8 km s^{-1} lies in the region concerning us here. Our L.S.R. velocity ($\sim$7.5 km s^{-1}) is within the errors identical to that which Lovas et al. (1982) determined from their 96 GHz $v_t = 1$ data and to the average value which Sutton et al. (1985) derive for the $v_t = 1$ lines in their 240 GHz methanol data. Lower excitation CH_3OH lines are narrower with somewhat higher velocities of $\sim$8.2 km s^{-1} (Johansson et al., 1984; Sutton et al., 1985). It should be noted that several of the lower excitation lines show broad wings and that their line shapes can be best fit by the sum of one component with $\Delta v \sim 2.5$ km s^{-1}, $v_{LSR} \sim 8.2$ km s^{-1} and a weaker feature with $\Delta v \sim 5.5$ km s^{-1}, $v_{LSR} \sim 8$ km s^{-1} (Johansson et al., 1984; Wilson et al., 1985). Our linewidths of order of 4 – 5 km s^{-1} are of the same order as the values found by other authors for highly excited CH_3OH mm-lines.

To determine the offset of the Methanol Emission Core (MEC) observed in torsionally excited CH_3OH relative to the hot core, we utilized the fact that the (6, 4) line of ammonia (NH_3) has a frequency only 24 MHz higher than the $10_1 - 11_2 A^+$ line of torsionally excited methanol. Hence, it is possible to measure both lines simultaneously using the maser receiver together with the 1024 channel autocorrelator in split mode. The relative intensities of the CH_3OH and NH_3 spectra obtained in this way are free from calibration errors. As NH_3 emission from levels as highly excited as the (6, 4) inversion doublet ($E/k = 513$ K) emerges predominantly from the hot core, a comparison of the measured spatial distribution of each molecule provides a sensitive means to check for offsets between the NH_3 and CH_3OH peaks.

We observed five points with offsets (0, 0), (0, −20″), (0, 20″), (−20″, 0), and (20″, 0) relative to our central position (Fig. 6). This five point raster was repeated until we reached an R.M.S. noise in main-beam brightness temperature of 0.03 K per channel for the (0, 0), and 0.04 K per channel for the other positions. The NH_3 spectra (Fig. 6) have typical hot core profiles. The CH_3OH profiles have a complicated shape and cannot be fit easily by gaussians. We used a least-squares method to fit a circular gaussian source model to the data for each molecule. Free parameters were intensity and position of the emission peak as well as the

Table 2. Measured line parameters

v_t	Transition	Source	Offset[a)] (arc sec)	T_B[b)] (K)	V_{LSR} (km s^{-1})	Δv (km s^{-1})	Notes
0	10_1-9_2 A^-	W3(OH)	(0,0)	0.05 (0.01) -0.66 (0.02)	-47.7 (1.0) -43.8 (0.1)	9.4 (1.9) 2.0 (0.1)	c)
		Ori-KL	(0,0)	2.20 (0.11) 1.07 (0.10)	8.6 (0.1) 8.2 (0.1)	1.9 (0.1) 6.9 (0.5)	d)
		W31	(0,0)	-0.23 (0.03)	0.8 (0.1)	2.4 (0.3)	
		W51D	(0,0)	0.16 (0.02)	60.3 (0.5)	6.6 (1.2)	
		W51E	(0,0)	∿0.25	∿59	∿15	
		DR21(OH)	(0,0)	<0.17	-	-	
		DR21	(0,0)	<0.18	-	-	
		NGC7538	(0,0)	-0.21 (0.01)	-58.3 (0.1)	4.4 (0.3)	
0	11_1-10_2 A^+	W3(OH)	(0,0)	-0.65 (0.03)	-44.6 (0.1)	1.9 (0.1)	
		Ori-KL	(0,0)	0.80 (0.10) 0.67 (0.10)	7.6 (0.1) 7.3 (0.2)	1.7 (0.2) 5.7 (0.5)	d)
		NGC7538	(0,0)	-0.17 (0.02)	-59.1 (0.2)	3.5 (0.4)	
1	10_1-11_2 A^+	W3(OH)	(0,0)	0.16 (0.01)	-44.0 (0.1)	2.4 (0.2)	
		Ori-KL	(0,0)	0.22 (0.02) 0.21 (0.03)	7.5 (0.1) 8.1 (0.1)	4.7 (0.4) 0.9 (0.2)	d),e)
			(0,-20)	0.25 (0.03) 0.18 (0.06)	7.7 (0.1) 7.9 (0.1)	3.9 (0.4) 0.7 (0.2)	d),e)
			(0,20)	0.10 (0.02)	7.6 (0.4)	4.0 (0.9)	e)
			(-20,0)	0.22 (0.02)	7.8 (0.2)	4.8 (0.4)	e)
			(20,0)	0.18 (0.02)	7.6 (0.2)	3.8 (0.5)	e)
		Sgr B2	(0,0)	<0.53	-	-	
			(0,60)	<0.68	-	-	
		W31	(0,0)	<0.48	-	-	
		W51D	(0,0)	<0.25	-	-	
		W51E	(20,-15)	0.08 (0.02)	53.1 (0.4)	4.8 (1.0)	f)
		DR21(OH)	(0,0)	<0.12	-	-	
		NGC7538	(0,0)	-0.06 (0.01)	-58.7 (0.3)	4.8 (0.9)	
1	12_2-11_1 A^-.	W3(OH)	(0,0)	-0.30 (0.02)	-44.0 (0.1)	2.3 (0.2)	
		Ori-KL	(0,0)	0.18 (0.03)	7.5 (0.3)	3.9 (0.6)	
		NGC7538	(0,0)	-0.13 (0.01)	-58.6 (0.2)	3.3 (0.4)	

Notes:

Errors are 1σ deviations from gaussian fits.

a) Offsets are $(\Delta\alpha,\Delta\delta)$ relative to the positions given in Table 1 of Menten et al. (1986).

b) Upper limits are peak-to-peak noise limits. For sources with a detected line, T_B is peak main-beam brightness temperature.

c) One emission and one absorption component used in fit.

d) Two emission components used in fit.

e) Complicated line shape which is poorly fit by gaussians.

f) The offset corresponds to the position of the compact HII regions W51e_1/e_2 (Ho et al. 1983).

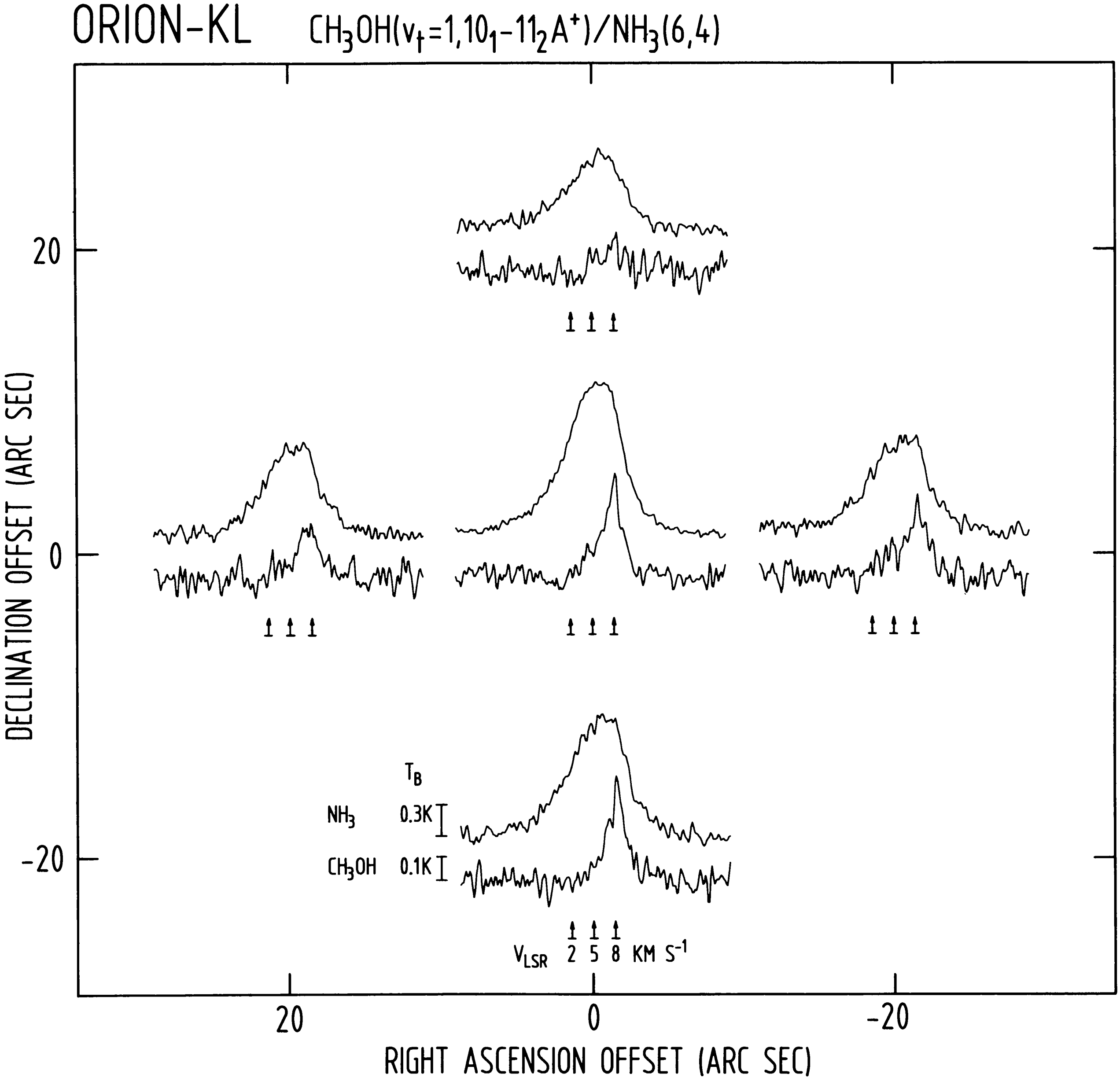

Fig. 6. Five point map of the CH_3OH $v_t = 1$, $10_1 - 11_2A^+$ line (lower spectrum of each pair) and the (6, 4) line of NH_3. Both lines were measured simultaneously. The offsets are $\pm 20''$ in right ascension and declination. The center position is ($\alpha = 05^h32^m46\overset{s}{.}7$, $\delta = -05°24'21''$). The arrows indicate L.S.R. velocities of 2, 5, and $8\,\mathrm{km\,s^{-1}}$. The spectra have been Hanning smoothed to an effective velocity resolution of $0.28\,\mathrm{km\,s^{-1}}$

source size. Such a fit was performed for every line channel in the velocity range 5.5 to $9.5\,\mathrm{km\,s^{-1}}$ (23 channels) for CH_3OH and -1.5 to $11.5\,\mathrm{km\,s^{-1}}$ (76 channels) for NH_3. We used the R.M.S. values given above as uncertainties for the input values. The final results, obtained by calculating the weighted mean of the single channel results, are presented in Table 3.

Although the MEC has to be "hot" in order to excite the transitions observed by us, the CH_3OH velocities and position rule out an identification of this region with the "hot core" ($v_{LSR} \sim 5\,\mathrm{km\,s^{-1}}$, $\Delta v \sim 10\,\mathrm{km\,s^{-1}}$) observed in NH_3 and several other molecules. However, it seems clear that the MEC is a well defined portion ($\leq 20''$) of the southern compact ridge cloud on the northern edge of the compact H_2CO emission mapped by Johnston et al. (1983) using the VLA. In this region one also finds the $(CH_3)_2O$ maximum (Friberg, 1984, Olofsson, 1984), CH_3OOCH (Johansson et al., 1984), and the southern component of the HDO emission (Olofsson, 1984). All these molecules are observed at velocities of ~ 7–$8\,\mathrm{km\,s^{-1}}$. CH_3CN emission from warm gas is observed towards both the MEC and the hot core (Andersson, 1985). In this context, it is interesting to note that the ^{13}CO interferometer measurements of Masson et al. (1986) show, besides the $5\,\mathrm{km\,s^{-1}}$ peak identifying the hot core, a second maximum at $7.7\,\mathrm{km\,s^{-1}}$ which is likely to be coincident with the MEC.

Table 3. NH_3 and CH_3OH source parameters determined by least-squares fit to our 5-point map

	$\Delta\alpha$ (arcsec)	$\Delta\delta$ (arcsec)	Deconvolved source size θ_S (arcsec)
NH_3	-0.7 ± 0.1	-5.5 ± 0.1	<18
CH_3OH	-3.2 ± 0.7	-9.0 ± 0.8	<17

Notes:
a) Offsets are relative to ($\alpha = 05^h32^m46\overset{s}{.}7$, $\delta = -05°24'21''$).
b) The source size given is $\theta_S = (\theta_F^2 - \theta_B^2)^{1/2}$, where θ_F is the half-power width of the gaussian source determined by the fit and θ_B the telescope beam (44″).
c) The errors given are 1σ formal errors of the weighted mean calculated from the results of the fits to the single line channels. These errors affect the *relative* positions of the NH_3 and CH_3OH emission centroids. The *absolute* positions are more uncertain due to an R.M.S. pointing error of $\pm 3''$

3.1.2. Rotation temperature and methanol column density in Orion

To determine the temperature and CH_3OH column density of the methanol distribution in Orion-KL, we constructed a rotation temperature diagram analogous to that of Johansson et al. (1984) including data from the line surveys of Johansson et al. and Sutton et al. (1985) as well as a number of Effelsberg measurements (see Fig. 7). Differing angular resolutions are taken into account by assuming the methanol source to be a gaussian source with an HPW of 30″ (an upper limit to its true size (Boland et al., 1983; Olofsson, 1984)). From this diagram we derive a rotation temperature of $T_R = 139 \pm 2$ K and a methanol column density (averaged over 30″) of $N(CH_3OH) = (9.8 \pm 0.4)\ 10^{16}\ cm^{-2}$. The uncertainties given are formal errors from the fit. This column density is in excellent agreement with the values given by Johansson et al. (1984) and Sutton et al. (1985) if one corrects their results for beam dilution. It is important, however, to note that the rotation temperature diagram method can only provide a rather crude means of determining temperatures in a region as complex as Orion-KL. The diagram is especially affected by the following phenomena:

a) The extent and position of the Orion methanol source may be different for transitions of different energy. For example, one can imagine for energetic reasons that very hot gas, as probed by torsionally excited methanol, is confined to a rather small region in the vicinity of the dominant heating sources (such as IRc 2), whereas low excitation emission may emerge from a region more extended and further away. Observational evidence for the last point is the fact that the peak of torsionally excited methanol lies only $\sim 4''$ south of the hot core, whereas Wilson et al. (1985) report an offset of $\sim 15''$ south for the low energy $2_1 - 3_0E$ line ($E/k = 19$ K).

b) In preparing the rotation temperature diagram, we assumed all transitions to be optically thin. This is certainly not true as can be seen from the detection of $^{13}CH_3OH$ lines by Johansson et al. (1984) and Blake et al. (1984) which point to $^{12}CH_3OH$ optical depths of ~ 2 in the $5_{-1} - 4_0E$ line at 85 GHz and ~ 4 in the series of $J = 5 - 4$ *a*-type transitions at 240 GHz (if one uses the observed $T_A(^{12}CH_3OH)/T_A(^{13}CH_3OH)$ ratios and assumes $^{12}CH_3OH/^{13}CH_3OH = {}^{12}C/^{13}C = 60$). The increase of optical depth with frequency and the fact that the transitions with the lowest excitation energies have the highest optical depths explain why the estimated column densities (N_1/g_1) of low energy Onsala lines (75 GHz $< \nu <$ 90 GHz) are systematically lower than those of the *K*-band lines observed at Effelsberg (19 GHz $< \nu <$ 24 GHz) and higher than the OVRO values (215 GHz $< \nu <$ 247 GHz). Because the Effelsberg lines are most likely optically thin, we have fit them separately and obtain $T_R = 109 \pm 5$ K and $N(CH_3OH) = (3.3 \pm 0.4)\ 10^{17}\ cm^{-2}$. Thus we conclude that T_R lies between 110 K and 140 K and $N(CH_3OH)$ (assuming a 30″ source) between $10^{17}\ cm^{-2}$ and $3\ 10^{17}\ cm^{-2}$.

c) Uncertainties in the absolute calibration of data taken at different telescopes also affect Fig. 7. It is of course ideal when

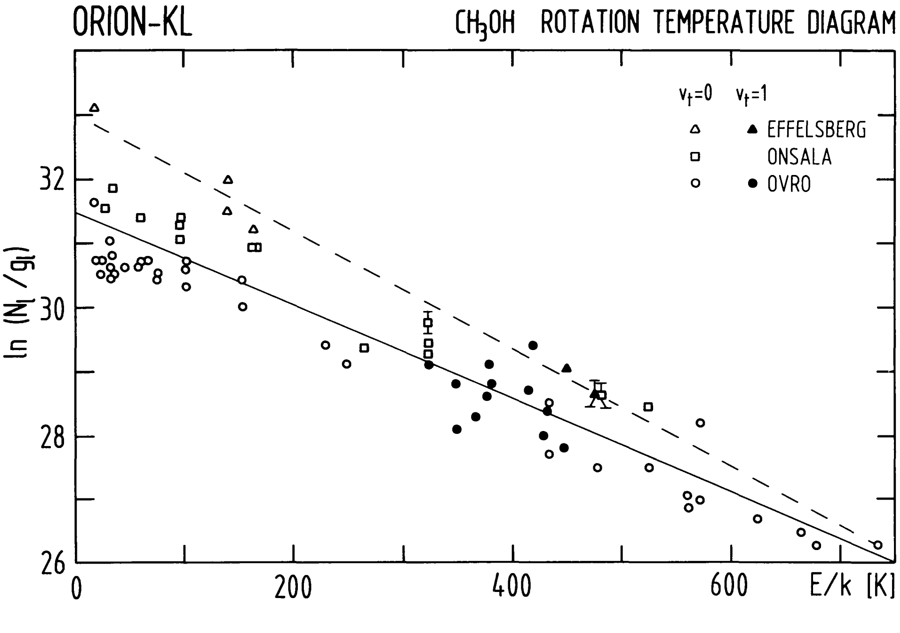

Fig. 7. Rotation temperature diagram (normalized column density vs. excitation energy) for a variety of methanol lines observed towards Orion-KL. Error bars have been plotted only if $\Delta(N_1/g_1) > 0.15$ (corresponding to 10% errors in T_B and Δv). The Effelsberg points represent the $2_1 - 3_0E$ and $9_2 - 10_1A^+$ lines (Wilson et al., 1984, 1985) and the data reported in this work. The Onsala data are taken from Johansson et al. (1984) and the OVRO data from Sutton et al. (1985). The full line is the fit to all data ($T_R = 139$ K) discussed in the text, and the dashed line is a fit to the Effelsberg data alone

one has available simultaneous measurements of ground state and torsionally excited lines (see Hollis et al., 1983).

Although the data in general are consistent with the assumption of LTE for all energy levels, it should be noted that the intensity of our $v_t = 1$, $10_1 - 11_2 A^+$ line is almost twice that of the $12_2 - 11_1 A^-$, whereas one expects equal intensity for both lines. Hence, departures from LTE may occur, but these are less important than for sources where an intense background continuum source is present, as in the cases of W3(OH) and NGC 7538 discussed below.

3.1.3. Methanol abundance

Using the methanol column density derived above and the recent dust continuum measurements at 113 GHz (Masson et al., 1985), we can compute an upper limit for the CH_3OH abundance in the MEC. From Masson et al.'s continuum map and their derived peak H_2 column density of $N(H_2) \sim 10^{24}\,cm^{-2}$ we estimate $N(H_2) \sim 10^{23}\,cm^{-2}$ for the central part of the MEC, thus arriving at a CH_3OH/H_2 ratio of $1 - 3\,10^{-6}$ which is somewhat higher than the result of Irvine and Hjalmarson (1984). This is at the high end of the methanol abundances which Menten et al. (1986) estimate for hot compact condensations in various molecular clouds. Compared with the CH_3OH/H_2 ratio of 10^{-9} for the cold dark cloud TMC-1 (Hjalmarson, 1985), it becomes obvious that the methanol abundance is substantially enhanced in these hot molecular cores. The methanol abundance can be higher than the value given above if the emitting region is appreciably smaller than the 30″ assumed in this work. Herbst and Leung (1986) have included one model with elevated temperature (50 K) in their most recent study of gas phase chemistry in dense molecular clouds, in order to approximate the conditions in the Orion ridge cloud. However, their model calculations predict a higher methanol abundance for TMC-1 than for Orion, and yield a value which is three orders of magnitude lower than our result. This suggests that non-gas-phase formation mechanisms are operating in the Orion MEC.

3.2. *W3 (OH)*

This source is seen in absorption in the $J_2 - J_1$ ($J = 2, 3, 4, 5, 6, 9$) transitions of E-type methanol (Menten et al., 1986). Wilson et al. (1984) found the $9_2 - 10_1 A^+$ line to be masing. VLA observations by Menten et al. (1985) confirmed this and showed the maser emission coming from two regions in the vicinity of the well studied OH maser spots (see e.g. Guilloteau 1982). Even stronger maser emission (~ 60 Jy) was detected in the $2_1 - 3_0 E$ transition (Wilson et al., 1985). The velocity range covered by the maser features coincides with that of the lines reported in this work, as well as with the velocities of the $J_2 - J_1 E$ lines. The linewidths of all non-maser lines are also in good agreement.

Both of the $v_t = 0$ lines reported here appear in absorption. The $v_t = 1$, $12_2 - 11_1 A^-$ line is also in absorption, while the $v_t = 1$, $10_1 - 11_2 A^+$ is in emission. The weak, broad emission feature, evident in the $J_2 - J_1$ lines overlaps with the blue side of the absorption. This emission is very weakly present in our $v_t = 0$, $10_1 - 9_2 A^-$ spectrum, and there may be a small indication of it in the other $v_t = 0$ line. Using the rotation temperature of 73 K and the CH_3OH column density ($7.9\,10^{14}\,T_{ex}\,cm^{-2}$) determined by Menten et al. (1986) from E-type methanol data, one calculates, under assumption of equal excitation temperature T_{ex} for all transitions, a line intensity for the absorption lines which is too low by factors of ~ 5 for both of the $v_t = 0$ lines, and ~ 140 for the $v_t = 1$, $12_2 - 11_1 A^-$ absorption if compared with the values observed by us. If one considers that the excitation energies of the $v_t = 0$, $10_1 - 9_2 A^-$ and $9_2 - 9_1 E$ lines are comparable, this implies large departures from LTE in the excitation temperatures of K-band CH_3OH lines. In particular, the results suggest $T_{ex}(10_1 - 9_2 A^-) \sim 1/5 T_{ex}(9_2 - 9_1 E)$. The A-type K-band absorption lines have probably excitation temperatures well below the gas kinetic temperature in W3(OH). In addition, to account for the torsionally excited lines, one presumably requires an excitation temperature higher than 100 K between $v_t = 0$ and $v_t = 1$.

Menten et al. (1986) have proposed that pumping by FIR radiation at ~ 50 microns is responsible for populating torsionally excited $v_t = 1$ levels which subsequently decay into the ground state. Because of the selection rules for torsional excitation ($\Delta K = \pm 1$) which result effectively in $\Delta K = \pm 2$ after a $v_t = 0 - 1$ and subsequent $v_t = 1 - 0$ transition, it is possible to have one K-stack overpopulated relative to its neighbours. In the case of W3(OH), this process explains the absorption between the $v_t = 0$ levels in the $K = 1$ and $K = 2$ stacks for A-type methanol ($10_1 - 9_2 A^-$, $11_1 - 10_2 A^+$) and the $9_2 - 10_1 A^+$ maser, and it appears that the $K = 2$ stack is overpopulated relative to the $K = 1$. The $v_t = 1$ transitions also show the "right" behaviour: Here, the $K = 1$ stack should be overpopulated relative to the $K = 2$, and indeed one observes the $12_2 - 11_1 A^-$ line in absorption and the $10_1 - 11_2 A^+$ in emission. In the latter case, the agreement of the line parameters with those of the absorption lines is fairly conclusive evidence that the transition is inverted but with small optical depth. In E-type methanol, the stacks with odd K seem to be overpopulated relative to those with even K for the torsional ground state as is evident from the absorption in the $J_2 - J_1$ lines and the $2_1 - 3_0$ maser.

3.3. *NGC 7538*

Excitation conditions for $v_t = 0$ methanol in NGC 7538 seem to follow the same pattern as in W3(OH): Both ground state lines observed by us are in absorption towards NGC 7538 as well as towards W3(OH). The same is true for the $J_2 - J_1 E$ lines measured by Menten et al. (1986). It is also probable that the $9_2 - 10_1 A^+$ line is masing in NGC 7538 with a maser luminosity of one tenth the W3(OH) value (Wilson et al., 1984). In view of these similarities one is tempted to apply the excitation scheme outlined for W3(OH) in the preceding section also to the case of NGC 7538. However, if the torsionally excited transitions observed by us are taken into account, there is a difference between the two sources: The $10_1 - 11_2 A^+$ line which is in emission in W3(OH) is seen in absorption towards NGC 7538. As in the case of W3(OH) however, the observed line intensities are higher than one expects from an extrapolation of the E-type methanol results of Menten et al. (1986) ($N(CH_3OH) = 1.3\,10^{15}\,cm^{-2}$, $T_R = 85$ K). The discrepancy is a factor of ~ 3 for both $v_t = 0$ transitions and ~ 20–40 for the $v_t = 1$ lines. Hence, departures from LTE are not quite so extreme as in W3(OH) but are considerable, nevertheless.

3.4. *W51*

Torsionally excited methanol (the 10_1–$11_2 A^+$ line in emission) was also detected towards W51 e_1/e_2. These compact H II regions are associated with dense clumps of hot molecular gas as probed by VLA observations of NH_3 (Ho et al., 1983). The distribution of lower energy methanol emission in the W51 region seems to be rather widespread as experience with the $J_2 - J_1E$ lines shows (Menten et al., 1986). We detected the $v_t = 0$, $10_1 - 9_2A^+$ line towards W51E and W51D (or IRS 1 and IRS 2 in the nomenclature of Ho et al., 1983). The observed line intensities are in both cases about a factor of 2 higher than expected from the E-type methanol data. The evidence suggests that in these cases, background continuum emission plays no role and, as a consequence, one does not see such drastic departures from LTE as in the cases of W3(OH) and NGC 7538. However, the fact that departures do occur suggests that some of the ground state E-type transitions are optically thick.

3.5. *W31C*

We observed absorption towards W31C (G10.6–0.4) in the $v_t = 0$, $10_1 - 9_2A^-$ line. The measured L.S.R. velocity agrees well with that of the NH_3 absorption observed by Ho and Haschick (1986) using the VLA. These high resolution measurements reveal the existence of several velocity components observed either in emission, or, if viewed against the compact continuum source, in absorption. Although no emission is observed in the $10_1–9_2A^-$ line, the $J_2 - J_1E$-type transitions with lower excitation energies ($J = 2, 3, 4, 5, 6$) show a broad emission feature as well as two maser spikes in the same velocity range as the NH_3 emission (Menten et al., 1986). The offset measurements of Menten et al., have shown that the broad emission feature is point-like relative to their 40″ beam, and that its position is 5″ north of the continuum peak, while the masers are situated 10″ NE of the continuum. These positions are also consistent with the VLA NH_3 results of Ho and Haschick.

3.6. *Excitation mechanism*

Under the conditions found in hot dense cloud cores which we probe by torsionally excited lines of methanol, collisional and radiative excitation are probably competitive processes. In the following we discuss qualitatively some observational constraints on both mechanisms.

As described in Sect. 3.2., a radiative pump mechanism is capable of producing the pattern of (maser-)emission and absorption lines observed in the case of W3(OH). Menten et al. (1986) estimate that minimum dust temperatures of $T_D \sim 50$ K are necessary to pump ground state levels via this scheme. This is consistent with $T_D = 45$ K determined by Thronson and Harper (1979) from their FIR observations of W3(OH). However, temperatures of this order of magnitude do not explain the observations of pure rotational transitions between levels within the $v_t = 1$ state. As Lovas et al. (1982) point out for E-type methanol, transitions from the torsionally excited to the ground state are far more rapid than transitions within the $v_t = 1$ state. In fact, the Einstein A-values of $v_t = 1 - 0$ transitions ($A \sim 0.5\,s^{-1}$) exceed those of the $v_t = 1 - 1$ transitions by 5 orders of magnitude. To maintain any substantial population in the $v_t = 1$ state, the radiative or collisional excitation rate has to equal the former value, which leads in the pure collisional case to difficulties because hydrogen densities in excess of $10^9\,cm^{-3}$ are needed in the optically thin case. However Menten et al. (1986) have given a lower limit of 0.3 for the optical depths of the $J_2 - J_1E$ lines from W3(OH). This and the fact that the optical depths of transitions from the first torsionally excited to the torsional ground state are 2–3 orders of magnitude larger than transitions within the ground state, reduces the densities required for collisional excitation to "reasonable" quantities of the order $10^6 - 10^7\,cm^{-3}$. To illustrate this, we take the example of the $v_t = 1 - 0$, $5_0 - 4_1E$ and the $v_t = 0 - 0$, $4_2 - 4_1E$ lines. Using the fact that both transitions have the same lower level, and assuming identical linewidths, we find:

$$\tau_{10} = 61 T_{ex}(0,0)\{1 - \exp[-291/T_{ex}(1,0)]\}\tau_{00}$$

where τ_{10}, $T_{ex}(1,0)$ and τ_{00}, $T_{ex}(0,0)$ are the optical depths and excitation temperatures of the $v_t = 1 - 0$, $5_0 - 4_1E$ and $v_t = 0 - 0$, $4_2 - 4_1E$ lines, respectively. From this equation we calculate, using Menten et al.'s $\tau_{00} = 0.3$ for W3(OH) and assuming, quite arbitrarily, $T_{ex}(1,0) = T_{ex}(0,0) = 50$ K, a value of $\tau_{10} = 900$. Thus, collisional excitation is capable of populating $v_t = 1$ levels. Observations of $^{13}CH_3OH$ mm-lines (Johansson et al., 1984, Blake et al., 1984) show that higher frequency $^{12}CH_3OH$ lines from Orion are also saturated with optical depths of a few, and a calculation analogous to the one presented above yields τ_{10} values of the same order of magnitude.

In order to allow radiative excitation to become important, high dust temperatures T_D are required to excite transitions in the $v_t = 1$ state. If the optical depths in these lines are high, the CH_3OH rotation temperature T_R tends to approximate T_D. Thus T_D should be rather high in the Orion MEC. In W3(OH) the situation is more complicated. While one derives $T_R = 73$ K from E-type methanol (Menten et al., 1986), a fit to the A-type lines observed by us yields a T_R of 340 ± 100 K, which points to the possible existence of a hotter component in this source. Guilloteau et al. (1985) have modelled the dust temperature distribution for W3(OH). For the region just outside the ionization front which they find likely to contain highly excited OH, they calculate values of $T_D \sim 200$ K. This region may also contain torsionally excited methanol, and in fact there is evidence from high resolution observations that CH_3OH and OH coexist in W3(OH) (Menten et al., 1985).

4. Conclusions

We have observed four K-band transitions of interstellar A-type methanol, two of which are from the torsional ground state with energies of $E/k \sim 150$ K and two from the first torsionally excited ($v_t = 1$) state ($E/k \sim 450$ K). All four lines have been detected in emission towards the Orion-KL region and in absorption towards NGC 7538. Towards W3(OH), one of the $v_t = 1$ lines is seen in emission, while the other three are in absorption. Torsionally excited methanol was also observed towards the compact H II region W51 e_1/e_2.

In Orion, the hot methanol probed by the $v_t = 1$ transitions is concentrated in a clump with angular size $<20''$. This methanol emission core is distinct from the "hot core" and the torsionally excited CH_3OH emission peaks $\sim 8''$ southwest of IRc 2. A Boltzmann analysis including a large sample of recent methanol data yields a rotation temperature of 139 K and a CH_3OH column density of $10^{17}\,cm^{-2}$ if a source size of 30″ is assumed. A high CH_3OH/H_2 ratio of $\sim 10^{-6}$ is derived. This is much larger than the ratio found in cold dust clouds and difficult to explain on the basis of current gas phase chemistry.

For W3(OH) and NGC 7538, our data, when compared with results for *E*-type methanol, reveal huge departures from LTE (*A*- and *E*-type lines have different excitation temperatures. One of the $v_t = 1$ *A*-type lines is likely to be inverted). Smaller departures from LTE apparently occur in the cases of W51 and Orion also. The excitation pattern of methanol lines towards W3(OH) can be explained by infrared pumping via 50 micron radiation, but deviations from this model are seen in the case of NGC 7538.

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