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Search for 183 GHz water maser emission in starburst galaxies

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Abstract. We have searched for water vapor emission at 183 GHz, redshifted at 157 GHz and 161 GHz, in the two ultraluminous starburst galaxies Mkn 1014 and VIIZw244. Due to the low energy level of the upper state of the 183 GHz transition ($\approx$ 200K), it is expected that the emission regions are extended, as they are in the Orion or W49N molecular cloud cores. Since the warm and dense gas, typical of star-forming cores, is expected to have a large surface filling factor in ultraluminous starburst galaxies, the maser H_2O emission at 183 GHz could have been detected. In fact, no water line has been detected in Mkn 1014 and VIIZw244 with an upper limit of σ = 1 mK. We compare the H_2O/CO emission ratio with that obtained towards the ultraluminous high-z object F10214+4724, and suggest that the amplification factor for the H_2O emitting cores in this galaxy should be higher than for the general CO emitting region. We conclude that the warm and dense H_2O cores are much less extended in the two observed starburst galaxies than in the Orion molecular cloud; this provides some information on the physical conditions and cooling processes of the interstellar medium in starburst galaxies.

Key words: masers – galaxies: ISM – galaxies: starburst – radio lines: galaxies – galaxies: Mkn 1014; VIIZw 244

1. Introduction

Water is thought to be one of the most abundant molecule of the interstellar medium. Unfortunately, the broad atmospheric lines prevent any direct detection in our own Galaxy. Attempts have been made, through the isotopic molecules HDO and $H_2^{18}O$ (Henkel et al 1987, Jacq et al 1988, 1990, Wannier et al 1991, Gensheimer et al 1996), and through the precursor ion H_3O^+ (Phillips et al 1992), and abundances of the main isotope of H_2O around 10^{-5} have been deduced. This is also confirmed by the detection in Orion of absorption lines at 2.66 microns with the K.A.O. (Knacke & Larson 1991). Very recently, observations with the ISO satellite of the $2_{12} - 1_{10}$ 179.5 μm line of ortho water in absorption against the continuum of the galactic center (SgrB2, Cernicharo et al 1997) has revealed that the H_2O molecule is abundant over very extended regions.

Water levels can be collisionally pumped in the dense (n(H_2) = 10^8-10^{10} cm^{-3}) star-forming regions to emit strong maser lines: the 6_{16}-5_{23} line at 22GHz has been widely observed, because of the atmospheric transparency at this wavelength, and the 3_{13}-2_{20} line at 183 GHz has been detected towards the Orion molecular cloud with the K.A.O. (Waters et al 1980), as well as the 4_{14}-3_{21} line at 380GHz (Phillips et al 1980). All these lines are well known to be masing, since they correspond to "backbones", i.e. levels with the lowest energy for a given rotational quantum number (de Jong 1973, Cooke & Elitzur 1985, Deguchi & Nguyen-Q-Rieu 1990). Neufeld and Melnick (1987) computed the total flux emitted by the H_2O lines in the shocked gas region of Orion. They concluded that H_2O is by far the main coolant, 40 % of the total cooling being provided by the far-infrared ortho-H_2O lines, in the shocked gas regions. Since then a series of higher-level maser lines have been detected (Menten et al 1990a,b; Melnick et al 1993). Neufeld and Melnick (1990, 1991) interprete the maser data in the frame of excitation models, and show that the minimum masing gas temperature is 200K. This favors slow ($\lesssim$ 50 km/s) non-dissociative shocks for the source of maser emission (Melnick et al 1993, Kaufman & Neufeld 1996a,b).

Even from the ground at 183 GHz, Cernicharo et al (1990) succeeded, with the IRAM 30m telescope, to detect in Orion the para H_2O line which turns out to be inverted with a huge flux of a few 10^4 Jy (main beam temperatures of the order of 2000K). Contrary to the point-like maser sources at 22 GHz, the 183 GHz maser emission is quite extended ($\sim$ 1 arcmin = 0.2pc), and represents a significant coolant in the star-forming region (Cernicharo et al 1994). González-Alfonso et al (1995) also found that the 183 GHz emission is spatially extended in the star-forming cloud W49N. The maser dominated 183 GHz H_2O emission is not confined to narrow shock regions, but on the contrary extends out to 2.2pc from the cloud center, and is very similar in extension and kinematics to molecular emission from dense gas tracers (CS, HCN, H_2CO..). Also extended 183 GHz H_2O maser emission has been detected in low-mass star forming regions, such as HH7-11 (Cernicharo et al 1996). Cernicharo et al (1994) show, with the help of an escape probability model for radiative transfer, that the 183 GHz line can be inverted

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for densities n(H_2) $\sim$ 10^5- 10^6 cm^{-3} and kinetic temperatures between 50 and 100K. The maser begins to saturate for a para-H_2O column density larger than 10^{18} cm^{-2}. Modelisation of the Orion region implies that the H_2O/CO abundance ratio is 0.3-0.5.

The detection of the 183 GHz transition of water should provide additional constraints to investigate the physical conditions in the extended star-forming regions that are found in the central region of starburst galaxies. For this purpose, we have tried to detect the masing 183 GHz line in two infrared ultra-luminous starburst galaxies, redshifted in a transparent window of the atmosphere, near λ=2mm. We have chosen two mergers clearly detected in CO at a velocity near 50 000 km/s with a redshift ideal for our purposes: Mkn 1014 (Sanders et al 1988b, Alloin et al 1992) and VIIZw244 (Alloin et al 1992). No H_2O line was detected in both galaxies with a 3σ upper limit of 3 mK. We discuss the main implications of these negative results on the determination of the physical parameters of the interstellar medium in starburst galaxies.

Table 1. Observational parameters

	Mkn 1014	VIIZw244
α(1950)	01^h 57^m 15.8^s	08^h 38^m 32^s
δ(1950)	00° 09′ 10”	77° 03′ 59”
z	0.1631	0.1324
I(CO) (Kkm/s)	1.0	0.76
ΔV_{CO} (km/s)	210.	80.
T_{mb}(CO) (mK)	4.5	9
I(H_2O) (Kkm/s)	0.6*	0.2*

* 3σ upper limit

2. Observations

The observations were made with the IRAM 30m telescope at Pico Veleta near Granada, Spain, in August 1993. Table 1 displays the observational parameters.

We observed simultaneously with three SIS receivers: at 3mm, we tuned to the CO(1-0) frequency to check with the previous observations of Alloin et al. (1992) that the pointing and calibration were optimum to obtain a high quality CO spectrum; at 2mm, we observed the redshifted 183 GHz H_2O line, and at 1.3mm we searched for the HCN(3-2) line. We used two 512x1MHz filterbanks and an AOS backend. The observing procedure was wobbler switching with a small throw in azimuth (1’). We calibrated the temperature scale every 10 minutes by a chopper wheel on an ambient temperature load, and on liquid nitrogen. Pointing was checked on broadband continuum observations. The relative pointing offsets between the 3 receivers were of the order of 3”. We checked the frequency tunings by observing molecular lines towards Orion, DR21 and IRC+10216.

We integrated for 7 and 15 hours on Mkn 1014 and VIIZw244 respectively. We obtained a noise-level of 1 mK at the H_2O frequency for both sources, at 60 and 29km/s resolution. The system temperatures were on average 300, 600 and 700K at 3, 2, and 1.3mm respectively.

Figs. 1 and 2 present our CO (1-0) spectra for Mkn 1014 and VIIZw244, together with the upper limits for the 183 GHz water line redshifted at 157 and 161 GHz, respectively. We derived the 3σ upper limits in Table 1 by assuming the same linewidths in CO and H_2O. The temperature scale is the main beam brightness temperature. The main beam efficiencies are 0.56 and 0.52 at 3 and 2mm, respectively.

We obtain for Mkn 1014 and for VIIZw244 a CO integrated intensity almost consistent with that obtained by Alloin et al (1992), although 10 to 30% lower. However, we note that in both cases their spectrum is composed of a narrow feature, that we retrieve entirely, and of a wider shoulder that could be due to the baseline, since some wavy structure is also seen beside. If the shoulder is included in the baseline, then our two spectra are compatible. Their reported CO FWHM are indeed 10 to 30% higher than our corresponding values.

No HCN (3-2) was detected, with an upper limit at 3σ of 9 and 6 mK in 10km/s channels, for Mkn 1014 and VIIZw244 respectively. This is perfectly compatible with what is expected from starburst galaxies, i.e. an HCN(1-0) intensity of the order of 20% of the CO(1-0) intensity (Solomon et al 1992a); HCN(3-2) is even weaker (Nguyen-Q-Rieu et al 1992).

3. Discussion

3.1. Dense cores in ultraluminous starburst galaxies

The spectacular ultra-luminous IRAS galaxies (ULIGs) have been recognized to be powered by violent starbursts triggered by tidal interactions and mergers (e.g. Sanders et al 1988a). They are among the most luminous objects in the Universe, and radiate at least 90% of their energy in the far infrared. Their molecular content is about 20 times that of a normal galaxy such as the Milky Way, and their star formation efficiency, traced by the L_{FIR}/M(H_2) ratio, is 10 to 50 times larger than for normal molecular clouds (Solomon & Sage 1988, Sanders et al 1991). Interferometric measurements of CO emission have revealed that the molecular component is strongly concentrated in the central kpc, and the average surface density can be as high as 10^5 $M_\odot/pc^2$, corresponding to an H_2 column density of 5 10^{24} cm^{-2} (Scoville 1991). This gas is for a large part at much higher densities than in normal Giant Molecular Clouds, as revealed by HCN observations (Solomon et al 1992a): this polar molecule traces gas at density larger than 10^5 cm^{-3}, while the CO molecule traces gas at $\leq$ 500 cm^{-3}. All these properties of the molecular component in ULIGs suggest that most of the

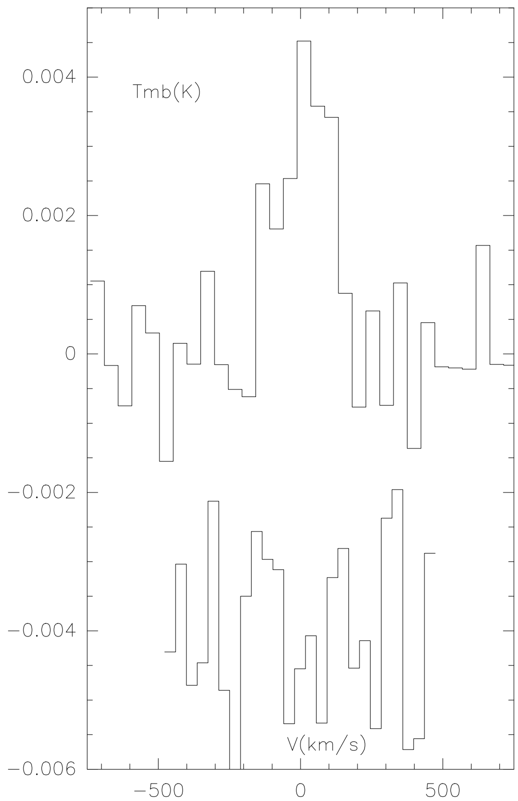

Fig. 1. Spectra at the frequencies of CO(1-0) and H_2O 183 GHz for the ULIGs Mkn 1014. The temperature scale is T_{mb}

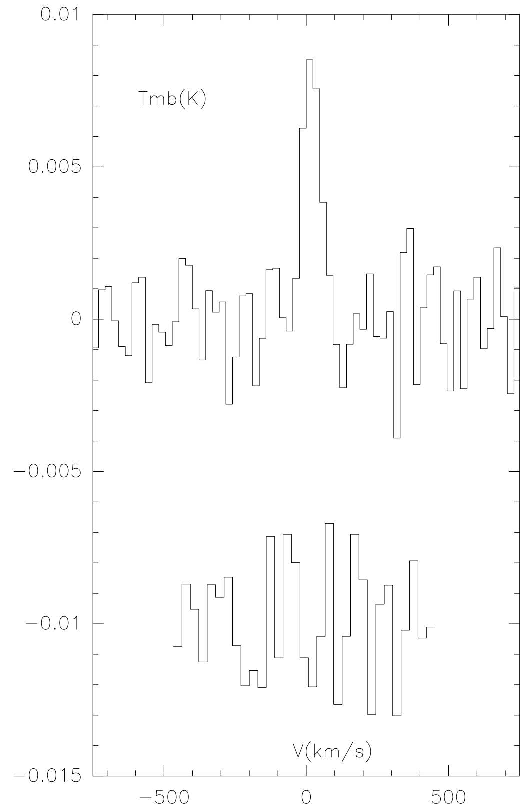

Fig. 2. Same as fig. 1 for VIIZw244

gas is in very dense regions similar to star forming cores, such as the Orion molecular core. The surface filling factor of these dense and warm cores, which is very small in a normal galactic disk (about 10^{-8}) should be enhanced here by 4 to 5 orders of magnitude, up to $\approx 10^{-3}$.

The most extreme example of these objects might be the high redshift IRAS source F10214+4724 (Rowan-Robinson et al 1993), with an apparent luminosity 1.8 10^{14} $L_\odot$ (H_0 = 75 km/s/Mpc and q_0=0.5). At the redshift of z=2.286, the apparent CO luminosity implies a huge H_2 mass larger than 10^{11} $M_\odot$ (Solomon et al 1992b). However there is now evidence that this source is amplified by an elliptical galaxy in the foreground (Elston et al 1994, Broadhurst & Lehár 1995, Graham & Liu 1995). In particular, HST images have shown that the main image is an arc, with an amplification of the order of 100 (Eisenhardt et al 1996). This high amplification factor concerns only the smallest optical source (of intrinsic size of 80pc), while the FIR amplification could be 30, and the molecular emitting region is amplified by an uncertain factor between 5 and 50. If this is taken into account, the F10214+4724 molecular content is perfectly similar to that of other ULIGs. The only other high redshift ULIGs detected up to now, the clover-leaf at z=2.556 (Barvainis et al 1994) and Q1202-0725 at z=4.69 (Omont et al 1996) are also suspected to be strongly amplified (several components are detected); it then appears that ULIGs could be the most extreme objects as far as molecular emission is concerned, and no intrinsically brighter object has been detected until now. Moreover, we cannot detect them at high z if they are not gravitationally amplified (Evans et al 1996, Solomon et al 1996).

3.2. Surface filling factor of dense cores

Given the high average molecular surface density, the high volumic density deduced for most of the gas, the high star-forming efficiency and the high dust temperature (between 50 and 100K), we can expect that such actively star-forming regions like the Orion dense core are quite numerous in ultra-luminous galaxies. In fact, observations show that most of the molecular emission comes from these warm dense cores (Solomon et al 1996).

For example, water thermal emission has been tentatively detected at 752 GHz in the starburst IRAS galaxy F10214+4724 (Encrenaz et al 1993, Casoli et al 1994), with a surface filling factor only slightly smaller than that of CO emission. This can be found from the comparison of observed antenna temperatures between CO and H_2O spectra obtained with the IRAM 30m telescope. Since both the CO lines ((3-2), (4-3) and (6-5)) and the 752 GHz H_2O line ($2_{11} - 2_{02}$ line of para water) are highly optically thick, no abundances or column densities can be deduced directly from observations, but antenna temperatures give instead an estimate of the surface filling factor. The CO data (Solomon et al 1992b, Brown & VandenBout 1992), have shown that the emission cannot be interpreted in terms of

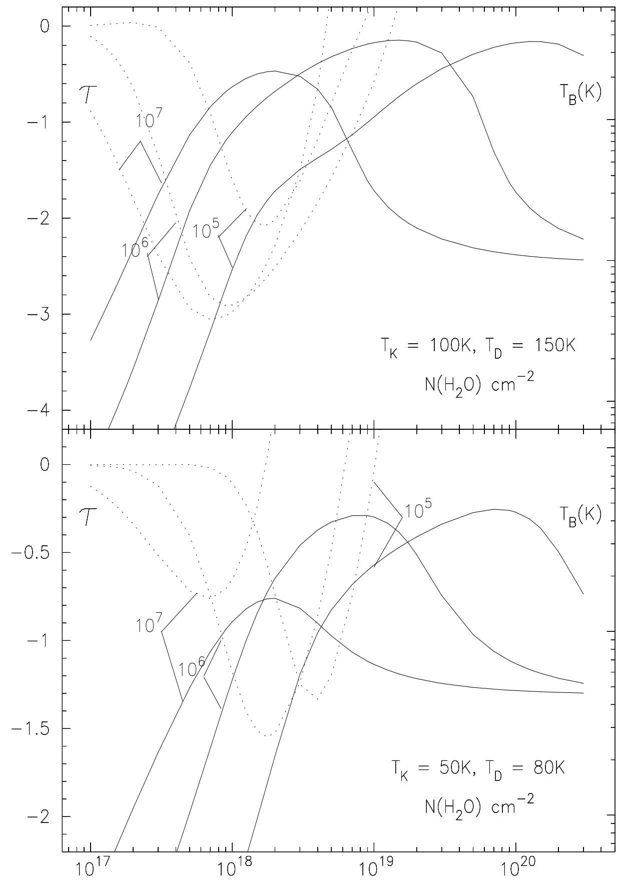

Fig. 3. Results from the LVG radiative transfer model for the $3_{13} - 2_{20}$ 183 GHz line of para-water for three different densities (n(H_2)= 10^5,10^6 and 10^7 cm^{-3}) and two gas temperatures (50 and 100K). The dust temperature is respectively T_D= 80 and 150K. The adopted line width is 20km/s. The expected brightness temperatures (solid lines) can be read on the right scale, and the optical depth (dotted lines) on the left scale.

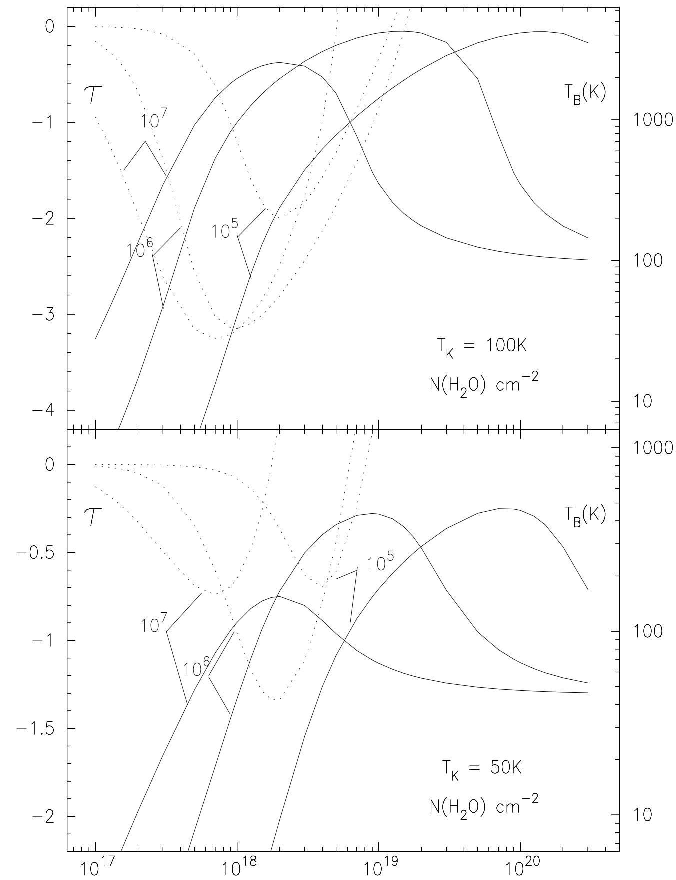

Fig. 4. Same as Fig. 3 without taking into account the dust grains

a single component at a given density and temperature, unless the average density is sufficiently low, such that the CO excitation is subthermal (the apparent peak brightness temperatures are in the ratio 1:0.55:0.16 for the CO 3-2:4-3:6-5 lines). The emission is more realistically coming from various components of different temperatures and densities, and it might be more interesting here to compare the equivalent surface filling factors of the various line emissions, as though they came from the same brightness temperature regions in F10214+4724. The brightness temperature of the emitting dense gas should be of the order of the kinetic temperature ~80 K (the measured FIR dust temperature). The rest-frame brightness temperature T_b has to be redshifted to T_b/(1+z)= 24K to give the apparent brightness temperature. Then, to get the measured antenna temperature, we have to take into account the size of the source at mm wavelength, of the order of 1.5”x0.9” (Downes et al 1995), and the dilution factor in the telescope beam (24” at CO(3-2), 18” at CO(4-3), 12” at CO(6-5) and H_2O). From the peak T_{mb} temperatures observed of 5.5, 5.5, 3.6 and 5mK, respectively, we deduce filling factors of 0.1, 5.5 10^{-2}, 1.6 10^{-2} and 2.2 10^{-2} respectively for the CO(3-2), CO(4-3), CO(6-5) and 752 GHz H_2O emissions, at a given velocity. These surface filling factors correspond to a total source size of 1.5” = 7.8 kpc, since the angular size distance is D_A= 1.08 Gpc (while the luminosity distance is D_L = 11.7 Gpc, with H_0 = 75 km/s/Mpc and q_0 = 0.5). This is however only the apparent magnified size of the source, which could be intrinsically lower (i.e. $\sim$ 1kpc). Fortunately, the estimation of the filling factors do not depend on the magnification values, as far as these are comparable for all mm lines. The relative filling factor of the dense H_2O emitting cores with respect to the more extended CO(3-2) emitting region is 0.22. This is very large for emission on kpc scales. By comparison, the size of the thermal HDO emitting core in Orion is 10”, even smaller than the 120” size of the 183 GHz maser emission (Jacq et al 1990, Gensheimer et al 1996).

As an order of magnitude, we will assume a comparable surface filling factor ratio (0.22) between the 183 GHz H_2O and CO(1-0) emission hot core; in Orion, the hot core emission (T_b $\sim$ 200K) has an extension of the order of 12” (Masson et al 1984), even smaller than that of the 183 GHz H_2O maser emission. With an average brightness temperature over 0.1pc of 1000 K for the maser and 80K for CO, as observed in Orion (Cernicharo et al. 1994), we expect to detect an antenna temperature for H_2O seven times higher than for CO, taking into account the different beams. This is obviously not observed: on the contrary, from the upper limits displayed in Table 1, we find at 3σ that the signals are 10 and 20 times lower than expected for Mkn 1014 and VIIZw244 respectively.

These low upper limits can be interpreted in two ways: either the number of hot cores of the Orion type in Mkn 1014 and VIIZw244 is an order of magnitude smaller than in the starburst F10214+4724 or the physical conditions are not appropriate to pump efficiently the 183 GHz line to become as bright as 1000 K. Another possibility is that the relative H_2O/CO filling factor in F10214+4724 is overestimated, because of different magnification factors: i.e. the locations and sizes of the H_2O and CO dense cores could be different. This is not likely however, since the CO magnification factor is already of the order of 10, and therefore the H_2O magnification would have to be 200, even larger than the optical value.

3.3. Water vapor excitation

It was shown that rotational transitions in the ground vibrational state of water is mainly excited by collisions with H_2 (Deguchi and Nguyen-Q-Rieu, 1990). At a kinetic temperature of 100 K, the critical density to excite the 183 GHz line is $\sim 5\ 10^4$ cm^{-3}. The 183 GHz transition is the lowest level masing transition ($3_{13} - 2_{20}$ of para-H_2O). The energy level of the upper state of this transition (200 K) is much lower than that of the well-known microwave ($6_{16} - 5_{23}$) maser transition (640 K) at 22 GHz. This explains why the 183 GHz emission region in Orion with a peak main beam brightness temperature of 2000 K is so extended, about one arcmin in size (0.2 pc), as shown by Cernicharo et al (1994).

In order to investigate the physical conditions in warm and dense cores, typical of the ULIGs starburst galaxies, we use a simple Large Velocity Gradient (LVG) model of radiative transfer in a spherical geometry. The collisional rates between H_2 and H_2O are derived from those of He-H_2O calculated by Green et al. (1993) by multiplying the latter rates by a factor of 1.35. The 25 lowest rotational levels in the ground vibrational state are considered in the model. An adopted line width of 20 km/s corresponds to the line width of the 183 GHz H_2O maser emission observed in Orion.

Fig. 3 shows the optical depth and the brightness temperature of the 183 GHz line as a function of the H_2O column density for a gas density n(H_2) of 10^5- 10^7 cm^{-3} and for T_K between 50 K and 100 K. The line is inverted in a wide range of physical conditions. We include the 2.7K cosmic background and the radiation due to dust embedded in the molecular clouds. The absorption efficiency of dust grains varies as $Q_{abs}(\lambda) = Q_{abs}(80\mu)(\lambda/80\mu)^{-p}$, with $Q_{abs}(80\mu) \approx 10^{-4}$- 10^{-3} and $p \sim$ 1.5-3.5 (Guibert et al 1978). The dilution factor at 80μ is $W = A_v Q_{abs}(80\mu)$, where A_v is the visual extinction. Fig. 3 corresponds to $W(80\mu) = 5\ 10^{-3}$, $p = 1.5$ for different values of the grain temperature T_D. The 183GHz line is inverted as long as N(H_2O) $< 10^{19}$ cm^{-2}. Beyond this limit the maser is quenched. For comparison, Fig. 4 shows the results in the absence of dust

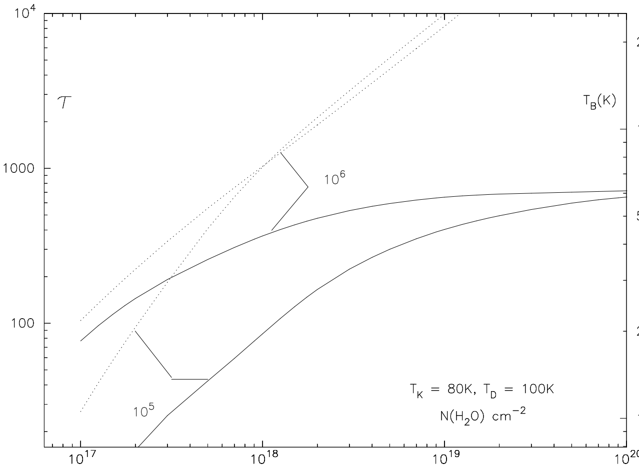

Fig. 5. Same as Fig. 3, but for the $2_{11} - 2_{02}$ 752 GHz line of para-water, observed in F10214+4724 by Encrenaz et al (1993). The assumed average kinetic temperature for this source is 80K, and the dust temperature 100K. However, the influence of dust is not significant.

grains. The pumping of the masers is essentially due to collisions. However, radiation by dust can contribute to the maser pumping when the gas temperature is low ($T_k < 50$K). In the absence of dust radiation, our results are similar to those obtained by Cernicharo et al (1994).

The upper limits obtained for the H_2O line intensities in Mkn 1014 and VIIZw244 can be reproduced only if the temperature is much below 50K (but the average dust temperature is already 49 and 33K in these two objects respectively). Also the column density, or the volumic density, could be so high that the maser is quenched. Quenching occurs at N(H_2O) = 7-8 10^{19} cm^{-2}, for n(H_2) = 10^5-10^6 cm^{-3}, and at N(H_2O)= 2 10^{19} cm^{-2}, for n(H_2) = 10^7 cm^{-3}, at T=50K. Since the H_2O abundance is expected between 10^{-4} and 10^{-5}, the corresponding H_2 column densities are very high, of the order of 10^{24} cm^{-2} and more. Other, less likely, explanations for our negative results could be a very low H_2O abundance, or extremely high densities (larger than 10^7 cm^{-3}).

We have also tried to reproduce the signal tentatively detected for the $2_{11} - 2_{02}$ line at 752 GHz in IRAS F10214+4724 by Encrenaz et al (1993). The source filling factor is 2.2 10^{-2}, for a rest-frame brightness temperature of 80K. Our model calculations with n(H_2) = 10^6 cm^{-3}, T_K = 80 K shows that the line is thermalized to $\sim$60 K (Fig. 5). The energy of the upper level of this transition is only at 137 K. The line becomes saturated at high water column densities (N(H_2O) $> 10^{19}$ cm^{-2}). The excitation by radiation from dust is not significant.

Encrenaz et al. also searched for the $4_{14} - 3_{21}$ line at 380 GHz in this galaxy without success. With the same physical conditions as above, our calculations indicate that the 380 GHz line is weak and becomes detectable only with a water column density higher than 5 10^{18} cm^{-2}. This means that the highest column densities have not a large covering factor in F10214+4724.

4. Conclusion

We have not detected the H_2O 183 GHz masing line in two ultraluminous starburst galaxies, and the 3σ upper limits are an order of magnitude lower than the expected signals. Predictions were based on the high surface filling factor of warm and dense molecular gas, similar to the Orion star-forming core, where 183 GHz emission has been detected with a very high brightness temperature on very extended scales (Cernicharo et al 1994). That most of the gas of ultraluminous starburst should be in warm and dense cores is deduced from the observations in these objects of high H_2 column densities, large volumic densities, and high dust temperatures, averaged over one kpc scale. This result could be explained if the water column density are so high as to quench the maser excitation.

Observations of water in distant starburst galaxies with ISO do not seem promising. For example, the $2_{12} - 1_{01}$ line at 179.5 μm in Mkn 1014 can be estimated to be $\sim 3\ 10^{-15}$ erg s^{-1} cm^{-2}. This predicted flux is $\sim$ 3 magnitudes below the detection limit of the Long Wavelength Spectrometer of ISO. The 179 μm line could be detected in absorption however (cf Cernicharo et al 1997).

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