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# On the occurrence of the 6.7 GHz $CH_3OH$ maser emission in UCH II regions

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**Abstract.** We present the results of a statistical survey of the 6.7 GHz $CH_3OH$ and 22.2 GHz $H_2O$ emissions towards a large homogeneous sample of ultracompact (UC) H II regions, performed to investigate the nature of the methanol emission: does it point out ionized regions or does it trace earlier stages of the star forming process?

The present detection rates are almost identical: 23% for $CH_3OH$ and 22% for $H_2O$. Even considered the uncertainties of the survey, the large number of non-detections is consistent with the scenario where methanol masers disappear during the UC phase, like water masers do. Moreover, the probability to have the $CH_3OH$ counterpart of a $H_2O$ source is at least 40%, indicating that these maser emissions are emphasizing two at least partly overlapping evolutionary phases. The comparison between the velocity ranges suggests that methanol and water masers form in different gas components related to the star forming process.

**Key words:** ISM: clouds – ISM: H II regions – ISM: molecules – radio lines: ISM

## 1. Introduction

The 6.7 GHz methanol ($CH_3OH$) transition, whose emission has been first detected by Menten (1991) towards a sample of star forming regions, produces one of the strongest Galactic masers. As other interstellar masers, the 6.7 GHz $CH_3OH$ line can be used as signpost of optically obscured regions where the (massive) star forming process occurs. The 6.7 GHz emission is one of the typical Class II methanol masers (Batrla et al. 1987) arising from the same regions where OH masers are also observed and being generally associated with ultracompact (UC) H II regions (Caswell et al. 1995b, Ellingsen et al. 1996a, Slysh et al. 1999).

In any case, to date it is not fully clarified when the 6.7 GHz phase occurs and which evolutionary star forming phases can be traced through such methanol emission. On the one hand, most of the 6.7 GHz surveys have focused their attention on samples mainly containing IRAS sources selected according to colour criteria, among which only a limited number had been previously detected as compact ionized sources (e.g. van der Walt et al. 1995, Walsh et al. 1997, Slysh et al. 1999, Szymczak et al. 2000). On the other hand, a recent high spatial resolution survey of Walsh et al. (1998) has allowed to compare the 6.7 GHz $CH_3OH$ emission with radio continuum and with $H_2O$ maser emission. Water maser emission is a precious tool that can be used in the effort to place the $CH_3OH$ phase in the chemical-physical evolution of a star forming region. High resolution surveys have indicated that $H_2O$ masers (22.2 GHz) could be sites of very young massive (proto-)stars prior to the development of an UCH II region and still deeply embedded in their natal high density molecular cores (e.g. Tofani et al. 1995, Codella et al. 1997). The results of Walsh et al. (1998) seem to indicate that also the methanol 6.7 GHz emission traces a pre-UCH II phase, associated with ammonia clumps, suggesting that the environmental requirements for $CH_3OH$ and $H_2O$ maser emission overlap, even if they are not exactly the same. These recent results call for new observations in order to verify them and clarify the nature of the 6.7 GHz emission.

In this paper, we analyse the $CH_3OH$ and $H_2O$ maser emission properties of a *homogeneous* and *unbiased* sample of UCH II regions (White et al. 1991, see Sect. 2) through single-dish observations performed with the Medicina (Italy) radiotelescope. It is clear that the association of the 6.7 GHz $CH_3OH$ maser with other masers and/or compact ionized sources can be demonstrated exclusively by high spatial resolution observations. However, the present observations are useful to achieve the following main aims: (i) to present a statistical analysis (using a large unbiased sample of UCH II regions and the information coming from the $H_2O$ emission) of the $CH_3OH$ occurrence during the evolution of massive star forming regions; (ii) to furnish a list of $CH_3OH$-$H_2O$-UCH II targets that can be used to select sources for further investigations we have planned at very high spatial resolution, using VLBI, continuing the work presented by Moscadelli et al. (1999); (iii) to improve the number of 6.7 GHz observations towards objects of the northern hemisphere, since the bulk of such investigations has been performed in the southern one (van der Walt 1995, Caswell et al. 1995b, Ellingsen et al. 1996b, Walsh et al. 1997, 1998).

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**Table 1.** Derived parameters for the $CH_3OH$ maser sources

| Name | $F_{\rm peak}$ (Jy) | rms (Jy) | FWHM ($\rm km\,s^{-1}$) | $V_{\rm peak}$ ($\rm km\,s^{-1}$) | $V_{\rm min}$ ($\rm km\,s^{-1}$) | $V_{\rm max}$ ($\rm km\,s^{-1}$) | $F$ ($\rm Jy\,km\,s^{-1}$) |
|---|---|---|---|---|---|---|---|
| 0.668–0.035 | 30.8 (4.3) | 3.1 | 1.54 (0.14) | +49.81 (0.04) | +47.6 | +73.2 | 100.8 (9.4) |
| 9.623+0.198 | 3400.0 (140.0) | 2.9 | 0.32 (0.01) | +1.69 (0.01) | –1.5 | +6.2 | 1377.2 (6.5) |
| 10.462+0.034 | 19.3 (2.3) | 1.4 | 0.86 (0.09) | +72.49 (0.04) | +59.0 | +77.6 | 85.4 (5.5) |
| 10.959+0.022 | 11.5 (1.0) | 1.5 | 1.00 (0.13) | +24.64 (0.06) | +23.4 | +25.6 | 18.3 (4.4) |
| 11.937–0.616 | 26.3 (0.6) | 1.4 | 0.86 (0.05) | +32.37 (0.02) | +31.4 | +41.7 | 38.4 (5.1) |
| 18.461–0.004 | 12.0 (1.2) | 1.2 | 0.44 (0.32) | +49.43 (0.01) | +49.0 | +49.9 | 11.6 (1.8) |
| 19.491+0.135 | 11.0 (0.7) | 1.2 | 1.05 (0.15) | +21.32 (0.05) | +21.6 | +22.3 | 21.5 (2.5) |
| 23.439–0.210 | 20.6 (2.1) | 1.2 | 2.06 (0.09) | +103.07 (0.04) | +93.8 | +107.5 | 60.4 (3.6) |
| 26.597–0.023 | 9.3 (1.2) | 2.2 | 0.47 (0.10) | +24.70 (0.04) | +24.5 | +24.9 | 9.25 (2.7) |
| 30.778–0.015 | 17.2 (2.6) | 2.5 | 1.13 (0.09) | +91.50 (0.04) | +90.8 | +92.2 | 30.1 (3.5) |
| 30.866+0.114 | 13.6 (2.0) | 2.4 | 0.51 (0.09) | +101.81 (0.03) | +100.2 | +103.6 | 19.1 (2.9) |
| 31.413+0.307 | 7.3 (0.4) | 1.0 | 0.82 (0.13) | +103.74 (0.07) | +94.3 | +105.1 | 15.2 (3.0) |
| 33.142–0.086 | 7.4 (0.6) | 1.0 | 1.55 (0.17) | +73.68 (0.17) | +72.5 | +74.7 | 12.2 (1.6) |
| 34.257+0.155 | 16.8 (0.6) | 0.8 | 0.56 (0.07) | +57.62 (0.02) | +55.3 | +58.3 | 12.7 (1.4) |
| 40.424+0.699 | 10.4 (1.1) | 2.5 | 0.59 (0.11) | +15.70 (0.04) | +15.3 | +16.4 | 10.9 (1.7) |
| 43.890–0.783 | 17.5 (1.8) | 2.6 | 0.38 (0.06) | +47.53 (0.02) | +47.0 | +52.6 | 11.8 (3.0) |
| 45.129+0.131 | 9.9 (1.0) | 1.6 | 0.74 (0.13) | +58.81 (0.02) | +57.2 | +58.5 | 7.2 (1.7) |

## 2. The sample

The 1.4 GHz survey of the Galactic plane performed with the Very Large Array (VLA) has been used. Zoonematkermani et al. (1990) observed a $140° \times 1\overset{\circ}{.}6$ strip detecting a homogeneous sample consisting of discrete sources down to a limiting flux of about 10 mJy. A comparison between the 1.4 GHz catalogue and the IRAS Point Source Catalogue (PSC) has allowed the selection from their IRAS colours of a homogeneous sample of 166 detected UCH II regions (White el al. 1991), which offers a precious opportunity to perform statistical investigations. In order to get the final input list, we have taken into account: (i) that the use of the Medicina radiotelescope precludes us from observing sources with declinations $\delta <$ –30°, and (ii) that the Medicina beam sizes (see Sect. 3) are definitely larger than the VLA angular resolutions of the survey of Zoonematkermani et al. (1990). As a consequence, we have auto-correlated the White et al. (1991) sample using a radius equal to $3'$, i.e. $\sim$ half of the Medicina beam size at 6.7 GHz. In this way, we have obtained a final list of 124 UCH II regions, 18 of them associated, within the selected radius, with another source; the statistical bias introduced using this subsample will be considered in Sect. 4, once shown the results. Finally, it is worth noting that, recently, a considerable fraction ($\sim$ 50%) of the targets of the present input list has been already observed using the 6.7 GHz $CH_3OH$ emission with the Medicina antenna by Slysh et al. (1999): with this survey we have (i) completed the $CH_3OH$ observations and (ii) observed the whole sample through the 22.2 GHz $H_2O$ maser line.

## 3. Observations

The observations were made with the 32-m radiotelescope at Medicina (Bologna, Italy).

The $CH_3OH$ observations were performed in 1997, using a dual-polarization uncooled receiver with HEMT amplifiers. At the frequency of the $5_1 \rightarrow 6_0$ $A^+$ $CH_3OH$ line (6668.518 MHz) the HPBW is about $5\overset{'}{.}6$. The antenna gain was about 0.11 K $\rm Jy^{-1}$ and the system temperature was around 120–140 K. The backend was a 1024 channel autocorrelator used with a 10 MHz bandwidth, corresponding to a spectral resolution of 0.44 $\rm km\,s^{-1}$ and a total velocity coverage of $\sim$ 450 $\rm km\,s^{-1}$. Some of the detected sources have been additionally observed with a resolution of 0.11 $\rm km\,s^{-1}$. The average detection level ($3\sigma$) of the $CH_3OH$ survey is about 4 Jy.

The $H_2O$ data were taken during several runs in 1993 and 1994. At the frequency of the observed water maser line ($6_{16} \rightarrow 5_{23}$, 22235.080 MHz) the HPBW is $\sim 1\overset{'}{.}9$. The antenna efficiency was 38% with a maximum gain of 0.11 K $\rm Jy^{-1}$. The system temperature was about 120 K in good weather conditions, and the pointing accuracy is $20''$ (rms). The backend was an autocorrelation spectrometer with 1024 channels. A 25 MHz bandwidth was used corresponding to a spectral resolution of 0.33 $\rm km\,s^{-1}$ and a total velocity coverage of $\sim$ 320 $\rm km\,s^{-1}$. The average detection level ($3\sigma$) of the $H_2O$ survey is $\sim$ 5 Jy.

All the spectra ($CH_3OH$ and $H_2O$) have been calibrated using the continuum source DR21 and have been corrected for telescope gain changes with elevation. The uncertainty of the calibration is about 20%. The observations were made in total power mode. For each source the integration time (on source) was 5 minutes.

## 4. Results and discussion

### *4.1. Detection rates*

Out of the whole sample of 124 UCH II regions, 27 show $CH_3OH$ maser emission and 29 show $H_2O$ maser emission. Two objects have been revealed for the first time as water maser sources: 23.265+0.077 and 43.237–0.045. Table 1 reports the derived spectra parameters for the detected $CH_3OH$ sources not already observed with the Medicina antenna by

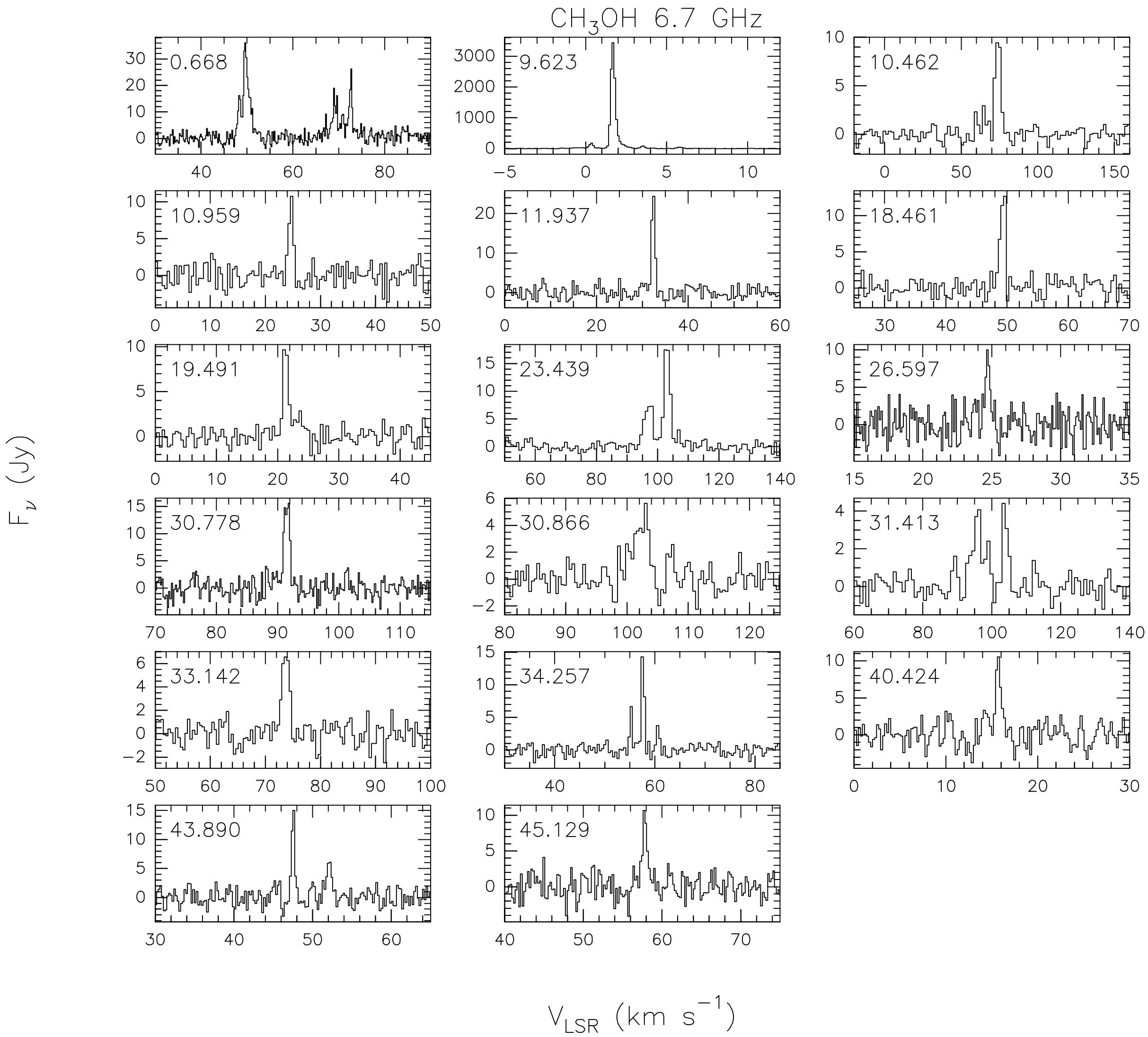


**Fig. 1.** Spectra of the detected $CH_3OH$ maser sources.

**Table 2.** Derived parameters for the new $H_2O$ maser sources

| Name | $F_{\rm peak}$ (Jy) | rms (Jy) | FWHM (km s$^{-1}$) | $V_{\rm peak}$ (km s$^{-1}$) | $V_{\rm min}$ (km s$^{-1}$) | $V_{\rm max}$ (km s$^{-1}$) | $F$ (Jy km s$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 23.265+0.077 | 10.6 (1.2) | 1.4 | 0.65 (0.05) | +77.12 (0.02) | +76.2 | +82.4 | 16.8 (2.0) |
| 43.237–0.045 | 132.0 (4.7) | 1.3 | 0.75 (0.33) | +10.76 (0.33) | –119.9 | +23.0 | 711.7 (12.9) |

Slysh et al. (1999): name of the UCH II region, flux density of the strongest component (Jy), noise of the spectrum (1$\sigma$; Jy), FWHM and velocity of the strongest component (km s$^{-1}$), extremes of the emission velocity interval (km s$^{-1}$) and integrated flux (Jy km s$^{-1}$) computed over the whole emission interval. The $CH_3OH$ spectra are reported in Fig. 1. Table 2 reports the derived spectra parameters for the new $H_2O$ sources, while the spectra are shown in Fig. 2.

The detection rates of $CH_3OH$ and $H_2O$ are calculated using the results of the observations performed with only the Medicina radiotelescope, because we expect that the literature data are biased towards a higher number of water sources with respect to that of methanol masers because of the definitely larger number of $H_2O$ surveys performed in the past.

The $CH_3OH$ detection rate is 22%; this value confirms the value of 25% found by Slysh et al. (1999) using the Medicina antenna for a sample of 76 UCH II regions observed at 5 GHz. Moreover, in addition to the 27 methanol masers detected by us, 17 other sources of the sample are known from the literature to have $CH_3OH$ masers, even if they have been not detected with the used radiotelescope either due to variability (Caswell et al.

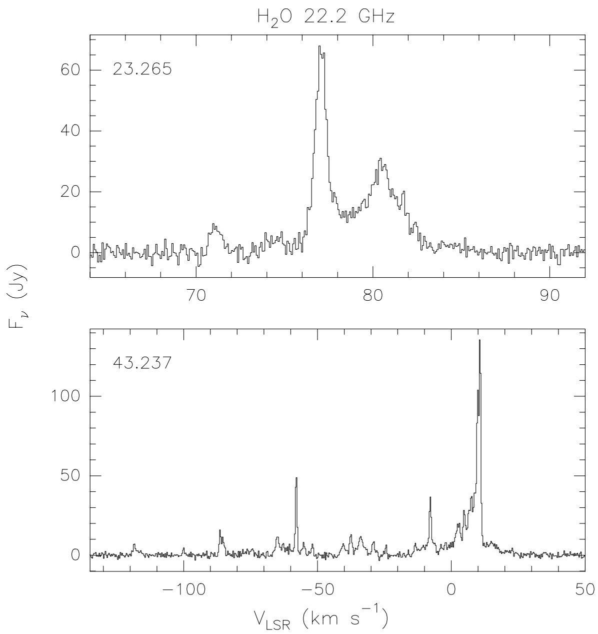


**Fig. 2.** Spectra of the newly detected $H_2O$ maser sources.

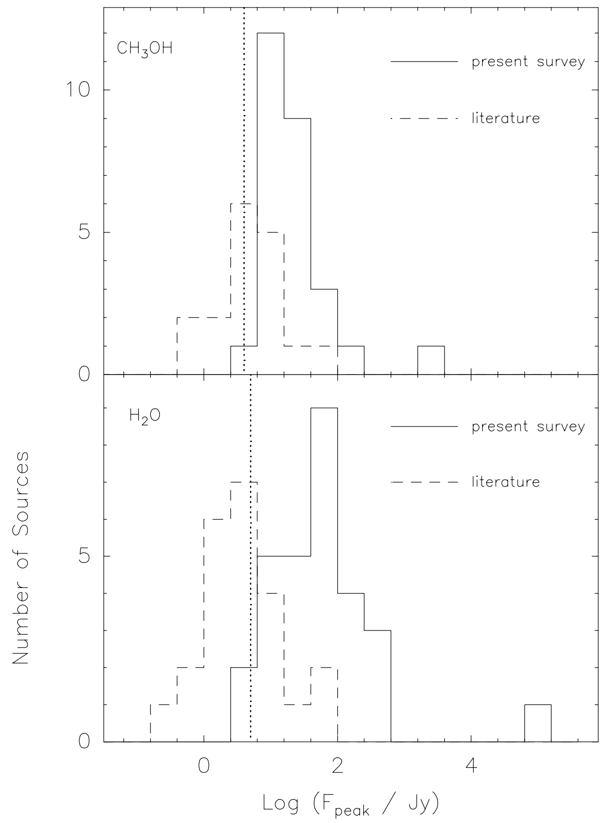


**Fig. 3.** Peak flux density distributions for $CH_3OH$ (upper panel) and $H_2O$ (lower panel) masers. The solid line represents the sources detected in the present survey, while the dashed one is for the masers given only by literature. The dotted lines stand for the average detection limits.

1995a, Slysh et al. 1999, Szymczak et al. 2000) or because our sensitivity was insufficient.

The $H_2O$ detection rate is 23%, in agreement with previous surveys of samples of IRAS UC candidates and UCH II regions done using the Medicina antenna (Palla et al. 1991, Codella et al. 1994). In addition, there are 24 other sources of the present sample which are associated in the literature with water masers and which have been not detected here for the above reported reasons, i.e. variability and/or low sensitivity.

The present survey confirms a generic association of 6.7 GHz $CH_3OH$ masers with high-mass star forming regions. Moreover, the detection rates found for the present UCH II sample are practically coincident for methanol (22%) and water (23%). *In case of close association of $CH_3OH$ masers with UC ionized regions, it was reasonable to expect a methanol detection rate definitely larger than that of water.* A possible explanation might be that $CH_3OH$ is associated with the UC stage but that its life-time is much shorter than that of the UC phase. However, this interpretation strongly contrasts with the results of Walsh et al. (1998), in particular with the large number of methanol spots in their interferometric maps without ionized counterparts. Moreover, recent near-infrared (NIR) observations (Walsh et al. 1999) have allowed to identify an example of a source where the $CH_3OH$ maser emission is coming from a site of massive star formation, but probably before the star has produced an UCH II region. Thus, the large number of non-detections at 6.7 GHz (even considering the overall percentage including sources given by literature) does not support the association of $CH_3OH$ with the UCH II regions and is consistent with the idea that $CH_3OH$ masers disappear during the UC phase as found for $H_2O$ emission. In this case, the same number of methanol and water sources would indicate that the two masers last for a comparable span of time during the pre-UC phase.

The results reported above are affected by: (i) the inadequate sensitivity at 6.7 and 22.2 GHz, (ii) maser variability and (iii) large HPBWs. Fig. 3 shows the distribution of the peak flux densities of the sources detected at Medicina (continuous line) and at other radiotelescopes (dashed line), and allows to have an estimation of how the obtained results are affected by the present sensitivities. The detection threshold of both masers (dotted lines) is comparable and enough lower than the highest detected values to allow the determination of the flux statistic over about three orders of magnitude. $CH_3OH$ has a distribution slightly shifted towards lower values with respect to that of $H_2O$; excluding the detections with peak fluxes greater than 1000 Jy, the average values are 83 and 24 Jy for water and methanol, respectively. However, the detection levels cut off the two distributions roughly in the same way, allowing the comparison between $CH_3OH$ and $H_2O$ maser observations. It is worth noting that, considering also the literature data, the overall percentages raise to 35% for $CH_3OH$ and to 43% for $H_2O$. Because the overall percentage for water, which we know not to be associated with the UC-phase, is higher than that of methanol, this finding also does not support a close association between the 6.7 GHz line and the UCH II regions. Table 3 summarizes the obtained statistics.

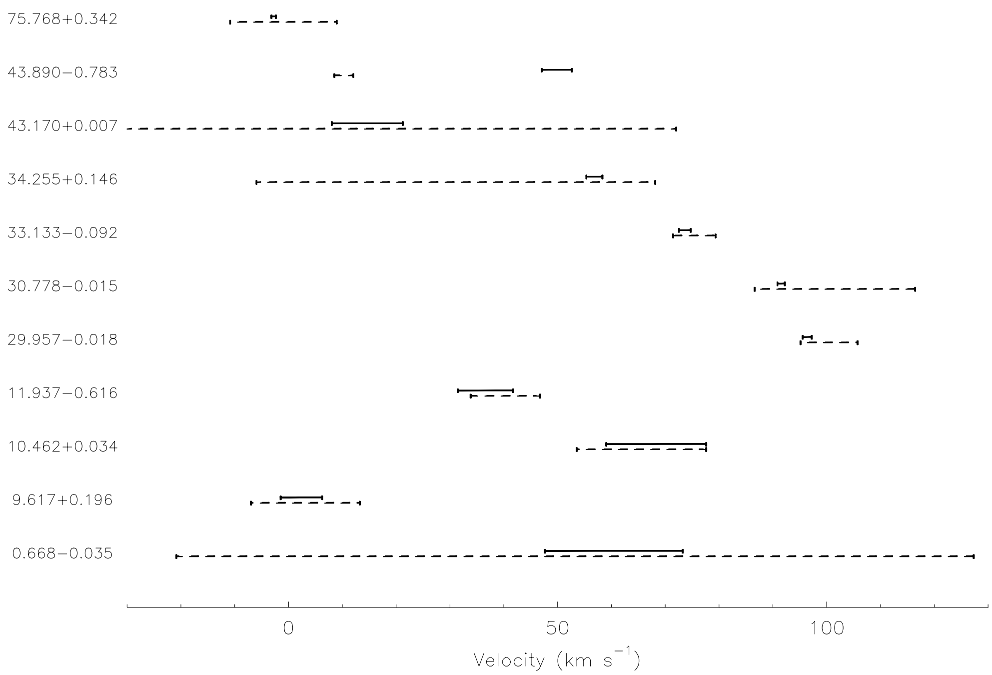


**Fig. 4.** Comparison between the velocity ranges of $CH_3OH$ (continuous line) and $H_2O$ (dotted line) for the sources (Zoonematkermani et al. 1990) detected through both emissions (see text). Note that to improve the clarity of the figure we have cut off the negative $H_2O$ velocities of 43.170+0.007, which reach values of about –130 km s$^{-1}$.

In Fig. 3 it is reported also the distribution of the sources given by literature (dashed line): note that, for each source, the highest value of flux found in the literature has been considered. We note similar distributions for both masers, with the majority of the sources around and below the detection limits, as expected. In order to estimate the bias introduced by the $CH_3OH$ maser variability, we have compared our results with those given by Szymczak et al. (2000), who observed a large sample of IRAS objects selected according to their colours, using the Toruń radiotelescope. The cross-correlation between our sample and their list of 6.7 GHz methanol masers indicates that Szymczak et al. (2000) found emissions above the Medicina sensitivity threshold towards 8 sources, which corresponds to $\sim$ 36% of our detections if only the sources in common between the lists are taken into account. By applying the same statistics to our whole sample, we expect to raise the number of detections from 27 to 37 and thus to increase the detection rate from 22% to about 28%. It is tempting to conclude that the results given by the comparison between the detection rates are not strongly biased by the maser time variability.

Finally, it is worth noting that, if the large HPBWs used for the present observations may create false associations, considerations based on the lack of $CH_3OH$-$H_2O$-UCH II sources are not affected by a HPBW bias.

### 4.2. $CH_3OH$ and $H_2O$ maser properties

If both $CH_3OH$ and $H_2O$ masers trace a pre-UC phase, the question naturally arises on which astrophysical environment they do actually trace, whether it is the same or it differs. In the following we compare the maser properties, first considering the sources where both the maser emissions are observed, and then the sources where only one maser species has been detected.

**Table 3.** Results of the maser survey towards UCH II regions

| | Detection Rates | Overall Percentages |
|---|---|---|
| $CH_3OH$ | 22% | 35% |
| $H_2O$ | 23% | 43% |

The overlap between $CH_3OH$ and $H_2O$ emission is remarkable: 11 sources ($\simeq$ 40% of detections) present 6.7 and 22.2 GHz emission. Note that if we take into account data from literature we have 23 (40–60%) sources with both maser counterparts. The comparison between the peak flux densities of both emission shows that, excluding 3 sources, water is more intense by a factor scattered over a wide range: 2–150. Fig. 4 shows the comparison between the velocity ranges of $CH_3OH$ (continuous line) and $H_2O$ (dashed lines). With only one exception, methanol velocities overlap with those of water, supporting the reliability of the association between the two maser sources. Thus, the $CH_3OH$ detection rate is higher for the $H_2O$ maser subsample with respect that of the whole UC sample. Therefore, the present survey indicates that the probability to have the $CH_3OH$ counterpart of a $H_2O$ source (and viceversa) is at least 40%, suggesting that the two emissions point out two evolutionary phases which overlap at least for a considerable fraction of their life-time.

Fig. 4 clearly shows also that methanol emission is associated with a velocity range definitely more limited than that of water. Moreover, if we compare the $CH_3OH$ velocities with that of the molecular clump hosting the star forming process, using the results of the CS observations reported by Plume et al. (1992) and Bronfman et al. (1996), it is possible to verify that they are well in agreement.

The narrower velocity emission range of $CH_3OH$ could simply reflect the lower peak flux densities (and consequently the

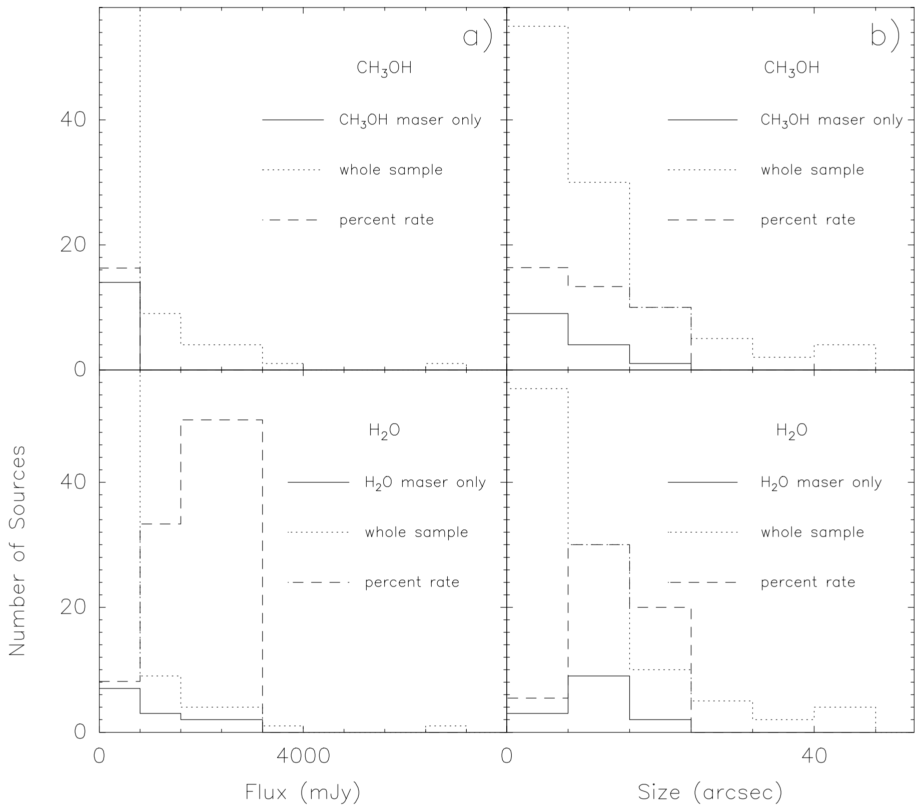


**Fig. 5. a** 1.4 GHz flux distributions of the whole UC sample (dotted line), and of the subsamples where only $CH_3OH$ (upper panel) or only $H_2O$ (lower panel) has been detected (continuous line); dashed line stands for the detection rates; **b** Same for **a** for UCH II size distributions.

peak-to-noise, PTN, ratios) of the $CH_3OH$ masers compared to that of the water masers. Then, assuming that the typical pattern of the $CH_3OH$ spectra is similar to that of water, the weaker, high velocity, maser features of methanol would be hidden by the spectral noise. We have investigated the relationship between the velocity emission range and the PTN ratio for both the $CH_3OH$ and the $H_2O$ spectra: while for the $H_2O$ spectra there is a clear trend of the velocity range to increase with increasing PTN ratio, no clear assessment can be made in the case of the $CH_3OH$, because the interval of PTN ratio sampled is too limited. If the methanol masers intrinsically emitted on a narrower velocity range with respect to that of the water masers, a possible interpretation might be that the $CH_3OH$ and $H_2O$ masers are tracing different portions of the gas involved in the dynamics of the early phases of the star forming process. Further high-spatial resolution observations are needed to demonstrate this scenario.

Fig. 5 shows the 1.4 GHz flux and size distributions of the UCH II regions of our sample detected through only $CH_3OH$ or $H_2O$ emission. In the previous discussion it was pointed out that both the methanol and the water masers are very likely not physically associated with the UCH II region towards which they are observed, but rather they are excited by a Young Stellar Object in their neighbourhood. Thus, the trend of the histograms shown in Fig. 5 cannot be explained in terms of a real physical link between the masers and the properties of the UCH II regions, but rather as due to selection effects. Fig. 5 shows that while the detection rate of water masers increases at large values of flux and size, no such trend is visible for the $CH_3OH$ subsample. If the UCH II regions with the largest fluxes and angular sizes were on average those closest to us, then the higher detection rate of water masers could reflect the fact that also masers of lower luminosity are detected. However, a distance selection effect should be even more evident for the $CH_3OH$ detections, which, on average, have a flux density lower than that of the $H_2O$ detections. We decided to show Fig. 5 because we think that the different behaviour of the $CH_3OH$ and $H_2O$ detection rates reflects some significant differences in either the excitation conditions of the two masers or their detectability. We also feel that our data do not allow us to discriminate between the possible causes and, raising the question, we leave it open to further discussion.

## 5. Conclusions

In this paper, the investigation of the 6.7 GHz $CH_3OH$ and 22.2 GHz $H_2O$ emissions towards a large homogeneous sample of UCH II regions has been presented. The aim was to collect further information in order to clarify which is the origin of such methanol emission: does it point out the UC phase of the high-mass star forming process or does it trace earlier stages? The main results are the following:

1. the detection rates are almost identical: 23% for $CH_3OH$ and 22% for $H_2O$. Even considered the uncertainties of the survey, the large number of non-detections is not in agreement with a close association of $CH_3OH$ with UCH II and is consistent with the scenario drawn by Walsh et al. (1998), where methanol masers disappear during the UC phase;

2. on the other hand, the probability to have the $CH_3OH$ counterpart of a $H_2O$ source is at least 40%, indicating that these maser emissions are emphasizing two at least partly overlapping evolutionary phases. Moreover, the comparison between the velocity ranges suggests that methanol and water masers form in different gas components related to the star forming process.

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