Astron. & Astrophys. 35, 1—5 (1974)

Identification of Type I OH Masers with Very Small H II Regions

H. J. Habing
Sterrewacht, Leiden

W. M. Goss and H. E. Matthews
Kapteyn Astronomical Institute, University of Groningen

A. Winnberg
Max-Planck-Institut für Radioastronomie, Bonn

Received April 16, revised June 12, 1974

Summary. We have mapped the radio continuum radiation at 6 cm with a resolution of $(7 \times 7/\sin\delta)$ arcsec in 11 fields surrounding 13 OH Type I masers. In all fields we find sources less than 1 arcmin in size. In 7 cases a source smaller than 4 arcsec is found to coincide within 1.5 arcsec with the OH maser position. These sources are thought to be very compact H II regions.
It is concluded that many, and possibly all Type I OH masers occur near stars that have recently arrived at or very near the main sequence and that have started to ionize the remaining gas from the collapsing prestellar cloud. We suggest that the OH maser phenomenon disappears when the H II region has expanded to sizes greater than some 15.000 AU.

Key words: OH masers – H II regions – star formation

1. Type I OH Masers and their Relation to Compact H II Regions

The large majority of known OH masers can be divided into two types, Type I and Type IIb, on the basis of their spectroscopic characteristics (Turner, 1970). Type IIb OH masers appear to be associated with the later stages of stellar evolution since they generally coincide with very cool, large stars (infrared objects, M type giants and supergiants). Type I OH masers are probably related to early stages of stellar evolution because they have preferentially been found in the neighbourhood of H II regions. For a review of earlier work on this subject see Mezger (1971). The preference cannot, in general, be a chance coincidence, since in many cases the average OH radial velocity agrees with the recombination line velocity of the H II region. In addition, accurate measurements of OH maser positions have shown that the OH masers do often occur within a few parsec projected distance of so called "compact H II regions" (H II regions with diameters $d < 1$ pc and emission measures $EM > 10^6$ cm^{-6} pc). Since compact H II regions are young objects, probably less than 10^4 yr old (Mathews, 1969), that surround massive stars, it follows that Type I OH masers occur during an early phase in the development of massive stars. However, this argument leaves open at least the following alternative possibilities. First, Type I OH masers might be produced in contracting protostars; for example, Mezger and Robinson (1968) have suggested that OH masers are skin-effects in such objects. Second, the masers might occur around stars that have already arrived on the main sequence; for example Gwinn *et al.* (1973) have proposed that Type I OH masers can be formed in shocked neutral gas surrounding an expanding H II region. The observable difference between the two possibilities lies in the presence or absence of an H II region that can be detected at radiowavelengths through its free-free emission.

An illustrative case is OH 133.95 + 1.06 or W3-OH. The radio continuum radiation near the maser has been mapped with a spatial resolution of about 2 arcsec by Wink *et al.* (1973) at 3.7 cm and by Baldwin *et al.* (1973) at 6 cm. The area contains two small H II regions, the smaller of which is the stronger radio source and has a diameter of 6300 AU and $EM \approx 10^9$ cm^{-6} pc. The OH maser is known to consist of points distributed on segments of a ring (Moran *et al.*, 1968) and both groups of observers suggest that this ring is actually located around the smaller H II region. Unfortunately the accuracy of the average OH position is not high enough to prove this suggestion beyond doubt.

A critical and as yet unanswered question is whether W3-OH is a typical case or an exception. Since an answer appears vital for an understanding of the physical conditions in the OH maser and, in a wider context, for an understanding of the chronological order of the phenomena that occur near and in forming stars, we have made an attempt to detect additional very small H II regions similar to the one near W3-OH.

We have mapped the centimeter continuum radiation in 11 fields containing 13 OH masers with accurately known positions. We used the Westerbork Synthesis Radio Telescope at 4995 MHz (6 cm) with an angular resolution of 7.2 arcsec × 7.2/sin δ arcsec. The field size is defined by the primary beam of 10.2 arcmin. The fields contain both point sources and extended sources. For two fields (containing ON-1 and ON-2) the results have already been published (Winnberg *et al.*, 1973; Matthews *et al.*, 1973). In this paper we describe the sources coincident with the OH masers. In a subsequent paper we will describe the extended sources in the fields and present contour diagrams of the areas. In the present discussion we will also use information on W3-OH and on OH 111.54 + 0.78 near NGC 7538 (Martin, 1973).

2. The Data

We selected 13 OH masers with accurately determined positions from the following lists: Hardebeck (1972), Hardebeck and Wilson (1971), Goss *et al.* (1973a) and Wynn-Williams *et al.* (1974). We excluded a few masers that were already scheduled in other observing programs at Westerbork. Maps of the observed fields were produced in the standard way (Brouw, 1971) and were then studied in detail using an interactive program (Ekers *et al.*, 1973).

We summarize the results of our search for continuum radio sources within a few arcsec from the 13 OH maser positions. The results can be divided into three categories. (1) Point sources identified with masers. (2) Extended sources identified with masers. (3) Masers without continuum sources. We discuss each category separately.

(1) Point Sources Identified with Type I OH *Masers*

In 7 cases we find an unresolved continuum source at the position of the OH maser; see Table 1. A representative example is the situation near OH 81.87 + 0.78 or W75 N, which is shown in Fig. 1. Observed and derived properties of the continuum point sources are given in Table 1, Columns (4) through (9). The 6 cm flux density, S, is in Column 4; the observed gaussian angular diameter, θ_{ob}, in Column 5; the distance, D, taken from various publications, is in Column 7. Column 9 contains the monochromatic power $P(=4\pi D^2 S)$. Column 6 contains an angular diameter, θ_{sp}, obtained by fitting a model spectrum through the observed flux densities. The model is based on free-free emission from a sphere

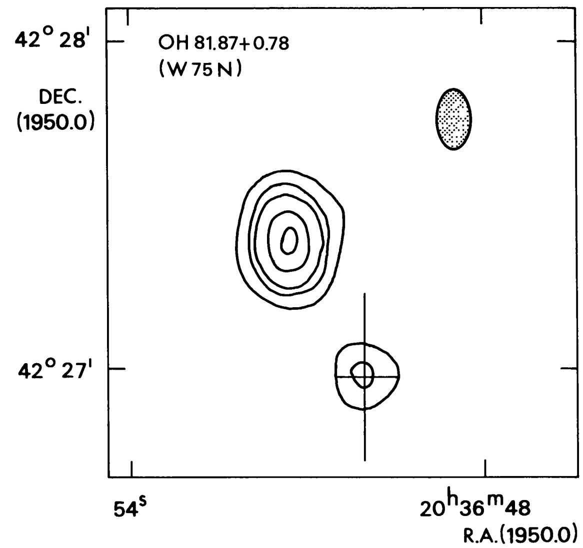

Fig. 1. Isophotes of the 6 cm continuum radiation near OH 81.87 + 0.78, also called W75 N. Contour values are 1, 3, 5, 10 and 15 units, where 1 contour unit is 3.6 K in brightness temperature. The synthesized beam is indicated in the upper right hand corner by a hatched ellipse. The larger source in the field has been detected previously (Wynn-Williams, 1971) and appears to have a flat spectrum in the cm wavelength range. The position of the OH maser, as measured by Hardebeck (1972), is indicated by a cross. The quoted positional uncertainties are shown. The r.m.s. noise is 1.2 K

Table 1. Continuum point sources identified with type I OH masers

OH maser			Continuum point source					
Name	l^{II}	b^{II}	S(6 cm) (m.f.u.)	θ_{ob} (arcsec)	θ_{sp} (arcsec)	D (pc)	d (AU)	P (erg s^{-1} Hz^{-1})
(1)	(2)	(3)	(4)	(5)	(6)	(7)	(8)	(9)
	OH 10.62	−0.38	2100 ± 200	< 4	4.5			
W33 B	OH 12.68	−0.18	50 ± 10	< 5	(0.7)	6600[f])	4600	26×10^{20}
	OH 45.07	+0.13	250 ± 30	< 5	1.5	9700[g])	14500	281×10^{20}
	OH 45.47	+0.05	92 ± 7	< 4	(0.9)	9700[g])	8700	103×10^{20}
ON-1	OH 69.54	−0.98	83 ± 6	< 1[e])	0.9			
ON-2	OH 75.78	+0.34	41 ± 6	≲ 2[e])	(0.6)	5500	3300	15×10^{20}
W75 N	OH 81.87	+0.78	19 ± 2	< 4	(0.4)	3000[e])	1200	2×10^{20}
NGC 7538 N	OH 111.54	+0.78	120 ± 20[b])	1.5[b])	(1.0)	3500[d])	5300	18×10^{20}
W3-OH	OH 133.95	+1.07	620 ± 20[a])	2.0	1.9	3000[c])	6000	67×10^{20}

[a]) Baldwin *et al.*, 1973.
[b]) Martin, 1973.
[c]) Reifenstein *et al.*, 1970.
[d]) Israel *et al.*, 1973.
[e]) Harris, 1974.
[f]) Robinson *et al.*, 1970.
[g]) Wynn-Williams *et al.*, 1971.

of uniform electron density with an angular diameter θ_{sp}. If the optical depth through the center of the sphere equals τ then the flux density from the source is given (Osterbrock, 1965) by

$$S=\frac{\pi k T_e \nu^2}{2c^2}\theta_{sp}^2(1-2\tau^{-2}+2\tau^{-1}e^{-\tau}+2\tau^{-2}e^{-\tau}),$$

where the symbols have their usual meaning. We always assume $T_e=8000$ K. If the value of S was available only at 4995 MHz we assumed $\tau=\infty$ and put the obtained value of θ_{sp} in parentheses. Column 8 contains the linear diameter, d, of the source obtained by multiplying Columns 6 and 7, except in the last two entries, where the diameter is obtained by multiplying Columns 5 and 7. Note that θ_{ob} is obtained from the observations by assuming a gaussian brightness distribution and hence differs, by definition, from θ_{sp}. The ratio θ_{sp}/θ_{ob} varies from 1.47 to 1.20 when τ increases from 0 to ∞ [Mezger and Henderson, 1967, Eq. (A.12)]. From the fact that the predicted diameters, θ_{sp}, do not contradict the observations we gain some confidence in the values in Column 6.

The positional agreement between continuum sources and OH masers is very good. The distribution of the differences in position for all nine sources has an r.m.s. value of 1 arcsec in right ascension and of 1.5 arcsec in declination.

So far we have tacitly assumed that the radiation from the small sources is free-free emission. We have at least three arguments to support this point of view. First, and most important, for four sources flux densities have been measured at other wavelengths: W3-OH (Wink *at al.*, 1973), ON-1 (Winnberg *et al.*, 1973), G 10.6−0.4 and OH 45.07+0.13. For the last two sources we measured flux densities at shorter wavelengths with the 100 m telescope of the Max Planck Institute. For G 10.6−0.4 we find 4900±500 m.f.u. at 2.8 cm wavelength and for OH 45.07±0.13 we find 960±200 m.f.u. at 2.0 cm. Judging from the 6 cm aperture synthesis maps there are no confusing sources in the Effelsberg beam and the fluxes given should refer to the sources mentioned. All four sources thus are thermal sources with appreciable optical depth at 6 cm. We assume that the remainder of the sources in Table 1 are similar. The second argument is that it is highly unlikely that the sources are extragalactic non-thermal sources; first because of the close coincidence in position with OH emission with galactic radial velocities, and second because of the rarity of extragalactic point sources at such high flux levels. The third argument is that since the sources must be galactic, we can assume that they are similar but physically smaller than the nearly extended sources. These are known to be thermal sources which, because of the velocity agreement between OH and recombination lines, are situated in the immediate neighbourhood of the point sources.

Table 2. Extended continuum sources coinciding with Type I OH masers

OH maser		Extended source	
l^{II} (1)	b^{II} (2)	S(6 cm) (m.f.u.) (3)	θ_{ob} (arcsec) (4)
OH 19.61	−0.23	3300	15[a])
OH 20.08	−0.13	910	25[b])
OH 45.47	+0.13	2000	25

[a]) Contains probably a source of 1200 m.f.u. and diameter <4 arcsec at the OH maser position.
[b]) Contains probably two sources of 410 m.f.u. and 250 m.f.u., respectively, and with diameters <4 arcsec. The stronger of these is at the OH maser position.

(2) Extended Continuum Sources Identified with Type I OH *Masers*

In three cases we found an extended continuum source coinciding with the maser. They have been listed in Table 2, where the symbols have the same meaning as in Table 1. However, as indicated in footnotes to Table 2, the first two continuum sources seem to contain unresolved components at the position of the OH masers. We cannot make a definite statement about such components because at their declination (−20°) the synthesized beam is very elongated (about 6 to 1). The third source seems to consist of two extended components. The presence of a point source of more than 25 m.f.u. at the maser position is excluded.

We suggest that the first two sources in Table 2 probably belong in Table 1 whereas the third may belong in Table 3.

(3) Type I OH *Masers without a Continuum Source*

In three cases we detected no continuum radiation from the OH position. These cases are summarized in Table 3, together with upper limits on three more maser positions, taken from the literature: on Orion A from Webster and Altenhoff (1970), on OH 205.1−14.1 from Johansson *et al.* (1974) and on OH 0739−14 from Goss *et al.* (1973b). In Table 3 the symbols on top of the columns have the same meaning as in Table 1. Column 4 thus contains the upper limit of the flux density of any possible point source within a few arcsec from the OH maser position (in m.f.u.). Note that the upper limit for the flux density of W75 S is due to Harris (1974).

It is meaningless to compare the upper limits to the flux densities directly with each other, because the distances to the sources vary over a factor of 20. We therefore calculated monochromatic powers $P\,(=4\pi D^2 S)$, which are given in column 6 of Table 3. It is interesting to compare these upper limits with the detected values of P in Column 9 of Table 1. The largest is $P=281\times10^{20}$ erg s^{-1} Hz^{-1} for OH 45.07+0.13 and the smallest is $P=2.0\times10^{20}$ erg s^{-1} Hz^{-1} for OH 81.87+0.78. Since for the detected sources P varies by two orders of magnitude it is impossible to attach any significance to

Table 3. Type I OH masers without continuum sources

OH maser	Continuum source				
Name	l^{II}	b^{II}	S(6 cm) (m.f.u.)	D (pc)	P (erg s^{-1} Hz^{-1})
(1)	(2)	(3)	(4)	(5)	(6)
W33 A	OH 12.91	− 0.20	< 15	4400[a])	< 3.5 $\times 10^{20}$
	OH 45.10	+ 0.12	< 20	9700[b])	<22 $\times 10^{20}$
W75 S	OH 81.72	+ 0.57	< 15[c])	3000[c])	< 1.6 $\times 10^{20}$
Orion A	OH 208.99	−19.39	<275[d])	500	< 0.8 $\times 10^{20}$
	OH 205.1	−14.1	< 5[e])	500	< 0.015 $\times 10^{20}$
OH 0739−14	OH 231.8	+ 4.2	< 7[f])	<2000	< 0.33 $\times 10^{20}$

References
[a]) Robinson *et al.*, 1970
[b]) Wynn-Williams *et al.*, 1971.
[c]) Harris, 1974.
[d]) Webster and Altenhoff, 1970, scaled from 11 cm wavelength as λ^2.
[e]) Johansson *et al.*, 1974, scaled from 2.8 cm wavelength as λ^2.
[f]) Goss *et al.*, 1973b, scaled from 2.8 cm wavelength as λ^2.

the non-detection of the sources in Table 3, with the exception of OH 205.1 − 14.1. The first 4 sources in Table 3 may be totally different from those in Table 1, but they may also be quite similar. We will come back to this point in the discussion in the next section.

3. Discussion and Conclusion

We discuss three aspects of the results presented in Section 2.
a. Most masers coincide with very compact H II regions.
b. Masers do not coincide with H II regions resolved by our beam.
c. Only a minority of the masers lack a radio continuum counterpart.

a. Most Masers in our Sample Coincide with Very Compact H II *Regions*
In the preceding setion we have shown that certainly 7, and very likely 9 out of our sample of 13 masers coincide with very compact H II regions. Hence, if our sample is representative for Type I masers, the majority of these masers coincide with very compact H II regions. To avoid misunderstanding: by "coincidence" we mean positional agreement to within the instrumental accuracy, i.e. to within a few arcsec, or, say, to within some 10.000 AU.
It has been suggested that these very compact H II regions represent late stages of stellar evolution, for example, planetary nebulae. We reject this possibility for two reasons. (1) No known planetary nebula coincides with an OH maser. (2) Old evolved objects do not occur, as a rule, in the immediate neighbourhood of extreme Population I objects such as extended H II regions. Therefore very compact H II regions appear to be associated with very early stages of stellar evolution.
We assume then that the source of ionization is a young star which either is on its way to the zero age main sequence, or has recently arrived there. We can estimate a lower limit to the Lyman continuum flux, L_{uv}, of this star directly from the number of recombinations in the nebula, which is related simply to the monochromatic power P of the very compact source. The largest value is $L_{uv} = 1.9 \times 10^{48}$ photons s^{-1} for OH 45.07 + 0.13, the smallest value is $L_{uv} = 1.3 \times 10^{46}$ photons s^{-1} for OH 81.87 + 0.78. According to Churchwell and Walmsley (1973) the first value corresponds to that of a ZAMS star of spectral type O9, the second to B1. However, these values of L_{uv} are likely to be lower limits. First, because P is taken at a wavelength with considerable optical depth and hence does not represent all recombinations in the nebula and, second, many Lyman continuum photons may be absorbed by the dust inside the H II region (Pottasch, 1974). Only IR, mm and cm observations will tell us how large L_{uv} really is, and whether the apparent absence of stars earlier than O9 is significant.

b. Masers do not Coincide with Extended H II *Regions*
No continuum source coinciding with a maser is resolved by our synthesized beam, hence they are at most 4 arcsec in diameter. However, one exception exists, OH 45.47 + 0.13. Nevertheless, resolved H II regions (that is: H II regions larger than 15 arcsec in diameter) occur in 10 out of the 11 fields observed. We consider that OH 45.47 + 0.13 is projected by chance onto an extended source and that, in fact, it is a case of a maser without a strong continuum point source. If we next assume that the small H II regions ultimately develop into extended sources, we thus conclude that the maser phenomenon disappears when the H II region expands beyond a limiting diameter, which we place at about 15.000 AU. This value is uncertain by at least a factor of 2.
The absence of coincident sources larger than 15.000 AU is probably not a selection effect. OH maser surveys have been carried out specifically near H II regions, and if coincidences with extended sources would occur in statistically significant numbers, one would expect this to happen even more frequently in our sample.
Calculations about the early dynamic evolution of very compact H II regions have been made by Mathews (1969).

These calculations were made for very idealized situations, notably for static initial conditions. Therefore the calculations may not be applicable to the objects under consideration. Ignoring this possible shortcoming we find a dynamic lifetime for the H II region of only 3000 yr. This value is supported somewhat by the observation that as a rule most of the H II regions in our 11 fields are separate, but well resolved objects. Estimating the ages of these well resolved objects to be between 10^4 and 2×10^4 yr we thus find that the small sources should indeed be considerably younger than 10^4 yr.

c. Only a Minority of the Masers Lack a Radio Continuum Counterpart

In our sample only 4 masers do not coincide with very compact H II regions. Even in these cases the upper limits to the monochromatic power P are rather insignificant when compared to those of detected sources. One is therefore tempted to conclude that all Type I OH masers coincide with very compact H II regions. Such a conclusion would imply that Type I OH masers cannot occur unless there was an O type star with a considerable Lyman continuum output within a distance of, say, 10.000 AU. This condition would then exclude that the OH maser was directly associated with a protostar.

However, this conclusion would have been based on the assumption that our sample of 13 OH masers has been selected at random. But, because OH masers have been looked for specifically near H II regions, it may be that our sample lacks systematically OH masers without continuum counterparts. An excellent example is OH 205.1 − 14.1, a pure Type I maser, detected by chance in a field without H II regions, but inside a T Tau association (see Table 3). If many more of such, as yet unknown, masers exist, this probably implies that the Type I OH maser phenomenon is produced already in or near a protostellar object. Only a statistically complete survey for OH sources can yield an answer.

Conclusion

Based on a study of a sample of 13 OH masers we propose the following sequence of events. When a massive star reaches the main sequence it will form a very small H II region. In this stage a Type I OH maser may appear within, say, 10.000 AU from the H II region. The maser will last for a few thousand years, until the H II region expands beyond a critical diameter, say, beyond 15.000 AU and a "normal" compact H II region appears. Whether or not a Type I OH maser appears already in the pre-main-sequence stage remains an open question, because of possible selection effects in the sample of masers that we studied.

Acknowledgement. The Westerbork Synthesis Radio Telescope is operated by the Netherlands Foundation for Radio Astronomy with the financial support of the Netherlands Organization for the Advancement of Pure Research (Z.W.O.). We thank Stella Harris for sending us a preprint about her recent work. H. E. Matthews thanks the Royal Society for the support of a European Exchange Fellowship and W. M. Goss thanks Z.W.O. for financial support.

References

Baldwin, J. E., Harris, C. S., Ryle, M. 1973, *Nature Phys. Sci.* **241**, 38
Brouw, W. N. 1971, Thesis, Leiden University
Ekers, R. D., Allen, R. J., Luyten, J. R. 1973, *Astron. & Astrophys.* **27**, 77
Churchwell, E., Walmsley, C. M. 1973, *Astron. & Astrophys.* **23**, 117
Goss, W. M., Lockhart, I. A., Fomalont, E. B., Hardebeck, E. G. 1973a, *Astrophys. J.* **183**, 843
Goss, W. M., Rieu, N.-Q., Winnberg, A. 1973b, *Astron. & Astrophys.* **29**, 435
Gwinn, W. D., Turner, B. E., Goss, W. M., Blackman, G. L. 1973, *Astrophys. J.* **179**, 789
Hardebeck, E. G. 1972, *Astrophys. J.* **172**, 583
Hardebeck, E. G., Wilson, W. J. 1971, *Astrophys. J. Letters* **169**, L123
Harris, S. 1974, *Monthly Notices Roy. Astron. Soc.* **166**, 29P
Israel, F. P., Habing, H. J., De Jong, T. 1973, *Astron. & Astrophys.* **27**, 143
Johansson, L. E. B., Höglund, B., Winnberg, A., Rieu, N.-Q., Goss, W. M. 1974, *Astrophys. J.* **189**, 455
Martin, A. H. 1973, *Monthly Notices Roy. Astron. Soc.* **163**, 141
Mathews, W. G. 1969, *Astrophys. J.* **157**, 583
Matthews, H. E., Goss, W. M., Winnberg, A., Habing, H. J. 1973, *Astron. & Astrophys.* **29**, 309
Mezger, P. G. 1971, in Highlights of Astronomy, Vol. 2, Ed. C. de Jager (Reidel Publishing Company, Dordrecht), p. 366
Mezger, P. G., Henderson, A. P. 1967, *Astrophys. J.* **147**, 471
Mezger, P. G., Robinson, B. J. 1968, *Nature* **220**, 1107
Moran, J. M., Burke, B. F., Barrett, A. H., Rogers, A. E. E., Ball, J. A., Carter, J. C., Cudaback, D. D. 1969, *Astrophys. J. Letters* **152**, L97
Osterbrock, D. 1965, *Astrophys. J.* **141**, 1285
Pottasch, S. R. 1974, *Astron. & Astrophys.* **30**, 371
Reifenstein, E. C., Wilson, T. L., Burke, B. F., Mezger, P. G., Altenhoff, W. J. 1970, *Astron. & Astrophys.* **4**, 357
Robinson, B. J., Goss, W. M., Manchester, R. N. 1970, *Australian J. Phys.* **23**, 363
Turner, B. E. 1970, *J. Roy. Astron. Soc. Canada* **64**, 221
Webster, W. J., Altenhoff, W. J. 1970, *Astrophys. Letters* **5**, 233
Wink, J. E., Altenhoff, W. J., Webster, W. J. 1973, *Astron. & Astrophys.* **22**, 251
Winnberg, A., Habing, H. J., Goss, W. M. 1973, *Nature Phys. Sci.* **243**, 78
Wynn-Williams, C. G. 1971, *Monthly Notices Roy. Astron. Soc.* **151**, 397
Wynn-Williams, C. G., Downes, D., Wilson, T. L. 1971, *Astrophys. Letters* **9**, 113
Wynn-Williams, C. G., Werner, M. W., Wilson, W. J. 1974, *Astrophys. J.* **187**, 41

H. J. Habing
Sterrewacht
Huygens Laboratorium
Leiden, The Netherlands

W. M. Goss
H. E. Matthews
Kapteyn Astronomical Institute
P. O. Box 800
Groningen, The Netherlands

A. Winnberg
Max-Planck-Institut für Radioastronomie
D-5300 Bonn 1
Auf dem Hügel 69
Federal Republic of Germany