OBSERVATIONS OF MASERS IN REGIONS OF STAR FORMATION

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1. INTRODUCTION

This review covers recent progress in observations of masers in regions of star formation, especially in the years since the reviews by Burke (1975) and Lequeux (1977). Four regions of special interest are described in more detail: Orion, W51, W49 and W3.

1.1 Type of Source Observed. There are four types of strong masers observed to date in regions of star formation: OH, H_2O, SiO and methanol (CH_3OH). Methanol masers near 25 GHz have been seen only in Orion, and Orion is also the only example of a region of star formation containing an SiO maser source. OH masers are widespread throughout the Galaxy, and are associated on a scale of $\sim$1 pc with compact radio continuum sources, IR objects and H_2O masers (see e.g. Evans et al. 1979). The main new OH surveys are by Turner (1979) and Caswell et al. (1979).

1.2 Discovery of New H_2O Sources. During the past three years, many new H_2O masers have been found in regions of star formation. The most extensive surveys are by Batchelor et al. (1979), Kaufmann et al. (1977) and Scalise and Braz (1979) for the southern hemisphere, and by Genzel and Downes (1977a, 1979) for the northern hemisphere. Additional H_2O masers have recently been found by Blitz and Lada (1979), Cesarsky et al. (1978), and by Rodriguez et al. (1978, 1979). These papers list nearly all of the H_2O masers known to date in regions of star formation. Figure 1 shows the distribution in galactic longitude of 168 H_2O masers listed in these papers. The histogram includes only H_2O sources which seem to lie in regions of star formation, and not the weaker class of H_2O masers coinciding with late-type stars. Although the diagram has not been corrected for observational selection, it shows major concentrations of H_2O masers at $\ell \sim 32^{\circ}$ and $\ell \sim 327^{\circ}$, that is, in directions tangent to spiral arms. There is no significant concentration of H_2O masers in the galactic center.

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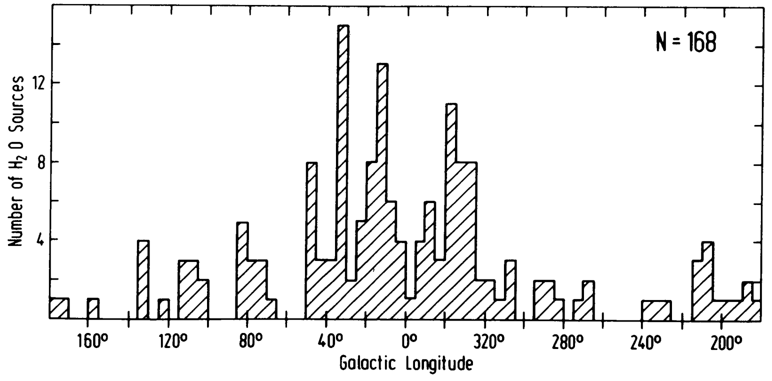

Figure 1: Distribution of 168 H_2O masers in galactic longitude. H_2O masers coinciding with late-type stars have not been included.

RECENT STUDIES OF PARTICULAR REGIONS

2. ORION-KL

Figure 2 shows the current information on H_2O masers in the Orion-KL region. The small black dots indicate the positions derived from VLBI measurements (Genzel et al. 1978 and in prep.) of the strong, "low-velocity" emission between V_{LSR} -10 to +30 km s^{-1}. The crosses show the positions of weak, high-velocity H_2O lines between -102 and +80 km s^{-1} measured with the Effelsberg 100-m telescope (Genzel and Downes 1977b and further, unpublished measurements). The VLBI relative positions can be tied to absolute coordinates by means of the accurate H_2O position measured for the 10.8 km s^{-1} line with the Berkeley interferometer (Forster et al. 1978).

This map is an improvement over previously published versions in that VLBI positions have now been obtained for the high velocity features near 67 to 70 km s^{-1} and 46 km s^{-1} in an experiment involving telescopes at Simeis, Crimea; Onsala, Sweden; Effelsberg, Haystack and NRAO.

The low velocity H_2O lines are clustered in nine or more "centers of activity" of extent 1 to 2 10^{16} cm shown in Fig. 2. The newest maps indicate that at least three of the H_2O centers of activity coincide with infrared sources (Table 1). Up to now the situation has been confused by resolution effects in VLBI measurements.

2.1 The Infrared Source IRc4 (Rieke et al. 1973) has the richest H_2O spectrum in number of lines and in the strongest integrated emission. It dominates H_2O VLBI maps on baselines ≥600 km, such as Onsala-Bonn and Haystack-NRAO. We have designated it "Source A" in previous papers.

2.2 The Infrared Source IRS2 (Wynn-Williams and Becklin 1974) has not yet received much attention in the literature. The new H_2O VLBI maps show that it has low velocity emission near 6-7 km s^{-1} and high velocity emission at 68.6, and 70.5 km s^{-1}. It is also located near the peak of

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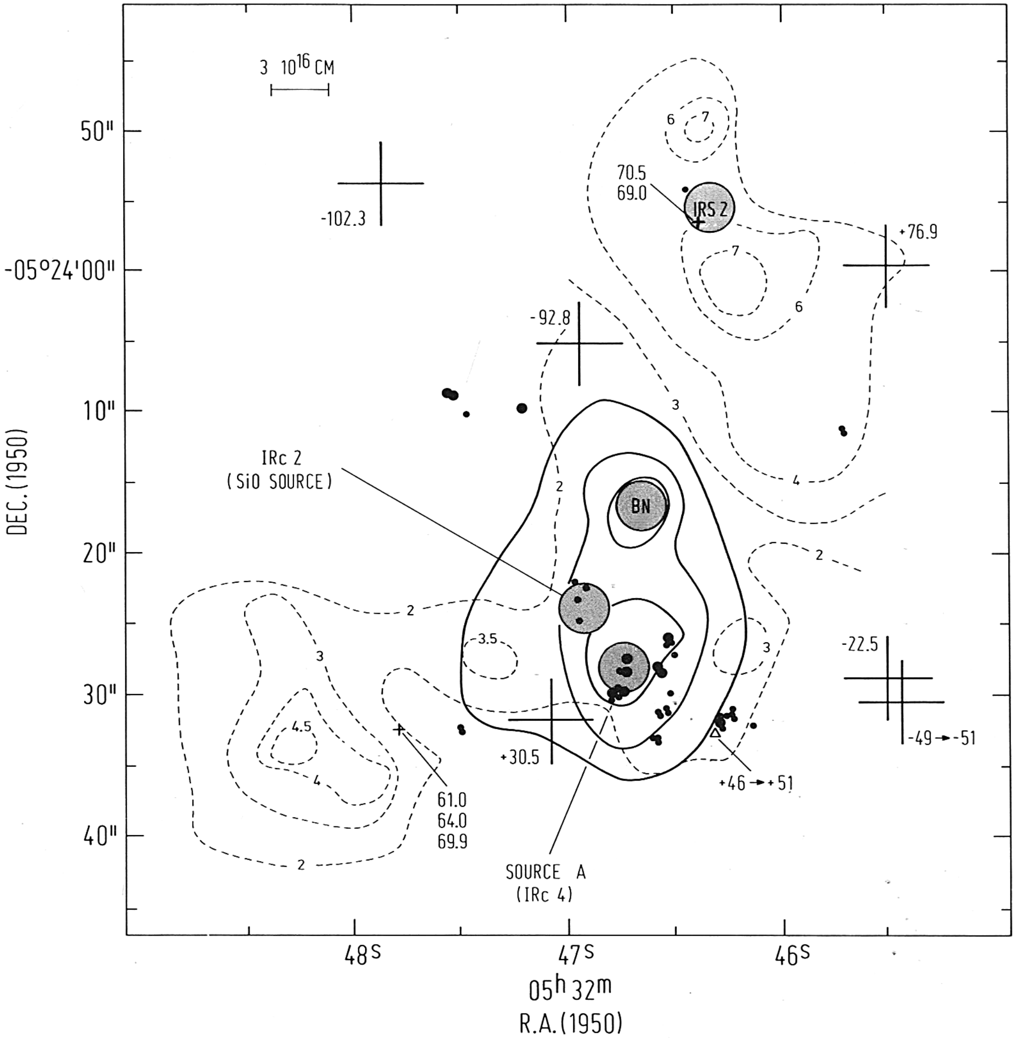

Figure 2: Positions of H_2O masers in the Kleinmann-Low nebula in Orion. The VLBI positions of the low-velocity H_2O features are shown as black dots (Genzel et al. 1978), superimposed on the contours of 20 μm infrared radiation (Wynn-Williams and Becklin 1974; Rieke et al. 1973). Shaded circles represent compact infrared objects. Crosses show the positions of weak, high-velocity H_2O masers measured with the 100-m telescope (Genzel and Downes 1977b and unpublished). High velocity H_2O features over 46 to 70.5 km s^{-1} have also been measured by VLBI. The dashed contours are those of the v = 1→0 S(1) transition of molecular hydrogen (Beckwith et al. 1978).

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Table 1. Apparent Coincidences of Infrared and Maser Sources in Orion

Infrared Source	IR Ref.	Position (1950)	Maser Source	Maser Ref.
IRc2	RLK73	$05^h32^m47.0^s$	H_2O "shell source" (75 km VLBI)	H79
=IRS3	WWB74	$-05^o24'24''$	SiO maser (v=0,1,2) possibly thermal SiO as well.	G79a
			OH maser at 17-23 km s^{-1}	NBM79
IRc4	RLK73	$05^h32^m46.8^s$	H_2O "Source A" ($\sim10^3$ km VLBI)	G78
		$-05^o24'29''$	OH maser 2-11 km s^{-1}	NBM79
IRS2	WWB74	$05^h32^m46.3^s$	H_2O low velocity (6-7 km s^{-1})	
		$-05^o23'55''$	H_2O high velocity (68-70 km s^{-1})	

Refs.: RLK = Rieke et al.; WWB = Wynn-Williams and Becklin; NBM = Norris et al.; G = Genzel et al.; H = Hansen

the molecular hydrogen emission at 2 μm, the contours of which are shown in Fig. 2, after Beckwith et al. 1978. The H_2 emission has the broadest lines near IRS2, IRc2 and IRc4 (Nadeau and Geballe 1979), suggesting that the high velocity maser emission, the broad plateau emission seen in molecular lines,and the H_2 emission at 2 μm are all related to mass-loss from the stars in the KL cluster.

2.3 The Infrared Source IRc2 (Rieke et al. 1973 = IRS3, Wynn-Williams and Becklin 1974) appears to be a different sort of object. In interferometer observations, the H_2O emission near -6 and +19 km s^{-1} is strong on the Haystack-U. Mass. 75 km baseline (Hansen 1979), is weak on the Haystack-NRL and Onsala-Bonn 600 km baselines (Genzel et al. 1978), and is completely absent on the Crimea-Bonn baseline. This indicates that the H_2O source is larger than most of the other H_2O masers in Orion-KL. The apparent angular diameter of the H_2O features is 0.03" to 0.13", about ten times larger than all the other H_2O maser features in Orion.

2.4 The SiO Maser Source in Orion = IRc2

The velocities of the H_2O features from IRc2 are the same as those of the SiO maser emission and on the basis of a simultaneous VLBI experiment on the 22 GHz H_2O and 43 GHz SiO lines Genzel et al. (1979a) have identified the SiO maser with IRc2. This result has now been confirmed by the Berkeley interferometer, operating on the 86 GHz SiO lines (Bieging et al., this Symposium). The VLBI observations of Genzel et al. show that the v=1,J=1-0 SiO lines at 43 GHz are partially resolved, have apparent angular diameters of 0.02", (1.5 10^{14}cm), and that the separate velocity components are coincident to within 0.05". Additional SiO observations with the Effelsberg 100-m telescope at 43 GHz have been made by Genzel (Center for Astrophysics), Schwartz and Spencer (NRL) and Pankonin, Baars and Downes (MPI). These observations of the J=1-0 rotational lines in the v=0,1 and 2 vibrational levels, show that the v=0 emission is unresolved (θ<10") and comes from the same position as the v=1 and v=2 maser lines. The v=0 emission has a sharp spike at -6 km s^{-1}, indicating that there is also maser emission in the ground vibrational state. In addition, there is weak (T_a^* ∿3 K) emission over a range of ∿37 km s^{-1} in the v=0,1 and 2 levels, which may be either thermal emission or weak maser emission (Genzel et al. 1980; see also Zuckerman 1979).

SiO emission was also searched for with the 100-m telescope in 27 other regions of star formation, all with negative results to ∿5 Jy. This is an order of magnitude better than previous limits, and an SiO maser with the same luminosity as the Orion source would have been detected in the sources searched, up to a distance of ∿8 kpc.

Since SiO emission is otherwise seen only from Mira variables or M supergiants, the presence of the SiO maser source in Orion has been puzzling for some time now. The velocity spread of the Orion SiO maser lies midway between that of the M giants and the M supergiants (see discussions by Snyder and Buhl 1974, Snyder et al. 1975, 1978), but the derived mass loss rate appears to be about two orders of magnitude higher.

The source IRc2 thus appears to be either an evolved giant or supergiant right at the core of the Orion molecular cloud or else is a unique object in the Galaxy.

2.5 OH and Methanol Masers in Orion

The main new OH maps are by Hansen et al. (1977) and by Norris et al. (1979). The latter map shows two concentrations of OH masers, which coincide with IRc2 and IRc4.

The positions of the 1.2 cm methanol masers in Orion have been measured by Matsakis (1979) with maser radiometers on the Berkeley interferometer. The CH_3OH masers seem to be much weaker than and not coincident with the H_2O, OH or SiO masers in Orion. Matsakis finds 10 concentrations, 6 of which were unresolved (in R.A.). The others had sizes of 6" - 8". The line brightness temperatures or lower limits were 1000 to 4000 K. The velocities are in the range 7 - 10 km s^{-1}, that is, in the normal range for the Orion molecular cloud. They may therefore be denser clumps in the general cloud material, excited by the infrared emission from objects in the vicinity. They do not appear to be in the circumstellar envelopes themselves, as do the H_2O, OH and SiO masers.

3. THE W51 REGION

The H_2O masers in W51 have been the object of several recent VLBI investigations (Walker et al. 1978, Mader et al. 1978, Genzel et al. 1978, 1979b, Downes et al. 1979).

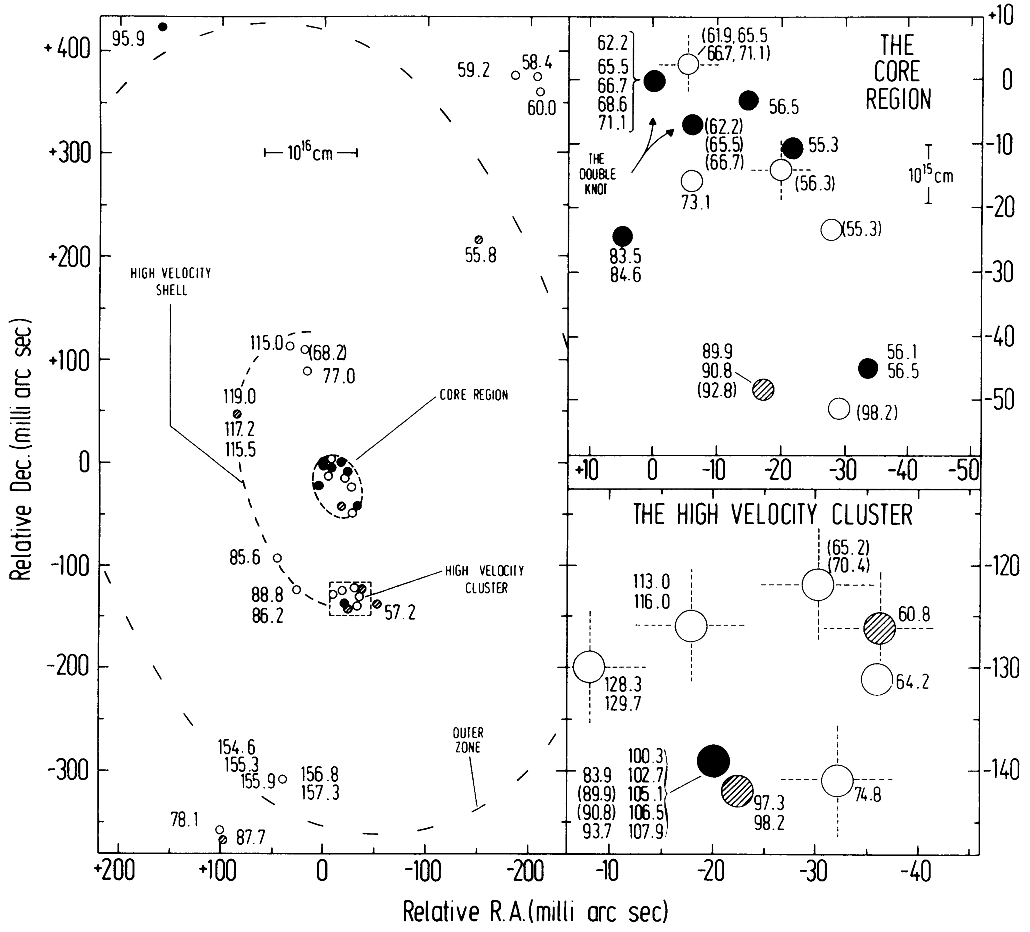

Figure 3. (from Genzel et al. 1979b). Positions of H_2O masers in W51 Main in December 1977, relative to the feature at 62.2 km s^{-1}. Labels are LSR velocities in km s^{-1}. The coordinate zero is $19^h21^m26.20^s \pm 0.02^s$. $14^o24'43.6'' \pm 0.4''$ (1950)(Forster et al. 1978). Relative positional uncertainties (2σ) are indicated by black circles for strong (>100 Jy) lines, shaded circles for intermediate lines (>50 Jy) and open circles for weaker lines. The diagrams at right show enlargements of the "Core Region" and the "High Velocity Cluster". Most of the low-velocity emission comes from the maser spots marked as the "Double Knot",which may be the location of the exciting star.

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3.1 W51 Main, the strongest source, is near (2.2"±0.8") but not coincident with a super-compact HII region (Scott 1978, Forster et al. 1978). The main new results are (i) a proper H_2O aperture synthesis of the intense, low velocity "double knot" at the core of the source (Walker et al. 1978), which results provide spectra across the source at intervals of 1 milli arc sec, and (ii) a series of VLBI maps of the structure of the entire source made by Genzel et al. (1979b). A map from the latter study is shown in Fig. 3. The strong low-velocity emission in the range 50 to 76 km s^{-1} appears to come from a core region of size $\sim 5\ 10^{15}$ cm, while redshifted high velocity features are in a "shell" or "arc" with a diameter of 3 10^{16} cm surrounding the core. A few of the high velocity features (e.g. near $V_{LSR} \sim 155$ km s^{-1}) come from an "outer zone" of diameter 9 10^{15} cm. Between November 1977 and March 1978 the source was observed by VLBI at monthly intervals, and was observed to undergo a nearly simultaneous flare in numerous high velocity features at different points on the map. These circumstances suggests an impulse of pumping energy from the star at the center of the low velocity emission. Independent of the pumping mechanism, the rise time of $\sim 5\ 10^{6}$ sec of the simultaneous flare and the diameter of typical maser cloudlets of 10^{14}cm imply a lower limit of 200 km s^{-1} for the propagation velocity of the pumping agent through the maser. As with the variations in W3(OH) (Haschick et al. 1977) this rules out the excitation of H_2O masers by ionization or shock fronts with velocities of 10 km s^{-1}. Genzel et al. (1979b) suggest that W51 Main is a massive, young O star surrounded by a disk of 5 10^{15} to 3 10^{16} cm which emits the low velocity H_2O emission. A stellar wind escapes from the disk (possibly in the manner described by Elmegreen and Morris 1979) and plows into a dense molecular cloud behind W51 Main. The redshifted high-velocity H_2O masers with velocities of 100 km s^{-1} appear in dense clumps at the wind/cloud interface.

3.2 W51 North is located 1.5' northwest of W51 Main and is a good example of the clustering of H_2O sources into "centers of activity". It has six such "centers" spread out in a 2" x 6" region (2 x 6 10^{17} cm), and a total velocity spread in the H_2O spectrum of 170 km s^{-1}. The dominant center of activity seems to have a "core"/"shell" structure very similar to that of W51 Main, although in contrast to that source the high velocity emission is mainly blueshifted (diameters in W51N are: core = 1 10^{15} cm, shell = 7 10^{15} cm, "outer zone" = 2 10^{16} cm; Downes et al. 1979).

4. THE W49 REGION

The main new results have been (i) an accurate position for the H_2O source (Dieter et al. 1979), (ii) studies of the H_2O variability (Little et al. 1977 and White 1979), and (iii) VLBI maps (Walker et al. 1977, Genzel et al. 1978, Mader et al. 1978). Figure 4 shows the spectrum of W49 N and the distribution of H_2O maser sources in a region $\sim 3\ 10^{17}$ cm across. The clustering of H_2O sources in W49 N seems to be typical for H_2O maser regions. Presumably the clusters represent Trapezium-type groups of newly-formed O stars. In W49 N the H_2O cluster is well separated from the nearest compact HII regions and the main OH source. Figure 4 (lower)

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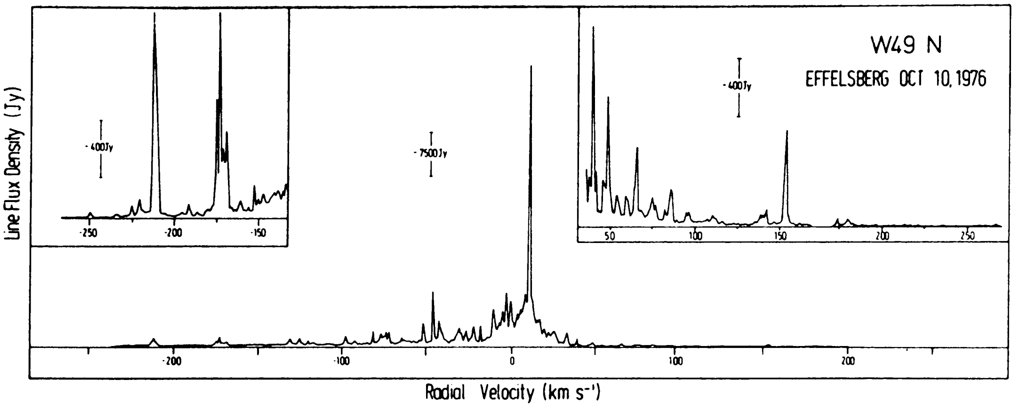
shows schematically the low velocity "centers of activity as large circles (strongest ones shaded). Several of the "centers" are surrounded by high velocity features (small dots; Walker et al. 1977) which presumably indicate that these stars are losing mass in the same manner as the stars in the K-L nebula, although with much greater luminosity and at about three times greater velocities. A new, extensive study of the high velocity H_2O in W49 N is in progress by Walker et al.



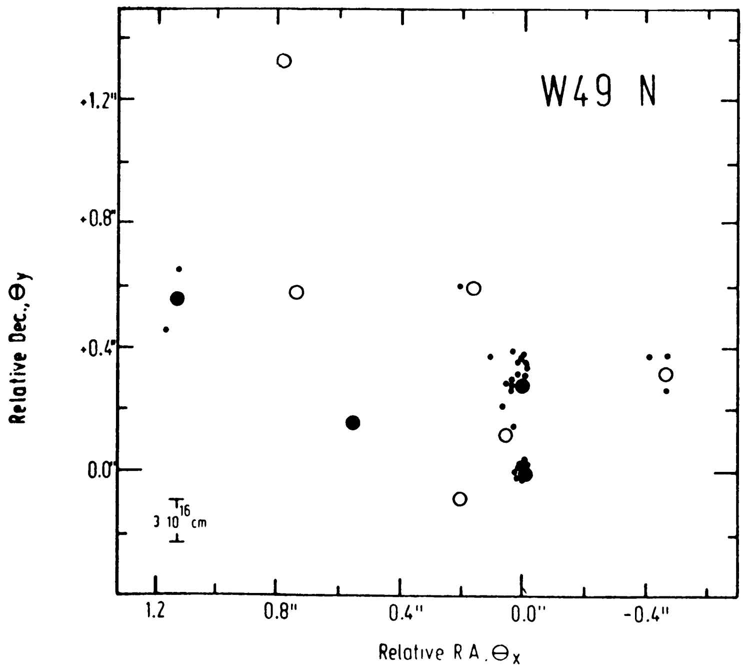


Figure 4. Spectrum and positions of H_2O masers in W49 N. The lower diagram shows nicely the clustering of H_2O sources into low-velocity "centers of activity" (large circles; strongest "centers" are shaded). High velocity features (shown in the insets in the H_2O spectrum at top) are found in swarms (small black dots) around some of the low velocity "centers". For H_2O velocities represented by the individual dots, see Walker et al. 1977, Genzel et al. 1978. The coordinate zero is $19^h07^m49.77^s \pm 0.05^s$, $+09^\circ 01'17.1'' \pm 0.5''$ (Dieter et al. 1979).

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5. THE W3 REGION

The region around the W3 radio continuum sources contains at least 5 H_2O maser sources; an overview of the maser positions is given in Downes and Genzel 1979.

5.1 W3(OH). The main new result has been the accurate position of the H_2O (Forster et al. 1977) which is about 7" east of the compact HII region. New VLBI maps of the H_2O source (Walker et al. 1978, Genzel et al. 1978) show that 90% of the H_2O intensity comes from a "center of activity" to the east of a "line" of weak H_2O spots, each with a single velocity. An extensive series of VLBI maps of this line of sources has been obtained by Giuffrida (1977) and collaborators.

The -50.3 km s^{-1} feature in the H_2O "center of activity" flared up in May-June 1977. The 4-day risetime was followed by a 25-day decay (Haschick et al. 1977). The pattern has been analyzed by Burke et al. (1980) whose calculations favor a collisionally pumped, cool (100-200 K) saturated maser with a large injection of energy (10^{39}-10^{41}erg) into a cloud of dimension 10^{14}-10^{15} cm in one or two days time at most.

The main new result in OH has been an accurate position obtained from the excited-state OH lines at 6035 MHz, (Moran et al. 1978): it shows that the OH masers are exactly coincident with the compact HII region. Since the W3(OH) HII region is optically thick at 6 GHz, the masers must be on the front side of the source. Moran et al. find that the maser spots occur in spatial pairs of right and left-circularly polarized features, and thus provide probably the best evidence to date for Zeeman splitting in OH. Moran et al. derive magnetic field strengths of 2 to 9 milligauss.

A remarkable aperture synthesis has been done with VLBI data in the OH ground state lines by Reid et al. (in preparation) who find numerous Zeeman OH pairs scattered over the face of the source. When the apparent velocities of the Zeeman pairs are averaged together, one obtains a velocity close to -45 km s^{-1} with a slow variation of $\sim\pm3$ km s^{-1} across the face of the HII region. Since this is also the velocity of NH_3 absorption and 23-GHz OH absorption toward the continuum source, the OH masers may occur in a relatively quiescent, dense cloud somewhat external to the HII region, and not in a turbulent shock close to the ionization front.

5.2 W3-IRS5 appears from H_2O VLBI maps to consist of two or three sources and may be a stellar group like the cluster in Orion-KL. Cal Tech infrared observations (see Wynn-Williams 1976) had indicated that the source was at least double,separated by 1", but recent speckle interferometry at 4.8 μm by Chelli et al. (1979) has resolved only a single source, roughly in the north-south direction, with a diameter of 0.28"±0.08". It would be of interest to pursue the investigation of source structure in the infrared to determine its relation to the H_2O masers.

6. OBSERVATIONAL PROSPECTS FOR THE FUTURE

A common trend of the maser, infrared and radio continuum observations has been to show the occurence of these sources in clusters somewhat similar to the Trapezium in Orion (cf Beichman et al. 1979, Evans et al. 1979, Habing and Israel 1979). For most of the sources the positional accuracy must still be improved to see whether the sources in various wavelength regions actually coincide on scales <0.1 pc.

Relative positions accurate to 0.5 milli arc sec can now be achieved for strong H_2O sources as a matter of course by the fringe rate method described by Moran (1976). We have attempted improvements by phase mapping and have obtained repeatable measurements to 0.1 milli arc sec for a very few high velocity features in W51 Main. The results are in general disappointing, however, and not in proportion to the effort required. Nevertheless, with the standard fringe-rate technique, it should be possible within the next year to obtain measurements of the relative proper motion of H_2O masers.

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DISCUSSION FOLLOWING DOWNES

Elitzur: It was suggested once by the group at Leiden that the SiO maser in Orion could come from infall of material. It seems to me that the observations you presented support this idea. The standing shock resulting from the infall could be the location of all the maser features of the different molecules which coincide in position and velocity.

Downes: The possibility certainly deserves further thought. However the VLBI distribution of H_2O maser "spots" from this source indicates radii of 10^{15}-10^{16} cm from the star. These radii, together with the velocity half-range of 11 to 17 km s^{-1}, imply a very large central mass if the velocities come from infall. Remember also that the upper limit of the infrared luminosity of the star is $\sim 2 \times 10^4 L_\odot$, which suggests a limit to the mass of the star of 10-20 $M_\odot$.

Bieging: What lower limit can you place on the brightness temperature of the SiO V=0, J=1-0 line in Orion, which you suggest may be a maser?

Downes: For the spike at -5 km s^{-1} in the V=0 source, the lower limit to the brightness temperature is 350±50K. For the broad feature, it is 150±30K.

Elmegreen: Various models of maser geometries, such as shells or protoplanetary-type disks, cannot be distinguished on the basis of velocity-position maps alone. Proper motions and/or accelerations are needed as well. What are the prospects for eventually detecting accelerations of individual components?

Downes: We expect to be able to establish proper motions in about a year. Accelerations are more difficult to observe because an apparent change in velocity may simply be due to a change in the relative inten-

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sities of two nearby, blended lines. It might be possible to attack this problem by searching for velocity changes among the features which show proper motions.

Booth: Comparison of the spectra of W3(OH) at 1665 MHz taken over the past ten years shows that a feature, now at -43.9 km s^{-1}, has moved in velocity by 0.2 km s^{-1}. It has decreased steadily in intensity during the same period, and its position (relative to the feature at -45.1 km s^{-1}) appears to have changed by 0.05 arc seconds. This may be an example of acceleration of material in the source, although we can interpret it as a beaming effect.