Part IX. Conference Summary

Cosmic MASERs: From Protostars to Blackholes
ASP Conference Series, Vol. 206, 2002
V. Migenes and M. J. Reid

Masers, from Protostars to Black Holes: Conference Summary

Mark J. Reid
Harvard–Smithsonian Center for Astrophysics, 60 Garden St., Cambridge, MA 02138, USA

Abstract. Astronomical sources of maser emission have now been studied for more than 30 years, and research related to masers spans a very wide range of topics in astrophysics. Over this period great progress has been made in many areas of maser research. This summary will put maser research into an historical perspective and focus on highlights from this conference.

1. Maser Research: 10 and 20 Years Ago

Approximately 20 years ago, H_2O, OH, and SiO masers were fairly well observed and known to be widespread. However, CH_3OH masers were largely unknown–only lines near 25 GHz had been discovered, and these lines were detected only in the Orion nebula. A theoretical foundation for understanding maser amplification had been constructed, notably by Litvak and Goldreich and co-workers. Also, some pumping models had been proposed, but these models were largely unconstrained by observations.

Two classes of masers were clearly recognized by 1980: interstellar and stellar masers. For interstellar masers, associated with star formation, there were a few outstanding VLBI maps of OH and H_2O masers. Astronomers were still actively arguing whether each clump of H_2O masers surrounded a (low mass) star or if a single (high mass) star excited a collection of clumps in an active region. The first maser proper motions, done for H_2O masers, revealed expansion in Orion and favored the single exciting star model; these proper motions also resulted in a geometric distance estimate. The importance of the Zeeman effect in OH masers was clearly documented. However, the dynamics of OH masers were uncertain, although several models existed. Masers from evolved stars, or stellar masers, were recognized to have a concentric shell or "onion" structure: SiO masers in a shell closest to the star, followed by H_2O, and then OH masers. However, few details (dynamics, densities, magnetic fields, etc.) had been established.

While the first extragalactic H_2O maser had been discovered 20 years ago, this maser seemed simply an analog of interstellar masers in our Galaxy and extragalactic masers were not really considered a promising field of study. The concept of "mega-masers" did not exist. However, about 10 years ago, the first international conference on masers was held near Washington, D.C. (see Clegg &

Nedoluha 1992). Significant advances in the field were obvious, but perhaps the greatest excitement involved the discovery and understanding of OH and H_2O masers toward the nuclei of active galaxies. As the papers at the current meeting testify, masers in the nuclear regions of galaxies are a fascinating phenomenon and extremely useful tools for studying processes near super-massive black holes.

2. Nomenclature

The nomenclature used to describe classes of masers is seldom uniform and highly subjective. I add my opinion here, mostly in the hope of minimizing non-descriptive terminology such as "Class I" or "Type IIb" masers, which I find hard to remember. I have long argued that the nomenclature should follow a physical approach, such as one based on the nature of the masing material. Thus, "stellar masers" should include those sources in which the masing material comes from the central star (e.g., a Mira). This is limited primarily to evolved stars and includes red giants, super-giants, and proto-planetary nebulae.

Similarly, "interstellar masers" should refer to sources in which the masing material is from the interstellar medium (e.g., W3OH). Of course, interactions with stars, mostly newly forming or formed stars, is needed to excite these masers, but the masing molecules seem to be from molecular clouds. These sources are predominantly associated with star formation processes, such as UCHII regions, hot cores, protostellar disks and jets. The 1720 MHz OH masers found at the interface between supernova remnants (SNRs) and molecular clouds would also fall into the "interstellar maser" group.

Finally, "nuclear" masers would cover the class of H_2O and OH masers found in the vicinity of the nuclei of active galaxies (e.g., NGC 4258 & Arp 220). While the material masing here could also be considered as "interstellar," these masers share little in common with "interstellar masers" and deserve their own grouping. Since there are true "interstellar masers" detected in the spiral arms of other galaxies, such as the H_2O masers in M 33, I prefer not to use the term extra-galactic masers, since it would lump together masers in spiral arms and the nuclei of galaxies.

3. Pumps

Somewhat surprisingly, maser pumps were not discussed extensively at this meeting. Possibly this is a signal that the basic natures of most maser pumps are considered fairly well understood. More likely, this indicates that pump models are extremely complex and progress toward detailed understanding will require very hard work.

The pumping of a few classes of masers appears to be reasonably well understood. Masers in comets are probably pumped by solar ultra-violet radiation and models reproduce the time variations of masers in comets very well. The pumping of radio recombination line (RRL) masers in MWC 349 also seems to be well in hand. In the cases of comets and RRLs, the geometry, the physical conditions of the material, and the radiation environment are tightly constrained, allowing detailed excitation and radiative transfer models to be constructed.

Another well-modeled maser pump is for the 1720 MHz OH masers associated with SNRs.

At this meeting we saw general agreement that Class II methanol masers (i.e., those generally associated with ultra-compact HII (UCHII) regions and strongest at 6.7 and 12 GHz) are probably radiatively pumped with far-IR photons, possibly involving torsionally excited states. Interstellar OH masers at 1665 MHz, which often populate the same regions, are also radiatively pumped via far-IR light. On the other hand, Class I methanol masers (i.e., those *not* directly associated with UCHII regions and strong at 23 and 44 GHz) seem to be collisionally pumped.

The long-standing debate over the dominant pump mechanism for SiO masers is still not settled. While many argue that collisional pumping can do the job, the slight positional offsets between different J-transitions, and the same J-transitions in different vibrational levels, leaves the subject open and might favor radiative pumping.

Finally, we learned that lasers (optical/infrared masers) are rare and a lack of strong pumping can be understood from two basic principles. Firstly, any given population inversion yields a smaller magnitude for the excitation temperature at a lower frequency (remember small, negative excitation temperatures produce the strongest masers). Secondly, the brightness temperature at which a maser saturates is generally greater that lower frequencies, which allows for greater exponential amplification.

4. Interstellar Masers

4.1. Associations

Interstellar masers come in a wide variety of species, including OH, H_2O, and CH_3OH, and are associated, at least loosely, with sources such as UCHII regions, embedded IR sources, hot molecular cores, Herbig-Haro objects, and outflows. As we heard in several talks, it is very hard to be more specific and to find clear-cut associational rules. For example, OH masers have long been thought to be directly associated with UCHII regions, from their birth and lasting until the UCHII regions expand to $\sim$ 0.05 pc. However, perhaps half of interstellar OH masers appear on the sky significantly offset from UCHII regions, sometimes far from any detected source.

There are many reasons for a high degree of associational complexity. The appearance of masers is strongly affected by the following: chemistry (sensitive to dissociation, ionization, temperature, and density), amplification (sensitive to velocity and magnetic field gradients), source lifetimes, and observational selection effects (including projection effects and limited instrumental resolution). For example, consider the well-studied region W3OH, which is shown in Fig. 1. From our vantage point, the two dominant newly formed stars, the TW object and the O-type star exciting the UCHII region, are well separated on the sky at angular resolutions better than a few arcseconds. However, were this source at a much greater distance, the two objects might not be resolved and one could conclude erroneously that many masing species and transitions came from the same object. A similar conclusion could also result were we to observe this region from another position in the Galaxy, such that the TW object became

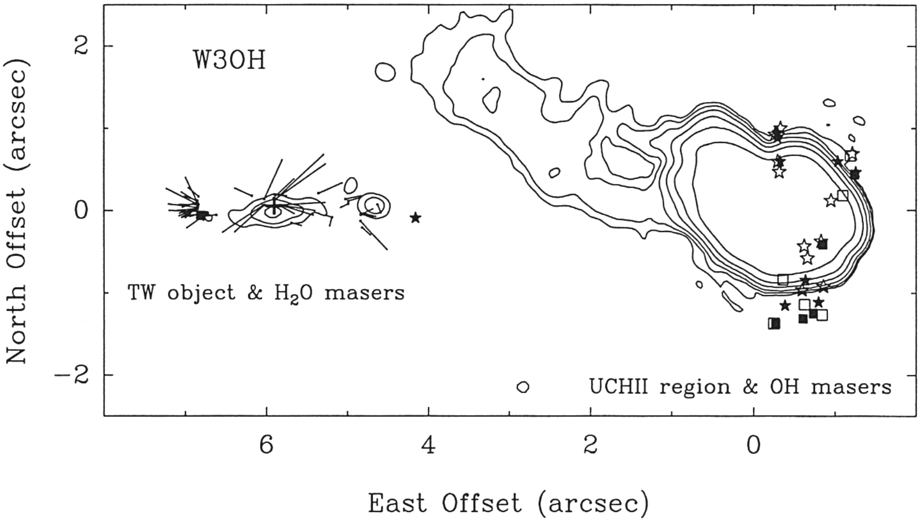


Figure 1. Masers in the massive star forming region W3OH: Radio continuum emission at 8 GHz from the enigmatic Turner–Welch (TW) source on the left and the UCHII region on the right are shown in contours. H_2O masers, and their proper motions, are indicated with lines. The center of the H_2O maser expansion (+) is coincident with the TW object. Not shown is the molecular hot core emission surrounding the TW object. OH masers, indicated with stars and squares, are found mostly near the UCHII region. Not shown are Class II CH_3OH masers. which are also seen toward the UCHII region. The projected separation between the TW object and the UCHII region is ≈ 0.07 pc.

projected toward the UCHII region. Undoubtedly this occurs in some massive star forming regions.

4.2. Structural Diversity

The strongest interstellar masers, OH, CH_3OH, and H_2O, have generally appeared as simple structures ("spots") when mapped with small numbers of radio interferometer baselines. The advent of large arrays of radio interferometers, including the Australia Telescope, MERLIN, and especially the VLBA, have presented us with some magnificent images of masers with complex and fascinating structures. Perhaps the most fascinating structures occur in CH_3OH and H_2O masers. At this meeting we have seen maps of these masers in which the following structures stand out: spherical expansion ("bullets"), bi-polar outflows, disks (tori and possibly rings), curved bow–, linear– and perhaps oblique–shocks, puffs (explosions), and maybe some evidence for infalling motions. Probably all of these structures are signposts for different physical processes occurring near extremely young stars; indeed, some structures indicate dynamical ages of less than ∼ 100 years!

4.3. H_2O masers

The diverse structures seen toward H_2O masers solves, at least in my mind, a long–standing problem in the interpretation of these masers. Early proper motion studies of H_2O masers showed a dominant global expansion. Models of these sources, which treated the masers as "bullets," clearly located a "center of expansion." However, when one traced the proper motion vectors backwards in time, they failed to intersect tightly at the center. The "bullets" behaved as if they had ricocheted off of unseen obstacles. Clearly the "bullet" interpretation was overly simplistic. H_2O maser structures are far more complex and, although ricocheting may be a somewhat inaccurate description of what happens, interactions of strongly outflowing material with the surrounding medium shape maser structures and allows them to move in a complex manner.

4.4. OH masers

Hydroxyl (OH) masers have been extensively studied over the past few decades. We know that some OH masers form in the molecular environment immediately surrounding UCHII regions. Physical conditions conducive to OH masers seem to be warm regions with $T \approx 100$ K and densities of $10^5 < n_{H_2} < 10^7$ cm^{-3}. Zeeman measurement indicate magnetic fields of ≈ 3 mG.

There is little dispute that interstellar OH masers are often associated with UCHII regions. Hence, some OH masers exist near massive stars that are not far from being zero-age main-sequence stars and are hot enough to ionize their surroundings. However, we learned that many (e.g., 50%) OH masers have no detected UCHII regions (i.e., < 1 mJy at 8 GHz). Possible reasons for the absence of UCHII regions include a central star of spectral type later than about B3, which produces few ionizing photons, or the existence of extremely dense circumstellar material, which can dramatically limit the size of an HII region owing to rapid recombination rates. However, perhaps there are other, more interesting, explanations for OH masers without HII regions.

Scattering of OH maser radiation by interstellar electrons between the source and the Earth is an important observational limitation (greatly enlarging apparent spot sizes) and, at the same time, a powerful method to assess fluctuations in the electron distribution in the ISM. There are, however, some "holes" in the electron distribution along the lines of sight to some OH maser sources, indicating the ISM electrons are very clumpy. The smallest apparent angular size for OH masers measured to date is < 2 mas, corresponding to a linear size of < 4 AU at a characteristic distance of 2 kpc. The current record high brightness temperature measured for an unscattered OH spot is $> 6 \times 10^{12}$ K.

4.5. CH_3OH masers

Class I methanol (CH_3OH) masers are those *not* directly associated with UCHII regions or strong infrared sources. Indeed the lack of clear associations is one of the central puzzles related to these masers. Notably, few papers at this conference reported on Class I methanol masers and several questions remain:

1) Is there a forming high-mass star (or stars) that excites the masers?
2) Are they formed at the interface of outflows or shocks associated with "distant" (> 0.1 pc) sources?

3) Are they associated with hidden low-mass stars?

In contrast to Class I sources, there were many papers describing work on Class II sources. Class II sources are often associated with UCHII regions and/or OH masers. Blind surveys suggest that the luminosity function of the underlying stars decreases with stellar luminosity, and may extend down to $\sim 10^3$ $L_\odot$, or a ZAMS spectral type of about B5. Perhaps, the luminosity function continues to even lower stellar luminosity. This might explain why a significant fraction of Class II methanol/interstellar OH masers are not directly associated with a detectable UCHII region, and possibly why some are found not to have detectable 10μm-wavelength counterparts.

Monitoring studies indicate that Class II methanol masers, like their associated OH masers, vary over a wide range of time scales. The distribution of the number of maser features versus variation time scale is roughly exponential, but with a long tail extending out to years.

Finally, quasi-linear methanol maser distributions have been extensively reported. These distributions often are bent and can also display organized velocity changes across the structures. It is unclear whether these structures represent low-mass proto-stellar disks, trace interstellar shocks, or perhaps have other origins.

4.6. Maser Chronology

Establishing an evolutionary time sequence for the formation and destruction of various masing species has been a central, but vexing, problem. For example, in the well-studied source W3OH (see Fig. 1), the lack of an ionizing source at the TW object/H_2O maser site (the weak 8 GHz emission is synchrotron in origin) and the presence of a hot molecular core suggests that this object is younger than the UCHII region/OH/CH_3OH site. Thus, for many years, the general consensus has been that H_2O masers occur at an earlier phase in the formation of a massive star than OH and Class II CH_3OH masers. Papers presented at this meeting generally concur with this theory, and some have expanded the discussion to forward chronologies similar to the one displayed in Fig. 2.

4.7. Supernova Remnant 1720 MHz OH Masers

Ground-state hydroxyl masers in the satellite-line transition at 1720 MHz have long been known to occasionally accompany both interstellar (e.g., UCHII region) and stellar (Miras and supergiant) masers. It was suspected decades ago that some 1720 MHz masers were also associated with supernova remnants (SNRs). However, over the last decade, this class of masers has been clearly identified and studied in great detail. These masers appear beyond the boundary of a SNR in what appears to be an irregular shock-compressed shell.

The masers only appear when the shocked layer is nearly perpendicular to the line-of-sight, providing long columns of gas. This is in contrast to stellar OH sources, in which masers occur in a *thick* shell. In a thick, uniformly expanding shell, the dominant amplification is from "caps" on the front and back along our line-of-sight, and *not* from the limbs. Thus, the shocked layer in SNR OH masers must be very thin so that geometric path lengths, perhaps more than Doppler velocity changes, limit amplification.

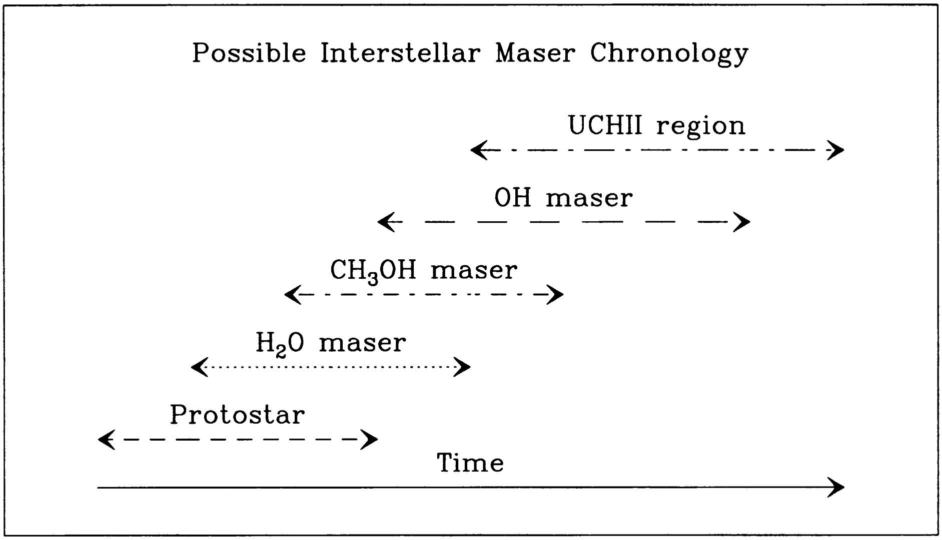


Figure 2. Possible chronology for masers associated with regions of massive star formation. Time increases toward the right. Note the considerable time overlap of various masing species and phenomena.

Models of 1720 MHz OH masers require specific physical conditions, including $T \approx 100$ K at densities of $n_{H_2} \sim 10^5$ cm^{-3}, and column densities of $10^{16} < N_{OH} < 10^{17}$ cm^{-2}. At densities of $\sim 10^5$ cm^{-3}, one expects magnetic fields of $B \sim 1$ mG, as observed from Zeeman splitting in these masers. Theoretically, these conditions are tightly constrained such that ultra-violet radiation dissociates H_2O to form OH and heats dust sufficiently (but not too much) to provide infrared radiation to pump the masers. Since these conditions are similar to those that support CH_3OH masers, it might be interesting to consider why CH_3OH masers are not found in these regions.

5. Stellar Masers

Stellar masers originate in the circumstellar envelopes of evolved giant and supergiant stars. These stars are usually variable (e.g., Miras, long period variables, semi-regular variables) and form modest (e.g., Miras) to copious (e.g., OH/IR stars) amounts of dust. A schematic representation of the various "layers" in a circumstellar envelope is shown in Fig. 3. At the center of the envelope is a pulsating, very cool star. Periodically shocks emerge from below the photosphere, possibly producing a chromospheric region. As the star approaches minimum light, it cools enough to promote metallic oxide formation, which enlarges the optical "$\tau = 1$"-surface to nearly twice the "real" radius. This "molecular photosphere" is significantly cooler than the star, resulting in extremely large decreases in visual light. At the outer region of the molecular photosphere, electrons from low ionization potential atoms (e.g., potassium and sodium) produce sufficient H^- free–free opacity at radio through far–IR wavelengths to form a "radio photosphere."

5.1. SiO Masers

Beyond the radio photosphere one finds SiO masers. The SiO masers seem to exist between "a rock and a hard place;" they are bounded on the outside by depletion of SiO onto dust grains and on the inside by radio continuum opacity and/or collisional quenching owing to very high densities. SiO masers have been well studied over the past decade. Proper motions measured with the VLBA indicate that outward motions of a few km s^{-1} are common over most of the SiO shell, but that inward motions sometimes occur. This suggests that either ballistic return of ejected material or some convective–like motion occurs within the SiO maser region.

5.2. H_2O masers

The formation of dust at the outer boundary of the SiO masers allows the momentum in the stellar (mostly infrared) luminosity to accelerate material in the envelope past escape speed. H_2O masers are observed in this accelerating region, at a characteristic radius of about 15 or more AU. Monitoring of stellar H_2O masers indicates that the peak H_2O emission is approximately at optical phase 0.3, close to the peak in total stellar luminosity. One can, in some cases (e.g., R Cas), see a damped, sinusoidal, "light curve" for an individual H_2O maser feature, which may indicate movement of material across the masing shell over $\sim$ 30 years. In general, masers in an accelerating shell have the longest coherent amplification paths near the shell limbs, and this has been observed in some stars (e.g., W Hya).

5.3. OH masers

At distances of several 10's of AU from a (Mira-like) star, the acceleration in the envelope diminishes and circumstellar material coasts outward at nearly a constant velocity. This terminal expansion velocity ranges from $\sim$ 5 km s^{-1} to $\sim$ 30 km s^{-1} or higher (especially in super-giant stars). Interstellar ultraviolet radiation dissociates H_2O, producing OH molecules and, when hydrogen densities decrease to below $\sim 10^7$ cm^{-3}, OH masers occur. If the OH masing shell is coasting outwards, then maser amplification from "caps" on the front and back side of the envelope should dominate over emission from the limbs. Interestingly, the projected extent on the sky of the OH masers may be similar to that of H_2O masers in the same star (e.g., U Her), as the OH caps subtend a smaller cone-angle (as seen from the star) but at a larger radius than (limb-dominated) H_2O masers. As in the case of interstellar maser associations, the importance of understanding the projection of the real (3-D) geometry onto the (2-D) sky cannot be under-estimated.

6. Unusual (and Fascinating) Objects

The H_2O super-maser feature in the Orion–KL region continues to flare occasionally, reaching peak flux densities over 10^6 Jy. Results presented at this meeting confirm the early findings of high linear polarization, line-center and line-width variations, and "large" ($\approx$ 10 mas) elongated structures on the sky. Astonishingly, the orientation of these structures seems to have changed considerably from earlier flares.

A bit to the east of the super-maser in Orion is a deeply embedded infrared reflection "nebula," IRc 2, which seems to be powered by a massive young star seen in the radio (and called source I). Early maps of the SiO masers associated with source I were interpreted as indicating a rotating and expanding disk. However, these maps were made with connected–element interferometers with limited angular resolution. When mapped with the VLBA, the true pattern of the SiO masers emerged as an "X–shaped" structure, which probably outlines the limbs of a bi-conical jet and/or a disk.

Recently, considerable attention has focused on stars in transition from the red giant to the planetary nebula phase, termed proto-planetary nebulae (PPN). At this conference we heard about two such objects. At the center of OH231.8+4.2 is a red-giant star, possibly with a companion. Near the red-giant star are unusual SiO masers, whose spatial and velocity structure may indicate orbital (and possibly infall) motion in a disk. On larger scales, OH masers mapped at 1612 and 1665 MHz give further indication of an "equatorial" structure such as a disk or ring. Finally on much larger scales, long jet-like emissions extend almost perpendicular to the equatorial structures and terminate in bow-shock features, reminiscent of double-lobed extragalactic radio sources.

Another PPN candidate is W 43A. This object shows a 1612 MHz OH maser spectrum, characteristic of an AGB star, but its H_2O maser displays a fast (150 km s^{-1}) bipolar outflow. We also heard that the nature of the extreme velocity edges of 1612 MHz spectra may provide clues to the evolutionary status of the central star. Sharp outer edges in the spectrum suggest a uniformly expanding shell; whereas irregular outer edges indicate variable mass outflow and may be a sign of a post-AGB phase. Indeed, the 1612 MHz spectrum of W 43A does have an irregular high-velocity edge.

7. Magnetic Fields

Since masers are strong, compact sources of emission from dense regions near forming or evolved stars, they are excellent probes of magnetic fields. The Zeeman effect is the simplest mechanism to give polarized maser emission and it has been clearly documented for OH masers, where the Zeeman splitting is often far greater than the line-width. In many interstellar OH masers clear Zeeman pairs have been identified in VLBI maps, and in some cases multiple Zeeman pairs originating in different transitions are seen toward the same position on the sky. In these cases, the Zeeman interpretation is solidly established.

Typical magnetic field strengths for interstellar OH masers are $\sim$ 3 mG. However, we learned at this conference that magnetic fields as high as 20 mG have been detected in the W 51 star forming region. The magnetic fields in these regions appear to have a large-scale organized structure, often with the same line-of-sight orientation of the field across an entire source. Thus, OH maser observations may reveal the full 3-D structure of the magnetic field near a newly formed (or forming) massive star.

Table 1. Magnetic Fields in Stellar Masers

Maser	B(Zeeman) (G)	R (cm)	$B^2/8\pi$ (dyne cm^{-2})	nkT (dyne cm^{-2})	ρv^2 (dyne cm^{-2})
OH(1665/7)	0.001	6×10^{14}	10^{-7}	4×10^{-7}	10^{-5}
H_2O	0.1	3×10^{14}	10^{-3}	6×10^{-5}	10^{-3}
SiO	10	5×10^{13}	10^{+1}	1×10^{-3}	10^{-2}

Early indications that the magnetic fields sensed by interstellar OH masers traced a coherent Galactic magnetic field have weakened statistically with increasingly larger data samples. However, tantalizing correlations of magnetic field directions among sources separated by $\sim$ 1 kpc are evident in the larger samples.

One of the unsolved mysteries of OH maser amplification is that, while elliptically polarized σ–transitions are plentiful, linearly polarized π–transitions have never been convincingly detected. Perhaps the explanation for this phenomenon is the long–standing conjecture that Faraday rotation within the maser amplification path weakens and de-polarizes π–transitions.

Early polarimetric observations of H_2O masers in star forming regions suggested magnetic field strengths of $\sim$ 100 mG, or about a factor of $\sim$ 30–times stronger than detected with OH masers in the same star forming regions. Since strong H_2O maser emission occurs at densities roughly a 1000–times higher than OH masers, this agreed well with the relation $B \propto n^{1/2}$, obtained from HI and thermal OH transitions at much lower densities.

While magnetic field measurements based on OH masers follow in a straightforward manner from a Zeeman interpretation, this is not the case for other (non-paramagnetic) masing species. For molecules such as H_2O, CH_3OH, and SiO, Zeeman splitting is always smaller than the line-width, and this complicates matters considerably. This is apparent in polarimetric observations of stellar masers. Table 1 lists various parameters characteristic of maser emitting regions in evolved (Mira-like) stars. The magnetic pressures ($B^2/8\pi$), inferred from a Zeeman interpretation, are less than or comparable to thermal (nkT) or ram/turbulent (ρv^2) pressures for OH and H_2O masers. Note, however, that the magnetic fields, estimated assuming a simple Zeeman interpretation, achieve quite substantial values for SiO masers, and this would imply magnetic pressures which are factors of 1000 or more greater than thermal or ram pressures. This seems unlikely and, hence, non-Zeeman interpretations of SiO maser polarizations, such as arising from anisotropic pumping, seem probable. Regardless of the polarizing mechanisms, the organized structures seen in the polarization properties of SiO masers are certainly fascinating.

8. Nuclear (Extragalactic) Masers

There has been tremendous progress over the past decade in the study of masers found in or near the nuclei of other galaxies. The host galaxies are invariably spirals, usually with weak AGNs. Nuclear H_2O masers have now been found in over 20 galaxies, albeit after many long hours on many telescopes. There are still no efficient search criteria for this class of masers. Dramatic time variations have been reported for some maser features, with the fastest variations coming from the galaxy IC 10 over time scales of hours.

The fascinating sub-parsec scale disk traced by H_2O maser emission in NGC 4258 has proved to be a "Rosetta Stone" for the study of accretion disks near super-massive black holes. However, while there have been extensive searches for other 4258's, it still is the only clean, well documented case we have. At this conference we heard that the H_2O masers in IC 2560 exhibit both high velocity components and possible Doppler velocity drifts in the systemic components. Should further observations show this galaxy to be similar to NGC 4258, the somewhat embarrassing uniqueness of NGC 4258 would be removed.

Great progress toward understanding OH mega-masers has been made recently. VLBA observations of the masers in Arp 220 revealed many surprising results. The 1667 MHz masers break up into many clumps with characteristic sizes of $r \sim 1$ pc and velocity spans of $\delta V \sim 100$ km s^{-1}. These clumps do not align precisely with the radio continuum emission in either nucleus. Also, the radio continuum emission seems dominated by many point-like sources, possibly radio SNRs. The small size and high velocity spread of the OH clumps, suggest a characteristic enclosed mass of $M \sim r\Delta V^2/G \sim 10^6$ M$_\odot$, provided that the motions are orbital or infall. The same conclusion holds even if the motions are outflow, if the velocities are comparable to the escape speed. Interestingly, the 1665 MHz maser emission seems to come from larger structures which are fully resolved with the VLBA and, thus, their nature is still largely unknown.

References

Clegg, A.W. & Nedoluha, G.E., (eds.) 1992 Astrophysical Masers: Proceedings of a Conference held in Arlington, Virginia, USA 9–11 March 1992, Lecture Notes in Physics 412 (Springer–Verlag, Berlin)

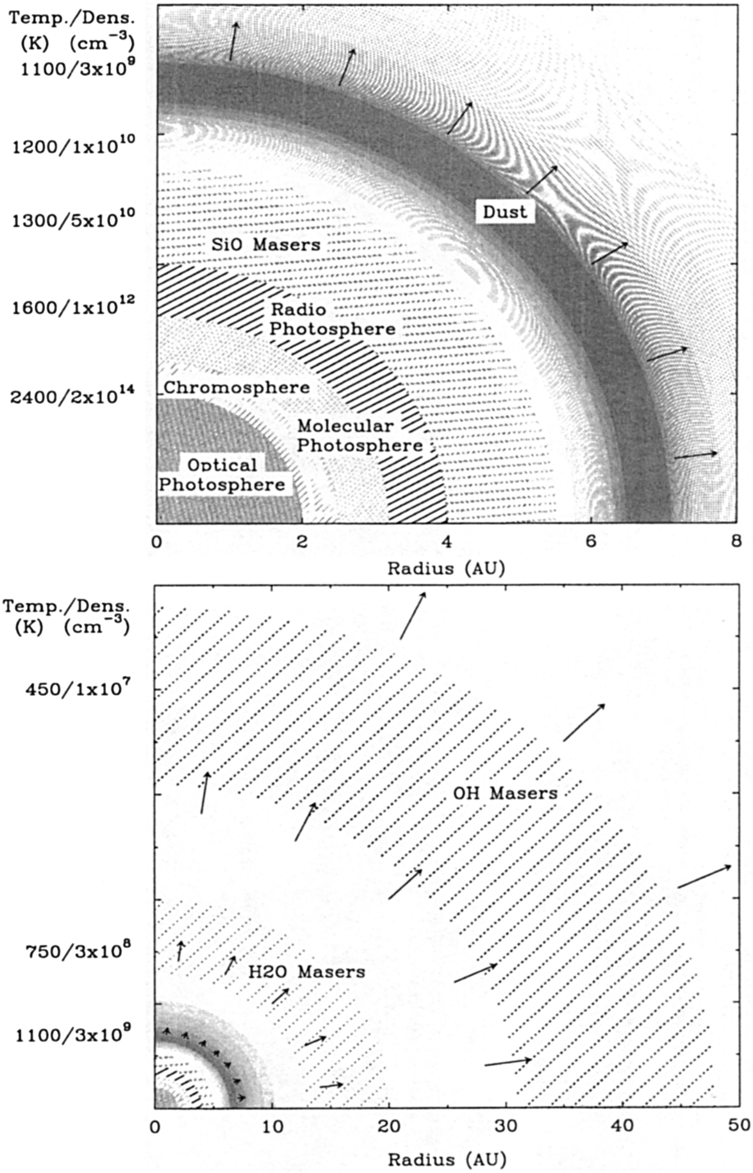
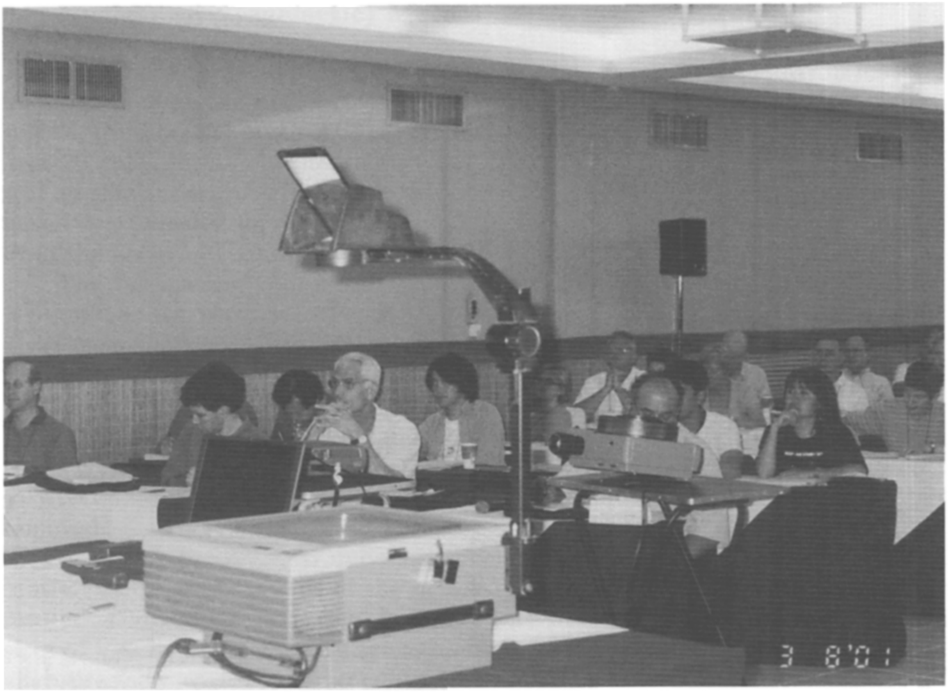
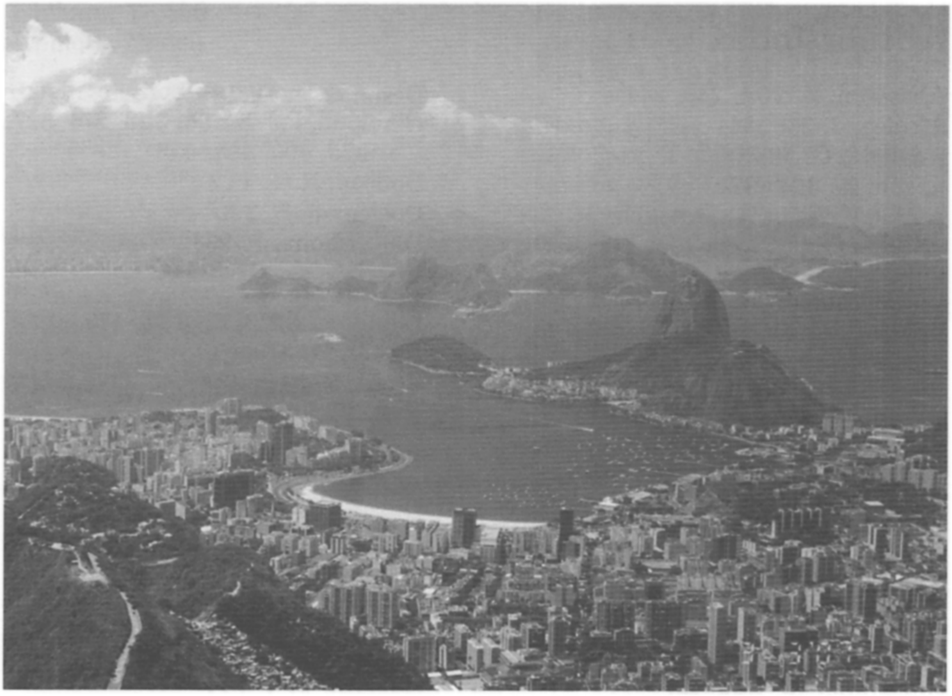


Figure 3. Schematic representation of the circumstellar envelope of a stellar maser. *Upper panel:* The inner envelope out to the dust-formation zone. *Lower panel:* The outer envelope out to the OH maser zone. The axes are in AU and characteristic temperatures and densities at certain radii are indicated on the vertical axis.



3 8'01

3 8'01




3 6 '01