Astrophysical Masers and their Environments
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IAU 242 closing summary

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Abstract. This paper focuses on highlights of the symposium and attempts to synthesize recent results in terms of key advances and unsolved problems related to maser research.

Keywords.

1. Introduction

In the six years since the second international meeting devoted to astronomical masers (held near Rio de Janeiro, Brazil), there have been many advances in observations and understanding of masers. In this summary, I will attempt to consolidate, from the roughly 130 talks and poster papers, where the field stands. As this is an opportunity to explore astrophysical problems without the constraints and formalities of refereed journals, I will attempt to be speculative and provocative. Likely some of these speculations will prove wrong, but hopefully they will stimulate new ideas for research.

Before starting, I would like to note the incredible complexity associated with maser emission. In order to understand observations fully, we must know the "chemistry," amplification process, and lifetimes of the masers. Chemical effects that control molecular maser emission include not only temperature (T) and total density (n_{tot}), but also ionization, dissociation, and sublimation of dust. Amplification in masers is very complicated and may involve details of the clumping of dense gas, the alignment of clumps, velocity and magnetic field gradients, beaming and saturation effects, and, of course pumping.

There are many examples of complicated phenomena that need to be explained. (1) While the crude nature of maser pumps (ie, whether dominated by radiative, collisional or chemical processes) is agreed upon for most molecules and classes of maser emission, we now suspect that, for example, many pumping routes are involved in the inversion of interstellar OH masers. (2) We heard that essentially all masers are variable, new data suggests that interstellar OH maser line wings can vary on timescales of 1000 seconds while the line centers are much more stable. These results are quite puzzling and seem to require disturbances propagating at the speed of light over one maser e-folding gain length. (3) The lack of many, if any, clear cases of pure π-component emission (seen as 100% linearly polarized) from interstellar OH masers is puzzling. The reason for this might involve the amplification in one cloud of a pi-component followed by further amplification in a second cloud by sigma-components (that are appropriately shifted in velocity to compensate for Zeeman splitting). (4) Any of the above mentioned complexities can be further "enhanced" by the dynamic process of cloud formation and dissipation.

As if our problems were not difficult enough, they are often compounded by the fact that astronomical images reveal only the 2-dimensional projection of the 3-dimensional structure. Also, when placing the masers in context, via complementary observations across the electromagnetic spectrum, the effects of absorption and scattering of radiation can be considerable.

2. Pumps

After decades of study, details of many maser pumps remain unknown. There is some general agreement on the broadest categorization of maser pumping: ie, are they dominated by collisional or radiative processes? For example, Class-I methanol masers are inverted predominantly by collisions, whereas Class-II methanol masers and interstellar hydroxyl masers are inverted mostly by radiative processes. Beyond these cases, it is becoming clear that population inversion can be a very complex process. Many levels and pumping routes seem to contribute to the inversions. However it is unclear to me whether the intrinsic complexity of pumping or our ignorance of atomic and molecular cross-sections is the main reason for our difficulties.

3. Millimeter and sub-millimeter wavelength masers

At this meeting we heard about large numbers of newly discovered sources of high-frequency masers. Even though (as V. Strelnitski pointed at in the Brazil meeting) it gets progressively harder to invert populations the higher energy levels involved, Nature manages somehow. There is hope that newly discovered extragalactic water masers in the sub-millimeter band may provide key data that constrain, for example, the physical conditions in AGN accretion disks.

4. Interstellar masers

4.1. *Characteristics*

The spatial distributions of interstellar masers can provide strong clues to their origins. The 2-point spatial correlation function, which is proportional to the probability of finding neighboring maser spots, is a power law for water masers. There is no clustering scale to give a physical scale length for the condensations or their amplification lengths. Rather, the structures are fractal in nature and can best be explained as owing their existence to turbulent processes. The outer scale length, where energy from e.g. strong proto-stellar outflows is deposited, seems to be ~ 0.1 pc. The inner scale for the dissipation of this energy appears to be associated with the scale of individual maser spots (~ 1 AU).

Hydroxyl masers, in contrast to water masers, do not follow a power-law spatial correlation pattern. They appear to cluster on a scale of ~ 100 AU. This probably indicates a true cloud formation size, which may find an origin in Rayleigh-Taylor instabilities between cool and dense material supported by a hot and light wind or plasma associated with a young star. More complex structures, such as lines or arcs of spots on the sky or “worms” on position-velocity diagrams have now been well documented but have yet to be explained.

The spatial correlation properties of methanol masers have yet to be fully explored. One might expect Class-II sources to display properties similar to that of interstellar hydroxyl masers, and Class-I sources to show more fractal structure similar to water masers. However, perhaps they will reveal interesting surprises.

4.2. *Variability*

The report of quasi-periodic variability of the 6.7 GHz methanol masers in G9.6 was one highlight of the Brazil maser meeting. While the evidence then was quite strong, there was only one source with well documented periodicity and some of us did not know what to make of this phenomenon. Perhaps a rare chance meeting of a star-forming region

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with an old Mira variable happened in the G9.6 case, and the IR variations of the Mira light were affecting the population inversion in a periodic manner.

We have learned in this meeting that the phenomenon is not unique to G9.6, but occurs in roughly 10% of sources surveyed. VLBA maps show that individual spots pulsate, while the overall form and distribution of the maser emission persists. The variability period among sources ranges between about 130 and 500 days, which is reminiscent of Mira variables. However, the chances of Miras wandering into so many star forming regions is vanishingly small. Perhaps embedded, pulsating, pre-main-sequence stars are responsible for the periodic maser emission. (VY CMa might be a high-mass example of such an object.) Should this speculation be correct, the variability statistics would imply that the duration of pre-main-sequence pulsations would be $\sim 10\%$ of the maser lifetime.

4.3. *Young stellar objects: disks & jets*

Maser emission is a common phenomenon in young stellar objects (YSOs). Most known interstellar masers seem to come from outflows in YSOs. Both fast and slow outflows are observed, probably related to high speed jets and the interaction (entrainment) of dense material with these jets. Water masers are the best tracer of fast outflows. Indeed motions of hundreds of km s^{-1} have been detected in many sources. These motions are usually not highly collimated and may proceed into solid angles of order a steradian. Slow outflows may be traced by many masering species, including water, CH_3OH, OH and occasionally SiO. It is unclear if fast and slow outflows reflect the same general processes, possibly differing in the amount of momentum transferred to the dense masering material from faster, lighter jets.

YSO outflows are thought to be related to disk-based accretion and may be important for solving the angular momentum problem in star formation. While evidence for outflows is abundant, clear evidence for disks is much harder to come by. The H-recombination line masers in MWC 349 appear to trace the limbs of an edge-on YSO disk. The young star Orion I (in the BN/KL region) provides what may be the best picture of a high-mass stellar accretion disk (seen in radio continuum) and its associated outflows (traced by SiO maser emission). Few other examples exist and they usually have less clear interpretations.

It is often hard to differentiate between an edge-on disk and its bipolar outflows. Indeed, this observational ambiguity is striking for the case of Orion I, where convincing claims have been made for orthogonal disk-jet orientations. Often one must rely on indirect indications of jet orientations. These include the H_2 2 μm emission, thermal SiO lines or other molecular emission associated with jets.

In addition to masers associated with (at least partially) collimated jets, some masers form in the relatively gentle expansion surrounding hyper- and ultra-compact H II regions. Interstellar OH and Class-II CH_3OH masers are the classic examples, although both species can maser in other circumstances. For example, weak OH maser action is known to accompany strong water masers in outflows.

Finally, interstellar masers are also found far from young stars in regions where shocks have propagated and probably dissipated enough energy to prepare dense material to maser. Class-I CH_3OH masers seem to fall into this category. Also, 1720 MHz OH masers are found at the interface of SNR shocks and dense molecular material.

4.4. *Magnetic fields*

Magnetic fields (B) derived from maser polarization (Zeeman) measurements are consistent with, and greatly extend, the correlation of B with total molecular density (n). Above a critical density of ≈ 10 cm^{-3}, $B \propto n^{1/2}$.

The most straight forward Zeeman results are for OH masers, where the Zeeman splitting is often larger than the line widths. This makes estimation of B fairly simple, and even gives the *full magnitude* of the B-field (as apposed to the line-of-sight component often measured in the small splitting regime). For decades OH maser B-field estimates have been ranged between 1 and 10 mG, associated with densities between 10^5 and 10^7, respectively. A natural explanation for the observed range is that for densities below 10^5 insufficient maser gain occurs, while for densities above 10^7 the populations thermalize.

Recent observations pose a challenge. Very large Zeeman splitting requiring magnetic fields of up to 40 mG have now been discovered in some OH masers. These values of magnetic field are reminiscent of the tens to hundreds of mG typical for interstellar water masers (which are thought to operate at significantly higher densities than OH masers). If physical conditions, other than density, are the same for all OH masers, this suggests total densities exceeding $\sim 10^8$ cm^{-3}. At such densities it is unclear how the OH masers could operate. It is unlikely that the $B \propto n^{1/2}$ relation breaks down at high densities, since water masers observations have extended the relation to even higher densities and magnetic fields. It is unclear what is going on in the high B-field OH masers.

One other result of Zeeman observations of interstellar OH maser remains quite robust. The magnetic field directions (toward or away from the observer) are highly ordered across entire sources (ie, ~ 0.1 pc). In nearly every source where high quality VLBI data are available, there are either 0 or 1 magnetic field reversals. When there is a reversal, one can "draw a smooth line" on the sky separating the two regions with differing B-field directions. The origin of such organized fields is unclear, but it is probably an important clue to the interaction of magnetic fields and material in massive star forming regions.

4.5. *Chronologies*

One of the most interesting, yet vexing, research goals is to establish a chronology for the formation and evolution of masers associated with star formation. Generally, we have thought that water are found in the youngest sources, followed by CH_3OH, and then OH masers. However, there is probably considerable overlap in time, and sometimes in space, for these masering species. At the Brazil maser meeting, I attempted to depict this general understanding in a figure, similar to Fig. 1.

Based on results presented at this meeting (or published since the Brazil meeting), the general chronology seems to stand the test of observations. The existence of molecular cores (eg, NH_3 cores) without masers suggests that a true protostar is needed for most strong masers (other than Class-I methanol masers).

Water masers have been found associated with mm-wavelength-only cores, which are thought to be among the youngest of star forming sources. Also, water masers may be associated with the first generation of star formation in a given region, followed by Class-II methanol masers which may appear only in the 2nd generation stars.

While OH masers, especially those associated with UCHII regions, are clearly around "old objects" (eg, main sequence OB stars), some weak OH masers have been found projected toward water-maser outflows, which are clearly quite young. The observation that water maser sources are nearly twice as numerous as OH masers, suggests that water masers are longer lived and/or are extend to lower mass stars than OH masers.

Class-I CH_3OH masers remain poorly understood. Clearly they are very young in the sense that they do not form around a YSO. However, it is unclear if there will be any significant star formation at the sites of these masers. They may simply occur at the interfaces of shocks from relatively distant forming stars and high density clumps of molecular cloud material.

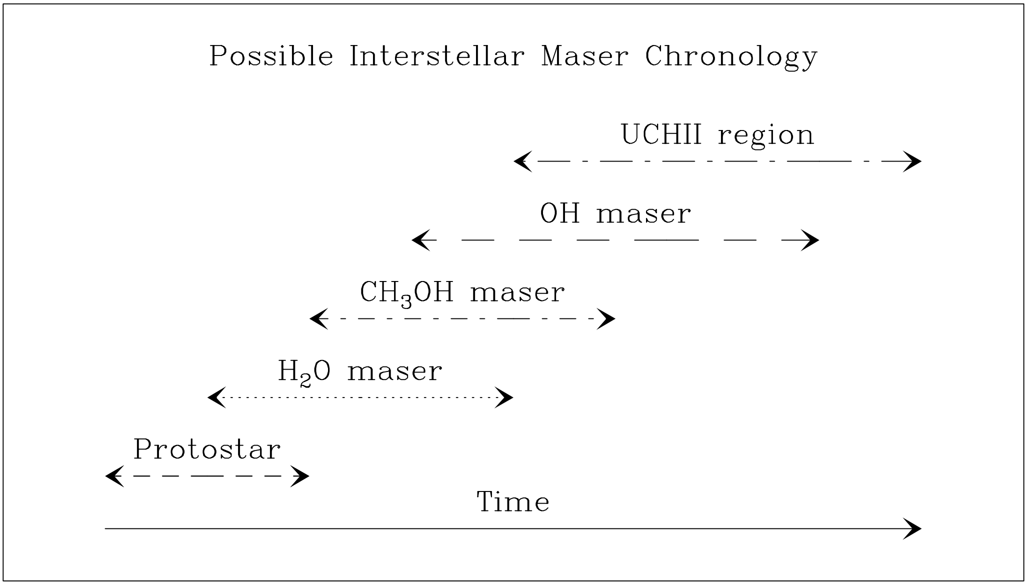

Figure 1. Possible chronology for masers associated with regions of massive star formation. Time increases toward the right. Note the considerable time overlap of various masering species and phenomena.

Finally, it is worth noting that attempting to infer age from spatial distributions, (projected) associations, and numbers is a risky enterprise. Factors other than age that may influence the observed properties are stellar mass, external ionizing sources, and shocks from nearby YSOs and even SNRs.

5. Stellar masers

5.1. *Standard model*

Evolved stars (eg, long period variables, Miras, AGB stars, red super-giants) display rich structure, and masers contribute a great deal to our understanding. A typical AGB star with circumstellar masers has a "surface" temperature below 3000 K, where the surface (at $R_* \approx 1-2AU$) is defined in line-free regions of the infrared spectrum. At this low temperature, hydrogen is predominantly atomic and free electrons (important for radio frequency opacity) come from the low ionization potential metals (eg, Na and K). Radio frequency opacity is dominated by H^- free-free interactions, which create a "radio photosphere" extending to about $2R_*$. The radio photosphere approximately matches a "molecular photosphere" seen in strong metallic oxide lines optically and in water and carbon monoxide lines in the infrared.

At about 2–3R_*($\approx$ 4 AU) in oxygen-rich stars, SiO masers form, expand outwards, and dissipate in roughly a stellar cycle ($\approx$ 1 yr). Beyond the SiO masers, dust forms copiously. Thus, SiO masers exist between a "rock (dust formation) and a hard place (strong continuum opacity)." Water masers are found at $\sim$ 15 AU and OH masers at $\sim$ 40 AU. Thus, masers trace most of the inner circumstellar envelope and provide excellent probes of physical and chemical conditions.

5.2. *Post-AGB stars*

Understanding the changes in appearance from AGB stars to post-AGB stars to planetary nebulae is one of the great challenges of modern astrophysics. The central stars show some

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Table 1. Magnetic Fields and Pressures in Stellar Masers

Maser	R (AU)	B (G)	n (cm^{-3})	T (K)	V_{exp} (km/s)	$B^2/8\pi$ ($dyne/cm^2$)	nkT ($dyne/cm^2$)	ρV_{exp}^2 ($dyne/cm^2$)
OH(1665/7)	40	0.003	10^6	300	10	$10^{-6.4}$	$10^{-7.4}$	$10^{-5.9}$
H_2O	15	0.3	10^8	500	8	$10^{-2.4}$	$10^{-5.2}$	$10^{-4.1}$
SiO	4	3	10^{10}	1300	5	$10^{-0.4}$	$10^{-2.7}$	$10^{-2.5}$
Radio Phot.	3	?	10^{12}	1500	5	?	$10^{-0.7}$	$10^{-0.5}$
Stellar Phot.	1.5	?	10^{14}	2500	15	?	$10^{+1.5}$	$10^{+2.4}$

signs of asphericity and VLA images of the radio photospheres indicate some significant elongations. The SiO and water masers appear as partially filled rings and show modest asymmetries. However, during the post-AGB phase, strong departures from sphericity are observed. These include evidence for disks (seen in SiO maser emission) and jets (seen in radio continuum and water masers). Understanding the transition from the AGB to the post-AGB is critical to understanding the beautiful and highly aspherical appearance of planetary nebulae. Clearly, masers can play a significant role in this field.

5.3. *Magnetic fields*

Magnetic fields have been estimated from maser polarization studies and these observations pose significant theoretical challenges. For Mira-like variables, OH masers indicate magnetic field strengths of a few mG at radii of $\sim$ 40 AU; however water and SiO masers show evidence of fields up to a few Gauss. Table 1 summarizes characteristic values for physical and dynamical variables as a function of radius, as well as rough estimates of the implied magnetic, thermal, and ram pressures. The factors of 100 or 1000 jump in magnetic field strength between radii of $\sim$ 40 AU (OH masers) and $\sim$ 15 AU (water masers) or $\sim$ 4 AU (SiO masers), respectively, stand out. Taken at face value, they would require the magnetic field strength to decrease as a high power of radius (eg, $B \propto R^{-4}$, between the water and OH masering radii. If the water and SiO magnetic field estimates are correct, then it appears that magnetic pressure dominates in these regions. Explaining how this happens may be both fascinating and challenging. Clearly, further observations and theoretical/computational work is required.

5.4. *Super- & hyper-giant stars*

VY CMa is one of the most luminous and interesting supergiants in the Galaxy. It is associated with a region of star formation, but there are no lithium lines in its spectrum, indicating that it is indeed a post-main-sequence star. Its luminosity has been estimated to be $\approx 5 \times 10^5$ $L_\odot$, which is near the maximum allowed for a red supergiant. However, recent trigonometric parallax measurements made with the VLBA, using its SiO masers as astrometric targets, indicate that rather than being at its commonly assumed distance of 1.5 kpc, VY CMa is $\approx 25\%$ nearer. This reduces estimates of its luminosity by about a factor of two.

There is evidence that over the past $\sim 10^3$ years VY CMa has been losing mass extremely rapidly and possibly asymmetrically. Complex asymmetric structures are seen in all maser species and in IR images, but a quasi-symmetry axis of $\approx 50°$ (E of N) appears in many images.

In the supergiant S Per, the water and OH masers appear distributed similarly, raising the question are they co-spatial or is this a projection effect. One clue is that Zeeman measurements indicate ~ 3 mG fields for OH masers and ~ 150 mG fields for water masers. This suggests that the masers are not co-spatial.

6. Galactic structure

The spiral nature of the Milky Way remains a large unknown, even after decades of research. Indeed, the most widely used models of the spiral structure of the Milky Way can be traced to the work of Georgelin & Georgelin in the 1970's. This situation may change soon. At this meeting we heard of about a dozen trigonometric parallaxes to masers in massive star forming regions measured with VLBI techniques. These parallaxes have accuracies as good as ± 10 μas. In the future the VLBA and VERA will provide ~ 100 high quality parallaxes that should serve to trace the number and the location of spiral arms in the Milky Way.

One side benefit of these parallax observations are proper motions of massive star-forming regions accurate to ~ 1 km s^{-1}. These motions will yield valuable data on the rotation curve and distribution of mass, especially dark matter, in the Milky Way. Also, the fundamental constants of the Milky Way, R_0 and Θ_0, should be directly measured with high accuracy soon.

7. AGN water masers

We now have a clear understanding that water masers populate both the sub-parsec scale accretion disks and jets associated with super-massive black holes in the centers of active galaxies. A wide variety of structures are inferred from observations, including thin and thick disks, narrow jets and wide angle winds. Water masers are proving exceptional, if not unique, probes of AGN disks, yielding images of warps, indications of spiral structures, and measurements of magnetic fields, densities and temperatures. Of course, they also supply by far the best measurements of super-massive black hole masses.

NGC 4258 remains the "Rosetta Stone" of AGN water masers. It has a remarkably thin disk (< 10 μas) which, if in hydrostatic equilibrium, suggests a temperature of 600 K. There is a clear warping. The (spatial) periodicity in the locations of the high velocity masers has been confirmed and is probably a result of spiral structures. Indeed, kinematic signatures of spiral structure might already have been detected.

Water masers in AGN can be precisely modeled and a combination of VLBA maser maps with maser accelerations measured from a time series of spectra yield a geometric distance estimate. NGC 4258 observations have yielded the most accurate, direct, distance for a galaxy; this helps anchor the extragalactic distance scale and improves the accuracy of estimates of H_0. The NRAO/CfA/MPIfR Maser Cosmology Project seeks to expand on the number and accuracy of AGN water maser distances, with a goal of measuring H_0 to $\pm 3\%$ accuracy, by directly measuring distances to galaxies in the Hubble Flow. Independent knowledge of the value of H_0 is crucial for braking cosmological parameter degeneracies, for example to establish the equation of state of dark energy. This project has already discovered and mapped the "NGC 4258-like" water masers in UGC 3789, a galaxy at about 50 Mpc distance.

8. OH megamasers

The physical picture of OH megamasers has become clear over the past years. These masers are associated with starbursts, which are the result of major mergers; they are not associated with AGN. Very dense gas ($n_H \sim 10^6$ cm^{-3}) is required to support these masers, and recent measurements of large Zeeman splitting (large B-fields) suggests even higher densities may be involved, if the relation between magnetic field and density seen in Milky Way star formation regions holds.

The model of a torus filled with clouds (each with low maser gain) that occasionally align both along the line-of-sight and in velocity, can possibly explain both high and low gain maser emission. Aligned, well-separated (along the line-of-sight) clouds can produce very highly beamed emission that is likely to be unsaturated. However, such a model does not explain why 1667 MHz masers are compact, while 1665 MHz masers are extended in Arp 220.

Other observed features of OH megamasers remain unexplained. For example, what leads to the origin of strong velocity gradients associated with arcs of maser spots in Arp 220? If gravitation in origin, the arcs enclose very large masses of $\sim 10^5$ $M_\odot$.

1720 MHz OH masers and weak formaldehyde masers have also been discovered in megamasers. Interestingly, a 183 GHz water maser has been discovered in Arp 220, even though no 22 GHz water maser is detected in this galaxy. So perhaps the 183 GHz water line can trace mergers and starbursts.

9. The future

In the next ten years we can expect many great discoveries in the field of maser research. I suspect that millimeter and sub-millimeter wavelength maser observations will be as common as centimeter wavelength observations are now. Blind surveys (of at least the Galactic Plane) should be completed for all major classes of masers. The Milky Way will be mapped with $\sim$ 100 trigonometric parallaxes and proper motions for star forming regions.

At this point it seems that masers may soon yield the best estimate of the Hubble constant: a 3% uncertainty is within reach. This result, coupled with other cosmological probes, may establish that $w = 1$, and with nothing left to solve but details, astrophysics will come to an end ;-). The constancy of fundamental constants should be further tested. But, hopefully, something quite unusual, such as the detection of hydrogen recombination-line masers from the epoch of reionization, will be discovered.

There have now been three international meetings on masers. The first was in Washington, D.C. in 1992 and the second near Rio De Janeiro in 2001. This meeting marks the third maser conference held on a third different continent: Australia. That suggests the next three maser conferences should be held in Africa, Asia, and Europe. If these meetings are held every 5 years, the 7^{th} international maser conference should be held in 2027 in the Antarctic.