Cosmic Masers - from OH to H_0
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IAU (Maser) Symposium 287 Summary

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1. Introduction

Almost exactly twenty years ago, the first of a series of conferences dedicated to cosmic masers took place in Arlington, Virginia in the USA (March 9–11, 1992). Two more followed, each on a different continent, in Mangaratiba, near Rio de Janeiro, Brasil (March 5–10, 2001) and in Alice Springs, Australia (March 12–16, 2007). As at all others, a large part of the international maser community convened from January 29 to February 3, 2012 in splendid Stellenbosch, South Africa, to discuss the state of the art of the field.

Here I'm trying to summarize the many contributions made in 70 oral presentations and by 45 posters. Adhering, roughly, to the order of themes as defined by the sessions at the meeting. I'm trying to be comprehensive, but I apologize beforehand for any undue omissions and misrepresentations.

2. Maser Theory and Supernova Remnants

Like many other a maser meeting, this one started with a theory session. An excursion to the thermodynamical basics of maser action [→ Strelnitski] was followed by a demonstration of how complex things can get by the description of class II methanol (CH_3OH) maser excitation via mid-infrared pumping, cycling through the molecule's torsionally excited levels [→ Sobolev channeled by Gray].

New ways of addressing the excitation of well known maser emission from the 1720 MHz $F = 2^+ - 1^-$ hyperfine structure (hfs) satellite line in the $^2\Pi_{3/2}, J = 3/2$ ground state of hydroxyl (OH) in supernova remnants (SNRs) were presented [→ Gray]. Closely related, a careful theoretical and multi-line observational (absorption) study of OH excitation predicts maser emission in the 6049 MHz $J = 3^- - 2^+$ hfs satellite line of the rotationally excited $J = 5/2$ state over a range of conditions thought to be prevalent in SNRs†, which was, however, not detected despite a sensitive search. The results appear in conflict with the OH column density distributions predicted for some chemical models of SNRs [→ Wardle].

1720 MHz OH masers are important tracers of the sub-mG magnetic fields of the 10^4 cm^{-3} density interstellar medium in which they are excited. Density- and also temperature-wise ($T \sim 100$ K) this post shock gas might also be expected to produce class I methanol masers *if* the elevated methanol abundance needed to produce high enough gain for observable maser emission can be attained (see §5.2). However, so far searches for 36 and 44 GHz CH_3OH maser emission toward SNRs have had little success with the Sgr A East SNR near the Galactic center being a spectacular exception. Observations of a Fermi satellite γ-ray selected sample of SNRs only produced a couple of

† Both the 1720 and the 6049 MHz line connect, in their respective rotational state, the hfs level with the highest energy and that with the lowest energy.

detections in these lines [→ Sjouwerman]. Very interestingly, vice versa, narrow spectral features in the 1720 MHz OH line have been found at the velocities of more than 50 narrow class I methanol maser features in a survey of more than a hundred sources containing such masers; these are *not* SNRs [→ Val'tts].

3. Bill Watson R. I. P.

With great sadness, the maser community has observed the passing of Bill Watson, one of its most eminent theorists. Prof. William D Watson, born January 12, 1942 in Memphis, TN, died on October 12, 2009 in Urbana, where he had been doing research and teaching since 1972 at the University of Illinois. In the early seventies, after an important contribution on the formation of molecules on dust grain surfaces, Professor Watson independently from and contemporaneously with another team established a chemistry driven by molecular ions as the basic paradigm of the gas phase chemistry of the interstellar medium. Ion-molecule chemistry explained the observed abundances of then newly detected molecules and predicted the observed strong deuterium enhancement as one of its natural consequences. After working on several other topics related to interstellar chemistry, Bill Watson went on to become a world expert on astronomical masers and, particularly, on the radiative transfer of maser radiation and its polarization properties. He completed a large number of studies on this very complex problem, significantly expanding fundamental work done in the early years of astronomical maser research. His work was always in unison with the forefront of observations. As an example, he correctly explained the origin of the high velocity features in the archetypical nuclear AGN maser NGC 4258 as originating in a ~ 0.1 pc sized ring, which was *subsequently* confirmed by Very Long Baseline Interferometry.

4. Polarization and Magnetic Fields

Models of molecular clouds in which magnetic fields are dynamically important (via ambipolar diffusion) predict that the relation between the magnetic field, B, and the density, n, is $B \propto n^{\kappa}$ with $\kappa \lesssim 0.5$. Observations (of the Zeeman effect) show that this relation holds over several orders of magnitude for $n > 100$ cm^{-3}, below which B is observed and predicted to be independent of n and has a value of ≈ 5 μG. In particular, it holds for 1720 MHz OH masers ($n \sim 10^4$ cm^{-3}, $B \sim 0.5$ mG; see §2) and for the elevated densities required for OH maser emission in high mass star forming regions (HMSFRs) ($n \sim 10^{6-7}$ cm^{-3}, $B \sim$ a few to 10 mG) and even for 22.2 GHz H_2O masers ($n \sim 10^{8-9}$ cm^{-3}, $B \sim$ tens of mG). Masers are good B-field probes since, even given the usually small splitting coefficient, i.e. the proportionality factor between the value of B and the frequency (or equivalent velocity) shift between right and left circularly polarized signal, B fields under the extreme conditions of maser regions (high n implies high B) are relatively easy to measure; the narrow line widths help. It is important to keep in mind that in many cases, whether a line is masing or not is a very sensitive function of density. For example, for many OH maser lines just a factor of two increase in density over the value at which optimal maser action occurs removes the inversion and, if a radio continuum background is present, absorption may be observed. In other words, within a certain range, Zeeman observations of all masers requiring a certain density for operation should deliver the same magnetic field strength. In particular, the values reported in the recent past for class I and class II methanol masers were orders of magnitude higher than expected, given the densities needed for their inversion (see §5.2) and fail to obey this requirement. Talks at the meeting make poorly known or unknown splitting coefficients

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responsible for this [→ Vlemmings, Sarma]. Theoretical calculations and laboratory measurements are urgently needed.

An increasing amount of Very Long Baseline Interferometry (VLBI) results map B-field configurations in the vicinity of, mostly, high mass young stellar objects (YSOs) [→ Vlemmings, Surcis, Chibueze], but now also of a solar-like, low mass YSO. The latter (VLA) observations, of H_2O maser emission in the famous IRAS 16293−2422, show that the protostellar evolution of this object appears to be magnetically dominated [→ de Oliveira Alves].

Interesting polarization results for evolved stars include the finding that a dynamically significant and ordered B- field is maintained over the whole of a circumstellar envelope [→ Amiri]. VLBI imaging of poloidal magnetic field configurations at the launching site of very high velocity water maser emission in so-called "water fountain" sources indicate a magnetic origin of the observed bipolarity. This result could have far-reaching consequences on the long-standing question whether magnetic fields play a role in the symmetry breaking mechanism that transforms a circularly symmetric envelope into an axially symmetric planetary nebula. [→ Amiri, Imai, also Claussen, Suarez].

The question which of two different models that had been proposed to interpret circular polarization of SiO masers for the applicable case of weak Zeeman splitting is the correct one can be addressed by observations of different maser transitions [→ Richter].

5. Star Formation Masers

The star formation session was dominated by presentations on methanol masers, which were the topic of a total of ten presentations in this and other sessions and ten posters. Below, I therefore dedicate some extra space on this molecule.

Other results on star forming regions include multi-epoch H_2O maser VLBI of two different deeply embedded objects in Cepheus A HW, tracing the motions of a bipolar outflow in one [→ Chibueze] and in the other revealing what had appeared to be a spherical expanding shell, but seems to be showing more complex filamentary structure and dynamics down to few AU scales [→ Torrelles].

5.1. *Spinning the Big Spin – Masers in Disks*

Masers in accretion disks have a long and chequered history. Consider, for example, one determines, via Gaussian fits, the centroid positions of two well-separated maser spots, A and B, peaking at distinctly different velocities, v_m and v_n, in the velocity channels m and n of the correlator that have been observed (e.g., with the VLA) with an angular resolution that is much coarser than the separation of the spots. Then fits to the emission in velocity channels i, with $m < i < n$, will yield centroid positions lying between the real positions of the spots that seem to move monotonously from A to B, mimicking a linear structure with a linear velocity gradient suggesting solid body rotation. This misinterpretation of data gave rise to the *Saga of the Rotating Methanol Maser Disks*†. Of course, such "disks"' are easily debunked by VLBI, which resolves the two maser spots into separate entities,

VLBI indeed delivered the exciting picture of a rotating disk structure whose material giving rise to SiO maser emission appears also to be flowing in polar direction. The whole scenario, documented by a multi-Very Long Baseline Array-epoch movie, is that of an

† It remains a mystery why none of the disk saga's proponents noticed that, in order to show solid body (and *not* Keplerian) rotation the mass of the protostar would have to be negligible compared to the mask of the disk.

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equatorially expanding "excretion" disk surrounding the peculiar radio source I in the Orion-KL region, whose inner part is photo-ionized [→ Greenhill].

Other bona fide maser emission from a disk, this time a completely photo-evaporating one, is that seen in (sub) millimeter hydrogen recombination line emission around the peculiar emission line B[e]star MWC 349 A, which excites a bipolar radio nebula. Fifteen year long monitoring of this object's polarization characteristics have yielded information on its magnetic field, while modeling its velocity distribution reveals Keplerian rotation in the disk's outer parts and more complicated kinematics in its inner parts [→ Thum, Báez rubio].

For a very long time, the MWC 349 A (sub)mm/far infrared recombination line maser/laser was one of its kind. It comes as a great relief that a second such source has now been found in Mon R2 IRS 2 [→ Jimenez-Serra].

5.2. *The Class I – Class II Methanol Maser Dichotomy*

For more than 25 years it has being realized that strong interstellar methanol masers come in two varieties: Class I methanol masers arise from outflows from high mass protostellar objects (HMPOs) often significantly removed from the driving source, whereas Class II methanol masers (cIIMMs) arise from the nearest vicinity of the HMPO; sometimes forming conspicuous rings revealed by VLBI imaging [→ Bartkiewicz presented by van Langevelde].

To build up the gain for observable maser flux, a common requirement for both maser varieties is a substantial CH_3OH abundance. For cIIMMs masers this is achieved by the heating of dust grains in the dense HMPO envelope that evaporates methanol-containing ice mantles and increases the gas phase methanol abundance by several orders of magnitudes. The warm grains, which attain an equilibrium temperature around 100–200 K emit intense mid/far infrared (IR) radiation that pumps the maser via torsional excitation†. Interestingly, the dust emission from these so-called *hot cores* is difficult or impossible to detect at near- or mid-IR wavelengths even when superior astrometry is achieved [→ de Buizer]. Submillimeter continuum emission is frequently detected, but often with too coarse resolution to establish a clear association with the masers. Here, the shortest wavelength band of the Photodetector Array Camera and Spectrometer (PACS) on Herschel at 70 μm promises to deliver crucial information [→ Pestalozzi] on the maser host sources' spectral energy distribution and luminosity.

Combining cIIMM proper motions from VLBI with interferometric observations of non-maser CH_3OH (from the torsional ground and first excited state ($\sim$ 400 K above ground) will yield, in addition to n and T, precious 3 dimensional velocity information on the closest vicinity of HMPOs [→ Torstensson, de la Fuente], allowing searches for infall, which is indicated in one object (AFGL 5142) from VLBI observations alone [→ Goddi].

In complete opposition to cIIMMs, class I methanol masers (cIMMs) work in the *absence* of a strong IR field, which means at significant offsets from HMPOs. An association of these masers with protostellar outflows has been established a long time ago and has recently been illustrated for very many sources by their coincidence with so-called extended green objects (EGOs), which are shocked regions [→ Cyganowski]‡

† Note that the Planck function, $B_\nu(T)$, for $T = 200$ K, has its maximum at 11.75 THz, corresponding to a wavelength of 25.5 μm, very close to that of the main cIIMM pumping transition identified by modelers.

‡ EGOs or "green fuzzies" are regions of enhanced emission in images made with the InfraRed Array Camera (IRAC) on the Spitzer Space Observatory using the camera's 4.5 μm filter. Imaged in the course of the Galactic Legacy Infrared Mid-Plane Survey (GLIMPSE), the emission in

Also for a very long time, it was known that the inversion of the observed maser lines follows naturally, over a range of physical conditions, from an interplay of both E- and A-type methanol's arrangement of energy levels in k-ladders and certain levels' transition probabilities (Einstein A-values). This is confirmed by statistical equilibrium/radiative transfer calculations. Whether some cIMM lines show maser action in some regions and not in others depends (for temperatures of up to a few hundreds K) on the region's density, which has to be between 10^4 and 10^5 cm^{-3}, significantly lower than required for cIIMMs. Actually, under conditions conducive for cIMM action, the strongest cIIMM lines, the 12.2 GHz $2_0 - 3_{-1}$ E and 6.7 GHz $5_1 - 6_0$ A^+ transitions, are predicted to show enhanced absorption, which is actually observed in some regions¶.

The physical conditions in the post shock gas hosting cIIMMs, n and T (for B see below), can actually be quite well constrained just by the fact which of the 25 known cIMM lines (including a new one [→ Voronkov, Walsh, Brogan]) are masing and which are not. Here extensive new surveys in the most prominent transitions, at 44 and 25 GHz, deliver an abundance of new data [→ Kurtz, Byun, Britton]. In particular, the H_2O southern Galactic Plane Survey (HOPS), which apart from the 22.2 GHz H_2O maser transition, covers several cI and cIIMM lines (plus multiple thermally excited lines from NH_3 and other species [→ Walsh]) has been most successful. Also, such surveys finally found the first long- sought after methanol masers in low mass star forming regions: Maser emission from cIMM lines was found in high CH_3OH abundance clumps of well known outflows [→ Kalenskii].

The elevated CH_3OH abundances required to produce an observable cIMM signal may also result, as for cIIMMs, from grain ice mantle desorption. However, in this case the necessary energy would be provided by a shock wave *and not* by central heating from the HMPO. A high CH_3OH abundance might even result from endothermic gas phase reactions, which require high temperatures (of order 10000 K), which may be reached in shocks. If cIMMs arise in shock fronts, why do they virtually never show high velocity emission and have velocity spreads of just a few km/s? In contrast, H_2O masers, which are unequivocally associated with shocked outflows have much larger LSR velocity spreads of many tens, even up to hundreds of km/s. The answer is likely that the cIMMs do barely have high enough methanol column densities to produce an observable signal. Therefore, the geometry of a swept up shell seen edge on, i.e. from a direction perpendicular to that of the outflow motion would produce the longest coherent gain path in the direction of the observer. The radial velocity of emission from such a configuration would *naturally* only have a small offset from the systemic velocity of the outflow source since the bulk of the outflow motion is in the plane of the sky. This scenario also implies that cIMM spots, partaking in the outflow, have large transverse motions, which for H_2O masers can be measured with VLBI. Unfortunately, cIMMs maser spots have all been found to be too large for successful VLBI. However, future proper motion measurements with the Jansky Very Large Array (JVLA) may prove the above picture directly.

In this context it is noteworthy that magnetic field strength determinations of cIMMS via the Zeeman effect will provide measurements in an ISM density regime barely covered by existing data and moreover deliver supremely important input for

this band is dominated by highly (shock-)excited lines of molecular hydrogen. The name derives from the fact that this emission was chosen to be color coded as green in false color presentations of multi-IRAC-band images.

¶ This enhanced absorption ("over-cooling") follows from the fact that for E-(A)-type methanol *all* levels in the $k = -1$ ($K = 0$) energy ladder are overpopulated relative to levels in the neighboring $k = 0$ ($K = 1$) ladder. The same gives rise to the prominent $4_{-1} - 3_0$ E and $5_{-1} - 4_0$ E ($7_0 - 6_1$ A^+ and $8_0 - 7_1$ A^+) *maser* lines near 36 and 84 GHz (44 and 95 GHz).

magnetohydrodynamic modeling of interstellar shocks. Unfortunately, as reported above (§4), the B-field values reported so far (also at this meeting) are marred by our ignorance of the Zeeman splitting factors.

5.3. *Periodic Methanol Masers*

With periods from 20 to > 500 days, 6.7 and 12.2 GHz cIIMMs periodicity, firmly established by observations with South Africa's own Hartebeesthoek Radio Observatory by our conference organizer Sharmila Goedhart in her dissertation is one of the most peculiar phenomena in all maser science [→ Goedhart]. VLBI appears to rule out a periodic infrared radiation pump, leaving a periodically varying 6–12 GHz radio continuum background as a possibility. A model for this has been worked out in the framework of a colliding wind binary scenario providing ionizing radiation [→ van den Heever, van der Walt]. *If* a variable continuum background were at the heart of cIIMM variability, this would raise the question whether *all* cIIMMs need continuum photons as seeds to operate. While the first detections of these masers found the most prominent ones associated with ultracompact HII regions, in contrast, subsequent interferometric imaging surveys actually found that most cIIMMs had no associated continuum emission at the few mJy level (at 8.4 GHz). Future, much more sensitive JVLA continuum surveys will address this question.

Finally, a comment on the chronology of masers in star forming regions, another perennial "chicken and egg" topic of maser and star formation conferences [→ Breen]. Clearly, H_2O and cIMMs are found in outflows and are thus accretion powered. CIMMs are frequently located quite far away from the outflow source (travel times of several ten thousands of years). Here we have the caveat that the transverse velocities are very uncertain and, given above arguments, may be quite a bit larger than the radial velocity spread, resulting in shorter time scales. In contrast, H_2O masers arise from within a few thousand AU (travel times a few hundred yr). The expansion time of an ultracompact HII region is thousands of yr, that of a hypercompact HII region hundreds of yr, comparable to the H_2O maser time scale. Critical questions are as follows: Before a HMPO has formed (started fusion): Can a H_2O maser outflow be driven, possibly by magnetically assisted disk-to-outflow angular momentum conversion? And, can accretion luminosity be sufficient to power a hot core and its associated cIIMMs ? Unequivocal evidence for disks and, in particular, high resolution imaging of outflow launching sites will address the first question, and evidence for the presence of radio emission at cIIMM positions the second.

6. Stellar Masers

The molecules producing circumstellar maser emission are either formed in or near the stellar photosphere (SiO, H_2O) or (OH) by photo dissociation in the other parts of the expanding circumstellar envelope surrounding mass losing evolved stars. They are observed, preferably, with interferometers [→ Richards]. Nevertheless, single dish studies give complementary interesting results, e.g., on the physical conditions in the extended atmosphere (by high excitation SiO maser line monitoring [→ Ramstedt]) or on the magnetic field via polarization measurements. For OH lines, such measurements, of over a hundred AGB and post-AGB stars, imply $B = 0.2$–2.3 mG [→ Wolak]. Monitoring the phase lag of OH maser variability between signals arriving from the blue- and red-shifted parts of the circumstellar shell, combined with angular shell size diameters from interferometry will deliver distances for ~ 20 objects [→ Engels].

IR interferometry and radio wavelength VLBI have enjoyed great synergy when IR imaging found the molecular regions just outside the photospheres of oxygen-rich Asymptotic Giant Branch stars (AGBs) (so-called MOLapheres) [→ Wittkowski] at the same distance from the stellar surface as SiO masers, which in many cases form beautiful rings, strongly indicating tangential amplification [→ Cotton, Al mutafki, Desmurs]. SiO masers, have the potential of probing the magnetic fields, via polarization measurements [→ Cotton], and also the dynamics in these interesting regions, as demonstrated by the spectacular movie made from 112 epochs of SiO maser Very Long Baseline Array (VLBA) imaging [→ Gonidakis].

7. Cosmology and the Hubble Constant: AGN and Megamasers

After a concise, but comprehensive introduction to the *Standard Model of Cosmology*, a status report on the Megamaser Cosmology Project (MCP) was given [→ Henkel]. The goal is to measure the Hubble constant, H_0, with a precision of a few percent to complement the existing cosmic microwave background radiation data in placing constraints on the nature of Dark Energy. The MCP's targets are active galaxies with 22.2 GHz H_2O maser mission originating from a < 1 pc region around the central supermassive Black Hole. Best suited are systems seen nearly edge on, such as the "Golden Source" NGC 4258 (see §3). Comparing the maser distributions' rotational speeds and radii, determined from VLBA imaging, with the measured centripetal acceleration (from spectral monitoring) directly delivers the systems' distances, D, which can be compared with the measured redshifts, yielding H_0 and also the Black Hole mass [→ Wardle]. Naturally, systems with $D >\sim 50$ Mpc are desirable, which are well partaking in the Hubble flow (and whose redshifts are not significantly influenced by local dynamics). Recently, a beautiful new example of such as system was found, UGC 3789, for which a distance of 50 Mpc was determined and an even farther system, NGC 6262 at $D = 152$ Mpc. Together, these two yield a Hubble constant of 67 ± 6 km s^{-1}Mpc^{-1}. [→ Henkel]. Another nice system is Mrk 1419 [→ Impellizzeri].

For NGC 4258 itself, we were shown what sophisticated modeling of 18 epochs of VLBI observations and 10 years of single dish monitoring can do for you: a detailed analysis of disk warping and elliptical orbits of maser clumps with differential precession [→ Humphreys] and, on top of all this, a highly precise distance.

To date, several thousand galaxies have been surveyed for H_2O megamasers, yielding just ≈ 130 detections. Obviously, increasing the sample is highly desirable as is any criterion that could help to increase the success rate. Cross-matching galaxies with H_2O megamaser detections with systems found in the Sloan Digital Sky Survey yields an increased maser detection rate for galaxies showing strong [OIII] $\lambda 5700$ emission. [→ Zaw].

Apart from nuclear disks, H_2O megamasers have been found in outflows from AGN and in the jets' interaction zones with the interstellar medium and new detections were reported. [→ Tarchi].

Interesting progress was also reported for H_2O "kilomasers", which are found in star burst galaxies. Spectacular JVLA imaging revealed such masers in several active locations in the merging Antennae system (NGC 4038/4039), likely marking the birth sites of super star clusters. In particular, its 80 times higher bandwidth (compared to the VLA) make the JVLA a tremendously efficient survey machine for extragalactic maser emission [→ Darling].

OH megamasers in the central starbursts of Ultra Luminous Infra Red Galaxies probably mark the most extreme star forming conditions in the local Universe. These masers even "contaminate" blind surveys for 21 cm emission from HI. Finding such systems

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and also formaldehyde (H_2CO) megamasers at higher redshift is highly desirable, among others in a H_2CO Deep Field [Darling, Baan], but have so far been unsuccessful (for OH at $z > 1$) [→ Willett]. Here the Five hundred meter Aperture Spherical Telescope, currently being built in south western China, holds great promise for the foreseeable future [→ J. Zhang]. FAST will have almost three times the collecting area of the Arecibo 300 m telescope, the existing OH megamaser detection machine, and a *much* larger sky coverage.

8. Maser Astrometry

Already at the previous maser conference a whole series of contributions reported high precision multi-epoch VLBI astrometry (mostly) of masers in HMSFRs, yielding accurate distances and proper motions. In the meanwhile this field has greatly expanded and about 50 parallaxes obtained with the Japanese Very Long Baseline Exploration of Radio Astronomy Array (VERA)† and the Bar and Spiral Structure Legacy survey (BeSSeL)‡ using the VLBA have established the location of Outer Galaxy spiral arms and even resulted in a revision of the Galactic rotation parameters [→ Reid, Honma, Sakai, Matsumoto]. So far, mostly 22.2 GHz H_2O masers and 12.2 GHz cIIMMs [→ Xu] have been employed. Astrometry with the much stronger 6.7 GHz cIIMMs has started with the European VLBI Network (EVN) and VERA and will soon (in mid-2012) be possible with the VLBA.

Sources discussed at our meeting include well and (up to now) not so well studied HMSFRs, for example ON 1 and 2 [→ Nagayama], W33 [→ Immer]. and the prominent W51Main/South region, for which H_2O and 6.7 GHz cIIMM astrometry allows a comparison of the sources from which emission in the different species arises, outflows (with measured expansion motions) traced by H_2O [→ Sato] and hot cores by CH_3OH [→ Etoka].

In addition, astrometry for the famous protoplanetary "rotten egg" nebula OH231.8+4.2 [→ Choi] and other post AGB stars [→ Imai] as well as the classical OH/IR hypergiant NML Cyg was reported [→ B. Zhang]. So far, SiO masers have not yet played a major role in VLBI/Galactic structure astrometry efforts. However, in the future this may change a great deal thanks to the extensive surveys for vibrationally exited ($v = 1$ and 2), $J = 1 - 0$ masers conducted with the Nobeyama 45 meter telescope that have led to the detection of well over 1000 sources [→ Deguchi]. These masers, around 43 GHz, can be observed with VERA and the VLBA.

Other surveys will find many more methanol and water masers (see §5.2). In particular, an interferometric follow-up of the 6.0/6.7 GHz Parkes/ATCA/MERLIN multi-beam survey in the 22.2 GHz H_2O line will certainly detect many new water masers associated with high mass star formation in the general vicinity of the methanol masers. However, it also has the potential of detecting H_2O masers associated with low mass YSOs have formed together with the high mass YSOs, probably in clusters. In fact, the luminosity of known such masers can be high enough to make them detectable at distances of many kpc and make them the *only* signposts for low mass star formation outside of the Solar neighborhood [→ Titmarsh].

† http:// veraserver.mtk.nao.ac.jp/outline/index-e.html
‡ http://www.mpifr-bonn.mpg.de/staff/abrunthaler/BeSSeL/index.shtml

9. Odds and Ends: New masers, Propagation/Scattering, New Facilities

Maser action from molecules other than OH, H_2O and SiO has been discovered, at centimeter wavelengths, in many lines from (mostly) non-metastable levels of ammonia (NH_3) and formaldehyde (H_2CO) NH_3 and H_2CO masers have been exclusively found in the hot cores around HMPOs, in the vicinity, but generally not coincident with cIIMMs [→ Menten, Brogan]. Interestingly, the H_2CO maser line is the 4.8 GHz $1_{10} - 1_{11}$ K-doublet transition, which is ubiquitously found almost always in absorption throughout the Galaxy (and even in others, even in the diffuse ISM. The excitation of this maser is unclear, but it strikes me as peculiar that in all of the 10 known maser sources the emission is very weak. The flux densities of most sources are around 0.1 Jy or smaller. The most luminous one known, in Sgr B2, ($\approx$ 0.5 Jy), has a luminosity that is roughly 100 times lower than that of the strongest 6.7 GHz cIIMM in that region.

Maser emission in (J,K = 3,3) inversion line of ortho NH_3† has been known for a while. In very few outflow sources [NGC 6334 I and DR21(OH)] it has been shown that this and sometimes also the (6,6) line, share properties of cIMM lines found in the same region, i.e. identical location of maser spots a and narrow single, component profile. In fact, this is the *only* known molecular line emission with a one-to-one correspondence to CIMM emission. In contrast, numerous (mostly weak) maser lines have found from non-metastable ammonia levels, even in the rare $^{15}NH_3$ isotopopologue, which is more than 200 times less abundance than $^{14}NH_3$. Non-stable levels, with $J > K$, decay rapidly down their K-ladders until they arrive at the lowest levels (with $J = K$). These are metastable and form a thermal distribution, which is the reason for ammonia's fame as a molecular cloud thermometer. Given the high transition probabilities of the FIR rotational lines connecting them, the non-metastable levels' populations are strongly influenced by the mid IR continuum, which, first, gives rise to maser action in certain lines and, second, places, as for cIIMMs, the maser's emission regions close to HMPOs.

In the (sub)millimeter range, HCN maser lines from within several vibrationally excited states have been found (plus the $J = 1-0$ line from the ground state). To these we may add H_2O masers in the vibrational ground state and the excited bending mode. The emission region of these vibrationally excited lines is pretty clear: The exceedingly high energies above the ground state (up to more than 4000 K) locates the origin of their emission very close to the stellar photospheres of mass losing stars with carbon-rich (HCN) and oxygen-rich (H_2O) chemistry, respectively.

Until a very short time ago, the only means to get information about the astrophysically very important water molecule was observing *maser* emission in lines emitted from high energies above the ground, which are are not sufficiently excited in the Earth's atmosphere to make it complelely opaque at and around their frequencies. Earlier space missions either observed, with modest angular resolution, only the H_2O $1_{10} - 1_{01}$ ground-state line near 557 GHz (SWAS and ODIN) or far- and mid- IR lines also with limited spectral resolution (ISO). This situation has changed with Herschel, which produces a wealth of H_2O data between 500 and 1400 GHz with excellent sensitivity and spectral resolution. However, one should keep in mind that interferometic observations of the maser lines accessible from the ground are the *only* means to get information on this molecule with an angular resolution better than 10″ [→ Menten].

† Ortho-NH_3 assumes states, J, K, with $K = 0$ or $3n$, where n is an integer (all H spins parallel), whereas $K \neq 3$ for para-NH_3 (not all H spins parallel). The principal quantum numbers J and K correspond to the total angular momentum and its projection on the symmetry axis of the pyramidal molecule.

Exploring the nature of all these masers will greatly benefit from the comprehensive or greatly expanded frequency coverage and much larger number of spectral channels available with the JVLA and the Atacama Large Millimeter Array (ALMA) [→ Wootten, Brogan], e-MERLIN and ATCA, with MeerKAT playing a role as well [→ Booth].

Observations of short time scale maser variability caused in part by (even anisotropic) interstellar scattering may provide information on the intervening interstellar medium, but also on the intrinsic line of sight dimensions of individual maser spots [→ Laskar, Deshpande, Mccallum].

10. Famous Last Words

Our field is like the (unsaturated) maser process – it stimulates itself and grows very rapidly! A few remarks:

• Big surveys are going on, but results need to be digested! Maser surveys need to be cross correlated with radio, IR and dust continuum surveys. In order to be useful, e.g., for planning VLBI observations, positions determined need to be listed with realistic uncertainty estimates.

• Think big! Compared to their predecessors, the new and upgraded facilities, JVLA, ALMA, e-MERLIN, and ATCA, offer awesome advances in *much* wider band correlator capability. Therefore, when planning your observation, make sure to use all the capabilities at your disposal. For, example, observe not just "your" target maser line, but cover as much bandwidth as possible, e.g., to get good continuum sensitivity or to cover other interesting lines. This is called "commensal" (= symbiotic) observing and hopefully will be a policy adopted and encouraged by observatories. Disk space is cheap and gets ever cheaper!

• Much more astrometry is needed! VERA and VLBA/BeSSeL run at full tilt! The EVN can also do astrometry. What about the Japanese VLBI and the East Asian VLBI Networks? We need VLBA-like capability in the southern hemisphere!

• If possible, all maser VLBI observations should use phase referencing, even if astrometry is not the goal. The resulting *absolute* position information is indispensable for comparative studies.

• It is worth to emphasize projects that have an impact on *all* of astronomy and even beyond, namely those that address Galactic structure, Local Group dynamics, precision H_0, protostellar collapse, magnetic fields: cIMMs could probe MHD shocks; the launching of protostellar outflows/shaping of planetary nebulae and other phenomena.

Finally, as a veteran of all the meetings in the series, I thank the organizers of this one very much for a perfect conference and the most pleasant time I had attending it.

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