

Part V. Extragalactic Nuclear MASERs

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Extragalactic H₂O masers

Lincoln J. Greenhill

Harvard-Smithsonian Center for Astrophysics,
60 Garden St., M.S. 42,
Cambridge, MA 02138 USA

Abstract. Study of extragalactic H₂O masers has progressed significantly in the 25 years since their discovery. Existing in star forming regions and in the accretion disks supermassive black holes, they are familiar and unfamiliar at the same time. A review of how our understanding has grown, up to the present day, is followed by comments on future prospects.

1. Historical Perspective

Galactic water maser emission in regions of star formation had been known for about a decade (Cheung et al. 1969) when Churchwell et al. (1977) discovered the first extragalactic source, in M 33 (Table 1). Several unsuccessful surveys of nearby galaxies had been conducted before the Churchwell et al. work (Dickinson & Chaisson 1971; Sullivan 1973; Andrew et al. 1975), concentrating on nuclei and fields around H II regions in the stellar disks. Ultimately, the location and origin of the maser in M 33 was not surprising, as it lay in IC 133, a prominent star forming region in the outer stellar disk.

The discovery of the first maser source in a galactic nucleus led to speculation that it was a beacon of particularly intense star formation (Table 2), of the type observed toward starbursts (Dos Santos & Lépine 1979; see also Moorwood & Glass 1983). This first “nuclear maser” lay in NGC 4945 (Table 1), which is one of the most luminous nearby far-infrared (FIR) galaxies, and which hosts a massive circumnuclear star-forming ring or disk of gas on 100 kpc scales (Moorwood et al. 1996). Because star formation rate is correlated with FIR emission, the subsequent discovery of more masers in FIR-bright galaxies was apparently easy to understand.

Interferometric observations of the structure of nuclear masers demonstrated that they have more compact structure than was expected for emission tied to distributed star formation in a starburst. Claussen & Lo (1986) used the VLA to demonstrate that the masers in NGC 1068 and NGC 4258 were compact on scales of less than several parsecs. Although nuclear starbursts can also be compact, the observed compactness was in fact the first clue pointing to a truly extraordinary phenomenon. In light of the Antonucci & Miller (1985) model for AGN structure, Claussen & Lo conjectured that the emission was tied to an interaction between nuclear outflow and gas in circumnuclear tori.

Table 1. Historical Perspective

Date ^(a)	Event	Reference
11/76	First extragalactic H ₂ O maser, in M 33	1
09/77	First nuclear maser, in NGC 4945 ^(b)	2
11/82	OVRO survey of late-type galaxies	3
09/83	First VLA & VLBI detections of compact structure	4
10/84		5
01/92	High-velocity lines discovered, in NGC 4258	6
	First wide bandwidth survey of 11 AGN	7
03/93	Narrow bandwidth surveys of 100s of AGN	8, 9
04/94	Discovery that NGC 4258 masers trace sub-pc accretion disk	10, 11
04/95	Detection of 6000L _⊙ (isotropic) maser at ~ 100 Mpc	12
08/95	First associations of masers with radio jets	13
11/95		14
06/97	Discovery of masers in an AGN wind	15
Today	Continuation of wide bandwidth surveys of AGN	9,16

^(a) Date of related observations (in *mm/yy* format) in all but one case. The report of weak jet-related maser emission in NGC 1068 by Gallimore et al. (1996) relied upon archival data obtained with the VLA by M. Claussen in 1983 and 1987. The paper was submitted in 1995 August. Data supporting the report of more intense emission excited by the jet in the radio galaxy NGC 1052 was obtained with the VLBA in 1995, again by M. Claussen.

^(b) Lépine & Dos Santos (1977) report an earlier detection of 5 ± 1 Jy emission toward the nucleus of NGC 253 at an LSR velocity of 253 km s^{-1} . However, later observations by Batchelor, Jauncey, & Whiteoak (1982), Nakai & Kasuga (1988), and Ho et al. (1987) only found emission on the order of tenths of Jy and no emission within 100 km s^{-1} of the velocity reported by Lépine & Dos Santos.

Citations: (1) Churchwell et al. (1977); (2) Dos Santos & Lépine (1979); (3) Claussen, Heiligman, & Lo (1984); (4) Claussen & Lo (1986); (5) Claussen et al. (1988); (6) Nakai, Inoue, & Miyoshi (1993); (7) Nakai et al. (1995); (8) Braatz et al. (1996); (9) Greenhill et al. (2002); (10) Greenhill et al. (1994); (11) Miyoshi et al (1995); (12) Koekemoer et al. (1995); (13) Gallimore et al. (1996), (14) Claussen et al. (1998); (15) Greenhill et al. (2000); (16) Braatz et al., Henkel et al., Nakai et al., and others, unpublished.

The years 1986 to 1992 marked a drought during which no H₂O masers were discovered in new galaxies (though a second weak maser was found in the nearby dwarf irregular galaxy IC 10 (Becker et al. 1993)). Up to this time, searches had emphasized FIR-bright and nearby star-forming galaxies, and nine of the eleven then known extragalactic H₂O masers were associated with the 83 known IRAS galaxies with $100\mu\text{m}$ flux density > 50 Jy. However, this selection criteria was misdirected. In retrospect, discovery of these nine masers may have depended more on proximity than on a (hoped for) direct physical relationship between maser emission (which we now know often arises in parsec scale structures) and IRAS far-infrared emission (which also originates on scales that are orders of magnitude larger). Among the larger number of H₂O masers known today, there is no apparent correlation. Galaxies with similar IRAS $100\mu\text{m}$ flux densities can have peak maser flux densities that differ by over an order of magnitude, and *visa versa*.

Table 2. Origin of Extragalactic H₂O Masers: Evolution of Thought

Year	Impetus	Realization	Reference
1976	Masers in disk of M 33	Association with SF	1
1977	Masers in a SF nucleus	High apparent luminosities	2
1983	Compact ($\lesssim 10$ pc) structure	Axially thick, circumnuclear disks. Probably not SF related	3 ...
1992+	Surveys	Certain association with AGN	4
1994	Structure of NGC 4258 maser	Origin in thin accretion disks	5, 6
1995	Locations of masers in NGC 1068 and NGC 1052	Origin in jet-excited material	7, 8
1997	Distribution of masers in Circinus	Origin in nuclear winds	9

Citations: (1) Churchwell et al. (1977); (2) Dos Santos & Lépine (1979); (3) Claussen & Lo (1986); (4) Braatz et al. (1996); (5) Greenhill et al. (1994, 1995b); (6) Miyoshi et al (1995); (7) Gallimore et al. (1996); (8) Claussen et al. (1998); (9) Greenhill et al. 2000a.

In the early 1990s there were two watershed discoveries in the study of extragalactic H₂O masers and perhaps AGN.

First, Braatz et al. (1996) discovered 11 new H₂O masers by targeting AGN, achieving sensitivities (3σ) on the order of 0.1 Jy, for galaxies mostly closer than 100 Mpc. This survey established a strong link between H₂O maser emission and AGN, specifically Seyfert 2 objects and Low Ionization Nuclear Emission Regions (LINERs). Though other surveys also concentrated on AGN (e.g., Nakai et al. 1995; Greenhill et al. 1995; Greenhill et al. 2002), they did not enjoy as large a sample of nearby galaxies and as uniformly high sensitivity.

Second, Nakai, Inoue, & Miyoshi (1993) made the serendipitous discovery of high-velocity maser lines symmetrically bracketing the already known emission near the galactic systemic velocity in NGC 4258. Their interpretation included three possible models: Raman scattering, outflow, or rotation, the latter being of particular interest given the earlier work of Claussen & Lo (1986). Very Long Baseline interferometric (VLBI) observation of the then known maser emission near the systemic velocity had been conducted in 1984 (Claussen et al. 1988), and the preliminary reduction revealed little specific structure. However, reanalysis of the data, interpreted in the context of the newly discovered high-velocity lines (Greenhill et al. 1994, 1995b) demonstrated that the emission probably arose in a sub-parsec diameter disk bound by a very massive and compact object.

Support for the disk model arrived from the *independent* measurement of the line-of-sight (centripetal) acceleration of the maser-emitting gas close to the systemic velocity. Observation of a drift in the line-of-sight velocity of one spectral feature by $\sim 10 \text{ km s}^{-1} \text{ yr}^{-1}$ (Haschick & Baan 1990) was not widely accepted because in general the NGC 4258 spectrum is a blend of many time variable features, and specifically, it was not possible to prove that a single feature had been tracked. However, analysis of archival data (1984-1986) obtained at Effelsberg (Greenhill et al. 1995a) and further observations by Haschick, Baan, & Peng (1994) demonstrated that on the order of 10 features distributed throughout the spectrum drifted in velocity at about the same rate, which solidified the interpretation of detectable acceleration. The magnitude of the drift matched

the predicted centripetal acceleration given the inferred disk rotation speed and radius, for an assumed distance of ~ 7 Mpc (Greenhill et al. 1994; Watson & Wallin 1994).

Observation of the NGC 4258 H₂O maser in mid-1994 with the then newly commissioned Very Long Baseline Array (VLBA), provided conclusive evidence in support of the disk model (Miyoshi et al. 1995). The VLBA observed both the systemic and high-velocity emission simultaneously with high angular resolution for the first time. The resulting model parameters were quite surprising: the disk obeyed a Keplerian rotation curve with deviations of $< 1\%$; the molecular gas lay as close as 0.14 pc from a $3.9 \times 10^7 M_{\odot}$ central object; the disk was thin, with a ratio of height to radius of $\ll 1\%$; and the disk was misaligned and counter-rotating with respect to the galactic disk. (N.B. Parameter values reflect updates by Herrnstein et al. (1999) following the measurement of a precision geometric distance to NGC 4258, based on maser proper motions and accelerations. The distance, 7.2 ± 0.5 Mpc, is the most precise yet measured for galaxy that is independent of the calibration of any Standard Candle.)

NGC 4258 defined a paradigm for the interpretation of spectra and VLBI images for other extragalactic H₂O maser, especially sources with high-velocity emission (e.g., NGC 1068). However, that paradigm has not been appropriate in all cases. First, the masers in NGC 1052 (Claussen et al. 1998) and Mrk 348 (Peck et al. 2001) exhibited distinctive, singular, broad emission features ($50\text{--}100 \text{ km s}^{-1}$), which are unlike the complexes of narrow lines associated with masers in accretion disks. VLBI observations have demonstrated conclusively that these maser source lie offset from their respective central engines entirely, and in close association with radio jets. In addition, VLA observations of the NGC 1068 maser have detected a site of H₂O maser emission in the vicinity of a jet-cloud collision ~ 20 pc from the central engine (Gallimore et al. 1996). These sources may be stimulated directly by jet-activity, perhaps as a result of entrainment or shock heating of ambient material. Two other sources may be similar, IRAS F22265-1826 (Greenhill et al., in prep) and IRAS F01063-8034 (Greenhill et al. 2002), for which VLBI data is inconclusive or not yet available. Second, the maser source in the Circinus galaxy exhibits two loci of maser emission, only one of which corresponds to an accretion disk. The second locus appears to trace directly structure in a wide-angle wind that originates $\lesssim 0.1$ pc from the central engine. The boundaries of the wind are set by the (warped) accretion disk and correspond to the boundaries of the ionization cone that has been detected on scales > 100 pc (Veilleux & Bland-Hawthorn 1997). When nuclear maser emission was first recognized to lie in accretion disks and in close proximity to super massive black holes, it was a surprise. The association of maser emission with jets and with the innermost reaches of an outflowing nuclear wind are surprises nearly as significant.

2. Today

Over 1000 galaxies have been studied in the hope of detecting H₂O maser emission. Table 3 lists seven galaxies for which H₂O maser emission is believed to be excited by star formation processes in a total of 19 regions. Except for sources in the Magellanic Clouds and one source in IC 10, which has been observed to

reach 120 Jy (Baan & Haschick 1994), the known masers in extragalactic star forming regions are weak and hence, challenging to study. VLBI images of the strongest two source in the northern hemisphere, IC 10SE and IC 133, have been published. The distribution of masers in IC 10SE (Argon et al. 1994) subtends ~ 0.1 pc. Emission in the IC 133 region comprises two regions that each subtend ~ 0.1 pc and are separated by ~ 0.3 pc (Greenhill et al. 1993). All three centers of maser activity are coincident with thermal radio continuum sources that are probably compact HII regions. Proper motions on the order of 1 to 10 $\mu\text{as yr}^{-1}$ have been measured for the IC 133 H₂O masers, using two epochs of data (Greenhill et al. 1993). The motions are suggestive of a poorly collimated bipolar outflow, as are observed in galactic high mass star formation. Unfortunately, no published studies exist of the structure and evolution of H₂O masers seen toward starbursts (i.e. M 82 and NGC 253), wherein star formation takes place in a rather more exotic environment.

Table 3. Extragalactic H₂O Masers Associated with Star Formation

Galaxy	Distance (Mpc)	$F_{\nu}^{(a)}$ (Jy)	No.	Ref.
LMC	0.05	3-20	6	1, 2, 3, 4
SMC	0.05	4-7	2	...
M 33	0.7	1	5	5, 6, 7
IC 10	1.3	0.2-120	2	8, 9
NGC 253	2.5	0.1	1	10, 11?
M 82	3.3	0.2	1	12
IC 342	3.9	0.2-0.4	2	13
M 101	2.5	marginal	1	7
NGC 2403	3.2	marginal	1	7
NGC 2366	3.2	marginal	2	7
NGC 672	8	marginal	2	7

^(a) Characteristic peak flux density or that at time of discovery.

Citations: (1) Scalise & Braz (1981); (2) Scalise & Braz (1982); (3) Whiteoak et al. (1983); (4) Whiteoak & Gardner (1986); (5) Churchwell et al. (1977); (6) Huchtmeier et al. (1978); (7) Huchtmeier et al. (1988); (8) Henkel, Wouterloot, & Bally (1986); (9) Becker et al. (1993); (10) Ho et al. (1987); (11) Lépine & Dos Santos (1977); (12) Claussen et al. (1984); (13) Huchtmeier et al. (1978).

Water maser emission has been detected and confirmed in 22 AGN (Table 4). Surveys have achieved a 5-10% detection rate for samples of nearby Seyfert 2 galaxies and LINERs (e.g., Braatz et al. 1996) that declines with distance, probably because of limited instrument sensitivity. At present IRAS F22265-1826 and NGC 6240 contain the most distant known masers, at ~ 100 Mpc. A survey of more distant Fanaroff-Riley type 1 radio galaxies (Henkel et al. 1998) and radio-bright quasars that are part of the VLBA calibrator survey

(Herrnstein, Beasley, & Greenhill, unpublished) have not detected any maser emission. (See also Matsakis et al. 1982.)

The classification of masers depends on spectroscopic signatures and where available, on structural signatures (i.e., angular distributions of emission mapped with VLBI). For purposes of taxonomy, H₂O maser sources may be grouped into four classes: disk origin, jet origin, peculiar, and unknown.

Of the known maser sources, three exhibit the spectroscopic and angular (i.e., VLBI) signatures of accretion disks: NGC 4258 (Miyoshi et al. 1995), NGC 1068 (Greenhill & Gwinn 1997), and Circinus (Greenhill et al. 2000a). Two other sources, for which imaging is incomplete or absent, exhibit (only) the spectroscopic signatures of disks with rotation speeds on the order of a few hundred km s⁻¹: NGC 5793 (Hagiwara et al. 1997), and one as yet unpublished (Braatz, private communication). One source, NGC 2639, though without detectable high-velocity emission has displayed a drift in Doppler velocity that is reminiscent of the centripetal acceleration among masers in NGC 4258 (Wilson et al. 1996).

The process by which maser emission is stimulated by jet activity in AGN is not understood, in particular the reason for the observed unusually broad line profiles. Four sources display these line profiles: NGC 1052 (Braatz et al. 1996), Mrk 348 (Falcke et al. 2000a), IRAS F22265-1826 (Koekemoer et al. 1995), and IRAS 01063-8034 (Greenhill et al. 2002). As previously mentioned, the first two sources demonstrate certain association with jets (i.e. the maser emission is offset from the presumed position of the respective central engines, and it lies along the line of sight to the jet). The second two sources are classified (here) as jet-induced because of circumstantial evidence. They exhibit broad line profiles but little more evidence is available. VLBI imaging of IRAS F22265-1826 (Greenhill et al., unpublished) has not detected radio emission from the known optical jet in that source (Falcke et al. 2000b), and IRAS F01063-8034 has been too weak to observe with VLBI, though the centroid velocity of the emission has been observed to change abruptly, a behavior otherwise unique to the NGC 1052 maser.

The class of peculiar masers includes three prominent sources that have suggestive spectroscopic characteristics (e.g., emission close to the systemic velocity but perhaps only one-sided high-velocity emission): NGC 3079 (Trotter et al. 1998; Sawada-Satoh et al. 2000), NGC 4945 (Greenhill et al., unpublished, and NGC 1386 (Braatz et al. unpublished). Though these sources have highly elongated angular distributions of masers, the distributions are broadened and display complex velocity structure. It is possible that the accretion disks of these galaxies are intrinsically thicker due to properties of the AGN. Alternatively, masers may occupy clumpy, fragmented material that lies beyond the outer edges of thin (“maser-dark”) accretion disks.

The remaining 11 nuclear maser sources not discussed so far fall in the “unknown” category. Most of these sources have nondescript spectra (e.g., a single line offset from the systemic velocity of the host galaxy), and many are too weak to be targets for VLBI imaging, excepting all but the most heroic efforts. However, because masers are time-variable, monitoring of known sources is important because line intensities can increase on time scales of weeks to

months, and new spectral features can appear that would make possible ready classification.

Table 4. Established Cases of H₂O Masers in AGN^(a)

Galaxy	Distance ^(b) (Mpc)	F _ν ^(c) (Jy)	Galaxy	Distance ^(b) (Mpc)	F _ν ^(c) (Jy)
NGC 4945	3.7	4	IC 2560	38	0.4
Circinus	4	4	NGC 2639	44	0.1
NGC 4258	7.3	4	NGC 5793	50	0.4
M 51	9.6	0.2	ESO 103-G35	53	0.7
NGC 3079	16	6	Mrk 1210	54	0.2
NGC 1068	16	0.6	ESO 013-G12	57	0.2
NGC 1386	12	0.9	Mrk 348	63	0.04
NGC 1052	20	0.3	Mrk 1	65	0.1
NGC 5506	24	0.6	IC 1481	83	0.4
NGC 5347	32	0.1	NGC 6240	98	0.03
NGC 3735	36	0.2	IRAS F22265-1826	100	0.3

^(a)Sources of maser emission whose confirmation by more than one observations has been reported in the literature. Marginal detections for NGC 3227 (Huchtmeier et al. 1988) and NGC 6946 (Claussen et al. 1984) remain unconfirmed.

^(b)Distances estimated directly from optical heliocentric velocity, assuming $H_0 = 75 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

^(c)Characteristic peak flux density or flux density at time of discovery.

References – NGC 4945: Dos Santos & Lépine (1979) – Circinus galaxy: Gardner & Whiteoak (1982) – NGC 1068, NGC 4258: Claussen et al. (1984) – NGC 6240: Claussen et al. (1984), Haigwara, Diamond, & Miyoshi (2001) – NGC 3079: Henkel et al. (1984), Haschick & Baan (1985) – Mrk 1, Mrk 1210, NGC 1052, NGC 1386, NGC 2639, NGC 5506, NGC 5347, NGC 5793, ESO 103-G 35, IC 1481, IC 2560: Braatz et al. 1996 – IRAS F22265-1826: Koekemoer et al. 1995 – M 51: Ho et al. (1987) – NGC 3735: Greenhill et al. 1997 – Mrk 348: Falcke et al. 2000a – IRAS F01063-8034: Greenhill et al. 2002.

3. Tomorrow

Extragalactic water maser emission, especially when studied with VLBI techniques, allows the radio astronomer to establish windows into regions around high-mass protostars and AGN central engines that are otherwise (1) obscured by considerable visual and infrared extinction and (2) too small to resolve without overwhelmingly large infrared apertures. Relatively few extragalactic H₂O masers are known today. However, those masers that are known make possible exquisitely detailed studies of specific cases, against which theories may be tested and generalizations constructed.

Extragalactic H₂O masers that are excited by star formation are understudied with respect to their counterparts in AGN, but they are no less valuable as astronomical probes. For example, differential astrometric measurement of maser positions permit the direct observation of galactic rotation in spiral galaxies, the estimation of peculiar motions, and the deduction of precision geometric

distances. With ground-based instruments, these measurements are feasible for targets in the Local Group, such as M33. However, the most immediately important target may be the LMC, for which uncertainty in distance is a dominant source of systematic error in the extragalactic distance scale, as now calibrated by observations of Cepheid variable stars (Freedman et al. 2001).

The scientifically profitable case of NGC 4258 remains the best motivation for continued study of extragalactic H₂O masers in AGN. Among known sources, the uniqueness of the rapidly rotating (and therefore) thin, quiescent accretion disk in NGC 4258 begs the question, are other similar sources detectable? A great many probably exist though detection depends on many factors, among which are (1) the anisotropic beaming of maser radiation (e.g., the NGC 4258 maser is only visible to < 10% of the Universe), (2) warps in accretion disks, (3) chance alignments among (amplifying) maser regions and background non-thermal continuum sources, and (4) the range of luminosities among masers. Nonetheless, pursuit of high-sensitivity, broadband surveys is necessary to answer the question. One NGC 4258-type maser out of more than > 1000 candidates searched is strongly suggestive of an answer. However, many past surveys relied upon spectrometers with bandwidths corresponding to < 800 km s⁻¹ (at a rest frequency of 22.2 GHz) and concentrated on emission close to the systemic velocity of each AGN observed. Of all masers with known high-velocity emission, only *one* displays its strongest emission close to the systemic velocity of the host galaxy (due to chance alignment with a background source). Hence, though successful, much past survey work may have been systematically biased against discovery of the type of source that is of the greatest interest. Recent surveys have begun to address this issue through the use of new instrumentation (see Braatz, this volume).

Study of extragalactic H₂O masers has progressed significantly in the 25 years since their discovery. They are familiar and unfamiliar at the same time, existing in (common) star forming regions and in the (exotic) accretion disks of supermassive black holes. VLBI observations, using intercontinental baselines, are critical to the use of these masers as probes of other galaxies and the local Universe. The VLBA and affiliated antennas is the bedrock of maser studies. The Australian Telescope Long Baseline Array has been a capable counterpart for southern sources however, development of a follow-on, VLBA-style, intercontinental array in the southern hemisphere would be critical to many studies, including measurement of the LMC distance. Such an array could form a precursor to the Square Kilometer Array, which is unlikely to be built until at least the middle of the next decade. A next-generation space VLBI mission would, equipped with a broad-band λ 1.3 cm receiver package and the necessary instrumentation to make possible precision spectral-line calibration, would perhaps be even more important than a southern VLBA, because it would permit extended study of many sources that have already been well observed and the further testing of astronomical theory.

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