Cosmic Masers - from OH to H_0
Proceedings IAU Symposium No. 287, 2012
R.S. Booth, E.M.L. Humphreys & W.H.T. Vlemmings, eds.

doi:10.1017/S1743921312006990

Maser emission during post-AGB evolution

J.-F. Desmurs

Observatorio Astronómico Nacional, Madrid, Spain
email: desmurs@oan.es

Abstract. This contribution reviews recent observational results concerning astronomical masers toward post-AGB objects with a special attention to water fountain sources and the prototypical source OH 231.8+4.2. These sources represent a short transition phase in the evolution between circumstellar envelopes around asymptotic giant branch stars and planetary nebulae. The main masing species are considered and key results are summarized.

Keywords. Maser, stars: AGB and Post AGB

1. Introduction

After leaving the main sequence, stars of low and intermediate mass travel across the Hertzsprung-Russell diagram and reach the asymptotic giant branch (AGB). During this phase, the star ejects matter at a very high rate (up to 10^{-4} solar masses per year) in form of a slow (5 to 30 km s^{-1}), dense, isotropic wind. The resulting circumstellar envelope often exhibits maser emission from several molecules, the most common being SiO, H_2O and OH. These masers arise at different distances from the star from different layers in the envelope, tracing different physical and chemical conditions. SiO masers are found close to the star (at few stellar radii), the water maser a little farther out (up to a few hundreds of stellar radii) and the OH masers even farther out, the (at up to a few thousands of stellar radii) see Habing (1996). As the star follows its evolution to the planetary nebulae (PN) phase, mass-loss stops and the envelope begins to become ionized, such that the masers emission disappear progressively. The SiO masers are supposed to disappear first, the H_2O masers may survive a few hundreds of years and OH masers remain for a period of ~1000 years and can even be found in the PN phase.

The evolution of the envelopes around AGB stars toward PNe, through the phase of Proto Planetary Nebulae (pPNe) is yet poorly know, in particular the shaping of PNe. While during the AGB phase the star exhibits roughly spherical symmetry, about 10000 years later, PNe are often asymmetrical (about 75% see Manchado *et al.* 2000), showing axial symmetry, including multi-polar or elliptical symmetry, and very collimated and fast jets. Bipolarity appears very early in the post-AGB or pPN stage evolution.

Sahai & Trauger (1998) surveyed young PNe with the Hubble Space Telescope and found that most of them were characterized by multi polar morphology with collimated radial structures, and bright equatorial structures indicating the presence of jets and disks/tori in some objects. They propose that during the late AGB or early PPN stages the high-speed collimated outflows carve out an imprint in the spherical AGB wind, which provides the morphological signature for the development of asymmetric PNe.

The mechanism explaining how axial symmetry appears during this evolutionary phase is still an open question. Several models have been proposed, that in general involve the interaction of very fast and collimated flows, ejected by means of magneto-centrifugal launching, with the AGB fossil shell. Interferometric observations of maser emission in such sources allow us to get access to the formation and evolution of these jets and with a very high spatial resolution.

This review will report mainly on recent results published since the previous IAU 242 maser symposium, held in Alice Springs in 2007.

2. Surveys

During the last years, several surveys have been conducted to discover new maser emission toward post-AGB objects. Deacon *et al.* (2007), searched for water masers (at 22 GHz) and SiO masers (at 86 GHz) using respectively the telescopes of Tibdinbilla-70m and Mopra-22m. They observed a list of 85 sources in total (11 of them in SiO), selected on the basis of their OH 1612 MHz spectra, and get 21 detections (3 in SiO), out of which 5 sources present high velocity profiles and one source show a wide double peak profile of the SiO maser. Suárez *et al.* (2007, 2009), searched for water maser in the northern hemisphere (with the Robledo-70m antenna) and in the southern hemisphere (Parkes-64m). They surveyed 179 sources (mostly pPNe & PNe) and detected 9 sources (4 pPNe and 5 PNe, one of these, IRAS 15103-5754, has water fountain characteristics, see Figure 1)

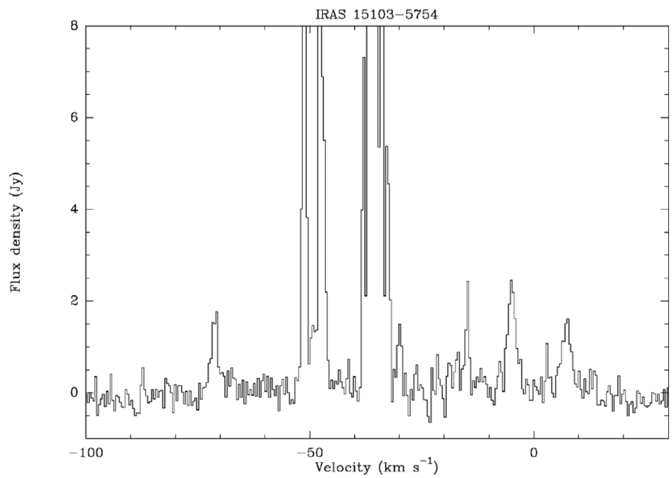

Figure 1. IRAS 15103-5754, first water fountain detected in a planetary nebula (Suárez *et al.* 2009).

Using the 100 m telescope of Effelsberg, Desmurs *et al.* (2010) undertook a high sensitivity discrete source survey for the first excited state of OH maser emission (J = 5/2, $^2\Pi_{3/2}$ at 6 GHz) in the direction of 65 PNe and pPNe exhibiting 18 cm OH emission (main and/or satellite lines). They detected two sources at 6035 MHz (5 cm), both of them young (or very young) PNe. And very recently, Amiri *et al.* (2012), conducted a sensitive survey with the Effelsberg antenna of water maser emission toward 74 post-AGBs, and found 6 new water fountain candidates showing a double peak profile.

3. Water Fountains

In the class of the proto-planetary nebulae, there is a very interesting sub-class of young pPNe called the water fountains. They present both hydroxyl and water maser emission,

https://doi.org/10.1017/S1743921312006990 Published online by Cambridge University Press

Table 1. Confirmed water fountains[a]

PNe	Other name	OH Velocity range (in km s^{-1})	H_2O Velocity range (in km s^{-1})	References
IRAS 15445-5449	OH 326.5-0.4		90	Deacon *et al.* (2007)
IRAS 15544-5332	OH 325.8-0.3		74	Deacon *et al.* (2007)
IRAS 16342-3814	OH 344.1+5.8		260	Claussen *et al.* (2009)
IRAS 16552-3050	GLMP 498			Suárez *et al.* (2007)
IRAS 18043-2116	OH 0.9-0.4		400	Walsh *et al.* (2009)
IRAS 18113-2503	PM 1-221		500	Gómez *et al.* (2011)
IRAS 18139-1816	OH 12.8-0.9	23	42	Boboltz & Marvel (2007)
IRAS 18286-0959	OH 21.79-0.1		200	Yung *et al.* (2011)
IRAS 18450-0148	W 43A/OH 31.0+0.0		180	Imai *et al.* (2002)
IRAS 18460-0151	OH 31.0-0.2	20	300	Imai *et al.* (2008)
IRAS 18596+0315	OH 37.1-0.8	30	60	Amiri *et al.* (2011)
IRAS 19067+0811	OH 42.3-0.1	20	70	Gómez *et al.* (1994)
IRAS 19134+2131	G054.8+4.6		105	Imai *et al.* (2007)
IRAS 19190+1102	PM 1-298		100	Day *et al.* (2010)
IRAS 15103-5754	G320.9-0.2		80	Suárez *et al.* (2009)

[a] +6 new water fountains candidates (see Amiri *et al.* 2012).

however their characteristics differ from those typical of AGB stars†. First of all, H_2O and OH maser spectra exhibit a double peaked profile with the peaks symmetrically distributed about the star velocity. But, unlike in AGB stars, H_2O maser are spread over a larger velocity range than the OH masers (see Imai *et al.* 2008 for example) and display higher velocity (up to 400 km s^{-1} see Figure 2) than the OH masers or AGB radial expansion wind (10-20 km s^{-1} te Lintel *et al.* 1989). High spatial resolution observations of the water masers emission in these objects reveals bipolar distribution and highly collimated outflows (hence the name of water fountain). The first member of this subclass of pPN, W 43A, was first observed by Imai *et al.* (2002) with the VLBA, and showed a well collimated and precessing jet with an outflow velocity of ∼145 km s^{-1}. When optical images are available, the masers appear coincident with the optical bipolar structures (see for example IRAS 16342-3814, Claussen *et al.* 2009 and this proceeding).

Table 1 shows a list of the confirmed‡ water fountains. Up to now, 14 sources have been identified as water fountains and 6 new sources have been recently found by Amiri *et al.* (2012) and are good candidates to be classified as such (they all present a double peak spectra and high velocity profiles). The most recent source confirmed to belong to this sub-class is IRAS 18113-2503 (Gómez *et al.* 2011, see Figure 2). The source shows the typical double peak spectra, with a very large velocity dispersion and the peaks of water emission are separated by about 500 km s^{-1} (from -150 to +350 km s^{-1} LSR). It is likely to be the fastest outflows observed up to now with a velocity of at least 250 km s^{-1}. The e-VLA map clearly shows a bipolar spatial distribution with a blueshifted part to the north and a redshited lobe to the south.

IRAS 19067+0811 is also an interesting source, observations in 1988 clearly detected a double peak H_2O spectrum covering a velocity range of twice of the velocity range of the OH spectra, but Gómez *et al.* (1994) only detected OH maser emission. And finally,

† OH masers in AGB star generally exhibit double-peaked profiles covering up to 25 km/s (e.g. te Lintel *et al.* 1989), and H_2O maser spectra present a velocity range within the OH maser one and their profiles are more irregular.

‡ The candidates sources IRAS 07331+0021 and IRAS 13500-6106 from Suárez *et al.* (2009) turned to be "classical" proto-planetary nebulae and not water fountain.

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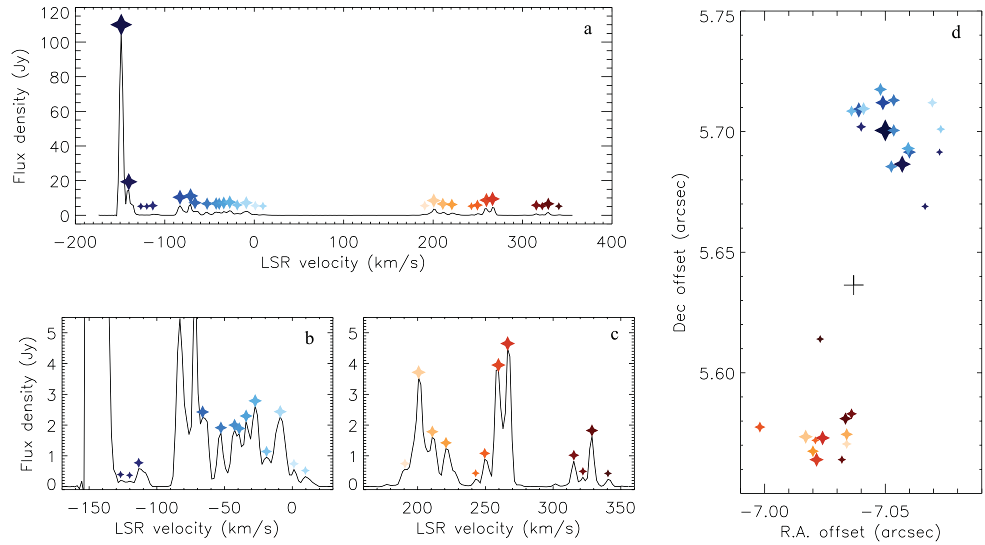

Figure 2. e-VLA spectrum and map of the water fountain IRAS 18113-2503, see Gómez *et al.* (2011) for details.

I would like to mention IRAS 15103-5754 a very peculiar source as it is the first confirmed water fountain that is not a pPN but a PN (see Suárez *et al.* 2009 and these proceedings).

3.1. *Outflows Proper motion*

A careful analysis of the 3D structure of jets (including proper motions studies) is a fundamental element for the development of theoretical models of the PN shaping mechanisms and of the nature of the outflows that give rise to the complex structure found in many pPNe and PNe.

In W 43A, VLBA observations of H_2O maser emission show very well collimated jets with a velocity of the order of ∼145 km s^{-1} (Imai *et al.* 2002, 2005). The proper motion analysis also demonstrates that the jets exhibit a spiral pattern and is precessing with a period of 55 years. In the source IRAS 16342-3814 (e.g. Claussen *et al.* 2009 and these proceedings) it is found that water masers lie on opposite sides of the optical nebula and their distribution is generally tangential to the inferred jet axis. Proper-motion measurements give a velocity of the jet at the position of the extreme velocity maser components of at least 155 to 180 km s^{-1} but no direct evidence for precession was found, maser features appear to follow a purely radial motion (no curve trajectories are observed). A detailed morpho-kinematical structure analysis of the H_2O masers from the water fountain IRAS 18286-0959 has been carried on by Yung *et al.* (2011) (see Figure 3). Observations are best interpreted by a model with two precessing jets (or "double helix" outflow pattern) with velocities of up to 138 km s^{-1} and a precessing period of less than 60 years.

This proper motion studies allow also to estimate other parameters like the dynamical age of these outflows and they are found to be surprisingly young, of the order of few tens of years, up to 150 years, which suggests that the evolutionary stage that these water-fountain sources represent is likely to be very short: 50 years for W 43A (see Imai *et al.* 2005), ∼30 years for IRAS 18286-0959 (Yung *et al.* 2011), ∼59 years for IRAS 19190+1102 (Day *et al.* 2010) and about 120 years for IRAS 16342-3814 (Claussen *et al.* 2009). VLBI astrometry of H_2O masers also allow to derive more accurate distance of these sources.

3.2. *Polarization and magnetic collimation*

The origin of the jet collimation is still an open question but several models (Chevalier & Luo 1994, García-Segura *et al.* 1999) have shown that the magnetic field could be a dominant factor in jet collimation (Blackman *et al.* 2001, García-Segura *et al.* 2005) in post-AGB stars. The Zeeman effect produces a shift in frequency between the two circular polarizations (LCP and RCP) that is directly proportional to the strength of the magnetic field (projected on the line of sight). Hence, by measuring this shift, we can deduce the value of the magnetic field. Several molecules giving rise to maser emission are sensible to this effect (like OH and H_2O), and then provide a unique tool for studying the role of the magnetic field in the jet collimation (of water fountains for example).

Full polarization observations measuring both linear and circular polarization toward the archetype water fountain W 43A have been conducted (see Vlemmings *et al.* 2006, Amiri *et al.* 2010). A strong toroidal magnetic field has been measured, with an estimated strength on the surface of the star as high as 1.6 G (see Vlemmings *et al.* 2006). Such a magnetic field is strong enough to actively participate in the collimation of the jets.

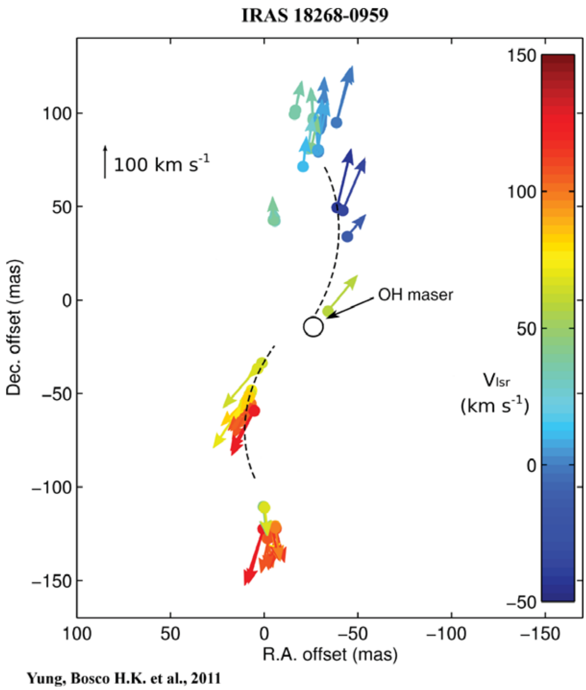

Figure 3. Proper motion of H_2O maser features measured in IRAS 18286-0959 (from Yung *et al.* 2011)

Recently, Wolak *et al.* (2011) published a single dish survey conducted with the Nancay radio telescope toward 152 late type stars, out of which 24 were post AGB sources. In more than 75% of the sample, they detected polarization features and a magnetic field strength of 0.3 to 2.3 mG. In summary, strong magnetic field are observed, strong enough to play a major role in shaping and driving the outflows in water fountains.

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4. SiO PPN

SiO maser are very rare in pPNe, very few sources have been detected, OH 15.7+0.8 (tentative detection), OH 19.2-1.0, W 43A, OH 42.3-0.1, IRAS 15452-5459, IRAS 19312+ 1950 and OH 231.8+4.2. The last one discovered is IRAS 15452-5459 (Deacon *et al.* 2007). The SiO maser emission of two of these sources has been mapped, W 43A and OH 231.8+4.2. In the first case, the spatial distribution was found to be compatible with a bi-conical decelerating flow and in the case of OH 231.8+4.2, the distribution can be described by a torus with rotation and infalling velocities. of the same order and within a range between ~ 7 and ~ 10 km s^{-1} (see Sánchez Contreras *et al.* 2002).

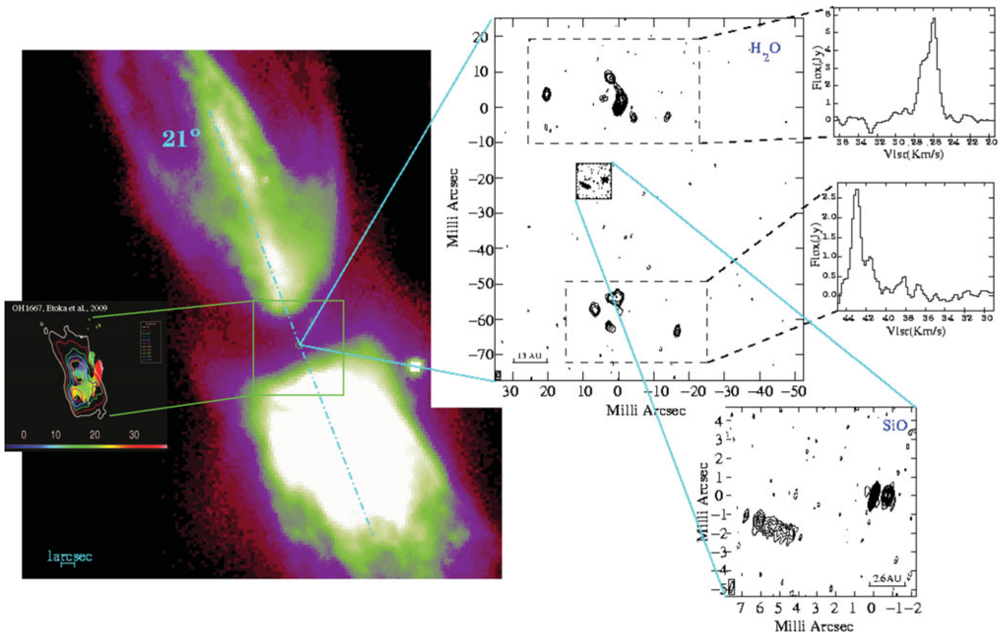

Figure 4. Composition image summarizing interferometric observations OH, H_2O and SiO toward OH 231.8+4.2

5. The prototype of bipolar proto Planetary Nebulae: OH 231.8+4.2

OH 231.8+4.2 (also known as the Calabash nebula or QX Pup) is well studied and prototype of bipolar pPNe. It is located in the open cluster M46 at a distance of 1.5 kpc ± 0.05 (Choi *et al.* 2012) and the inclination of the bipolar axis with respect to the plane of the sky, $\sim 36^o$.. The central source is a binary system formed by an M9-10 III Mira variable (i.e. an AGB star) and an A0 main sequence companion, as revealed from optical spectroscopy by Sánchez Contreras *et al.* (2004). This remarkable bipolar nebula shows all the signs of post-AGB evolution: fast bipolar outflows with velocities $\sim$200–400 km s^{-1}, shock-excited gas and shock-induced chemistry. Mid-infrared MIDI observations (Matsuura *et al.* 2006) show the presence of a compact circumstellar region with an inner radius of 40-50 AU. An equatorial torus is observed at distances greater than 1 arcsec, however, no trace of rotation is found at this scale and the gas is in expansion, as shown by CO and OH emission data (Alcolea *et al.* 2001, Zijlstra *et al.* 2001). Hubble space telescope observations clearly show two extended lobes and PdBI

CO observations measured a traveling speed of the molecular outflow of the order of 400 km s^{-1}.

OH 231.8+4.2 still shows intense SiO masers, contrarily to what happens in the majority of pPNe. The SiO maser emission arises from several compact, bright spots forming a structure elongated in the direction perpendicular to the symmetry axis of the nebula.

Figure 4 is a composition image summarizing OH, H_2O and SiO maser emission observations compared with the HST image of the nebula (taken with the WFPC2 Bujarrabal *et al.* 2002). The left panel presents the velocity map of the OH maser emission at 1667-MHz aligned over the L-band image obtained at the VLT by Matsuura *et al.* (2006). Top right panels show the total intensity map of the H_2O maser for the two main regions. The small square map at bottom right indicates the position of the map of SiO maser obtained by Sánchez Contreras *et al.* (2002). OH 231.8+4.2 is a strong emitter in the OH ground state line at 1667 MHz. This strong maser emission, radiated by the circumstellar material around OH 231.8+4.2, was mapped with MERLIN by Etoka *et al.* (2009) The OH maser distribution (4 arcsecond) traces a ring-like structure presenting a velocity gradient that is explained by the authors as the blueshifted rim of the bi-conical outflow. The distribution of the polarization vectors associated with the maser spots attests a well-organized magnetic field which seems to be flaring out in the same direction as the outflow. H_2O maser emission is distributed in two distinct regions of ∼20 mas in size, spatially displaced by 60 milli-arcs (less than 100 AU, comparable to the size of the AGB envelopes) along an axis oriented nearly north-south, similarly to the axis of the optical nebula. The expansion velocity of the H_2O masers spots is very low compared to water fountain jets and lower than that of the OH maser spots. Proper motion observations (Leal-Ferreira *et al.* 2012, Desmurs *et al.* 2012) derived velocities on the sky of the order of 2–3 mas/year. Taking into account the inclination angle of the source, this corresponds to an average separation velocity of 15 km s^{-1}. Moreover, the H_2O emission is not as well collimated as in water-fountains. Linear polarization of H_2O maser yields a value of the magnetic field, assuming a toroidal structure, of 1.5–2.0 G on the stellar surface (see Leal-Ferreira *et al.* 2012). SiO masers are tentatively placed between the two H_2O maser emitting regions and rise from several compact features tracing an elongated structure in the direction perpendicular to the symmetry axis of the nebula. Probably this is a disk rotating around the M-type star. The distribution is consistent with an equatorial torus with a radius of ∼ 6 AU around the central star. A complex velocity gradient was found along the torus, which suggests rotation and infall of material towards the star with velocities of the same order and within a range between ∼ 7 and ∼10 km s^{-1} (see Sánchez Contreras *et al.* 2002).

Acknowledgments

I would like to acknowledge financial support from the Visiting Scientist grant from the National Research Foundation of South Africa. I would like also to acknowledge V.Bujarrabal for his very useful comments and careful reading of the manuscript. Thank's POD!

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