Water Fountains in Pre-Planetary Nebulae

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Summary. We review the recent Very Long Baseline Array and Hubble Space Telescope observations of the "water fountain" pre-planetary nebulae, with long time scale comparisons of historical water maser spectra. Parallax, proper motion, dynamical ages, and acceleration measurements are discussed for three sources (IRAS19134+2131, IRAS16342-3814, OH12.8-0.9). The fifth water fountain pre-planetary nebula candidate is confirmed (IRAS19190+1102) with high angular resolution observations. (The fourth, W43A, is not discussed in this paper.) Further such observations, and, as well, time monitoring of the water maser spectra are crucial next steps for the understanding of this short transition phase in the evolution to planetary nebulae.

Key words: pre-planetary nebulae, masers

1 Introduction

It is now well-accepted that asymptotic giant branch (AGB) stars evolve into planetary nebulae (PN); however the mechanisms and details are still uncertain. What seems to be clear is that the period of transition (the so-called pre-planetary nebula — PPN — phase) is probably rather short, and thus observational evidence of what transpires during this interesting phase is somewhat lacking. We know from observations of AGB stars and PN that the geometry of the circumstellar material changes dramatically from a nearly spherical distribution to many different geometrical shapes [15], and that this transition period (or earlier) is very likely when the shaping occurs.

A particularly interesting sub-class of PPNe is the group of so-called "water-fountain" nebulae, whose distinguishing characteristic is the presence of very high-velocity red- and blue-shifted water and OH maser features (one of the most extreme cases, IRAS16342−3814 — hereafter I16342, has water maser features with radial velocities separated by more than 250 km s^{-1}). Since the discovery of the high velocity water masers in I16342 [12], several more water-fountain PPN candidates have been discovered, and high angular resolution observations of the water masers in several of these sources have been obtained using the NRAO's Very Long Baseline Array. Table 1 lists the known and candidate water fountains and the velocity extent of the water maser emission as determined from single-dish spectra.

Table 1. Known (Top Five) and Candidate (Bottom Six) Water Fountain PPNe

Source	Other Name	Radial Velocity Extent ($\mathrm{km\,s^{-1}}$)	Reference
IRAS16342-3814	OH344.1+5.8	260	[13]
OH12.8-0.9		100	[6]
IRAS18450-0148	W43A,OH31.8+0.0	180	[13]
IRAS19134+2131		105	[13]
IRAS19190+1102		100	[11], [3]
IRAS15445-5449	OH326.5-0.4	90	[5]
IRAS15544-5332	OH328.5-0.3	80	[5]
IRAS18043-2116	OH0.9-0.4	205	[5]
IRAS18286-0959		210	[7]
IRAS18460-0151	OH30.1-0.2	300	[7]
IRAS18596+0315	OH37.1-0.8	60	[5]

Molecular masers are, of course, ubiquitous in the circumstellar envelopes of oxygen-rich AGB stars; in general the spatial distribution of masers in the AGB stage traces more or less spherically symmetric shells of gas, with SiO masers near the stellar photosphere, water masers further out in the shell (a few tens to a hundred A.U.), main-line OH masers next, and finally in the far reaches of the circumstellar envelope (a few hundred to 1000 A.U.), the 1612 MHz OH masers. The total velocity spread of these masers is set by the expansion speed of the AGB ejecta, which typically lies in the 5-20$\mathrm{km\,s^{-1}}$ range. In the water-fountain nebulae, the water masers appear to have been re-born in a fast outflow. The high-velocity outflows traced by the water masers appear to be highly collimated based on VLBA observations of five sources (see Table 2), and are likely the manifestations of the active sites at which the circumstellar environments are being shaped by these jets.

In this review, we will briefly report on recent interesting results of VLBA and Hubble Space Telescope (HST) observations of the water fountain IRAS19134+2131 [9], VLBA observations of OH12.8-0.9 [1], show VLBA results confirming a fifth water fountain PPN, IRAS19190+1102 [4], and discuss our recent interpretation of the water fountain I16342 [2].

2 IRAS19134+2131 & OH12.8-0.9

Imai, Sahai. & Morris [9] recently published VLBA observations of the water fountain PPN IRAS19134+2131 (hereafter I19134), along with optical images taken with the HST to detect and locate an optical nebula with respect to the water masers. Figure 1 shows the detected optical lobes and the extent of the water masers in this PPN. The agreement in size and orientation of the optical nebula and the water

Table 2. Properties of Water Fountain PPNe

Source	I16342	W43A	I19134	OH12.8	I19190
Estimated Distance (kpc)	2	2.6	8.0*	8	2
Water Maser Angular Extent (mas)	3000	920	140	110	285
Water Maser Linear Extent (A.U.)	6000	2400	1120	880	570
One-Sided 3D Outflow Velocity ($\mathrm{km\,s^{-1}}$)	152	145	89	58	52
Dynamical Age (yr)	125	50	40	90**	100
Optical Lobes Detected	Yes	No	Yes	No	No
Outflow Collimation (deg)	6	5	10	15	18
Reference	[2]	[8]	[9]	[1]	[4]

*Distance measured by trigonometric parallax
**Dynamical age estimate from acceleration

masers strongly suggests that the lobes have been formed along the collimated fast outflow.

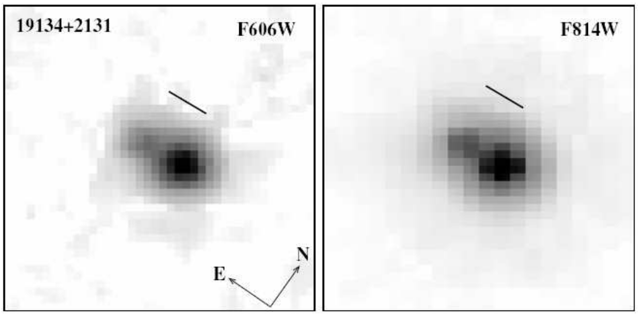

Fig. 1. From [9]. Image of the PPN I19134, made with ACS/HST through a) the F606W, and b) F814W filters. The solid line above the bipolar nebulosity shows the position angle and size of the water maser high velocity outflow.

Imai, Sahai, & Morris used the VLBA to obtain absolute astrometry of the water masers in I19134 over six epochs to analyze the maser motions which consist of the combination of annual parallax, secular motion, and intrinsic motions within the flow. They obtain a distance to I19134 of $8.0^{+0.9}_{-0.7}$ kpc from the Sun. A precise distance measurement to I19134 allows physical parameters to be accurately determined; VLBA observations of other water fountain PPNe hold the promise of accurate distances to other members of this important transition class of objects.

Boboltz & Marvel [1] have used the VLBA to observe the water masers in the water fountain source OH12.8-0.9 (hereafter OH12.8). They show that, although the spread in radial velocities from this source does not rival that from other water fountain sources (see Table 1), OH12.8 does show the hallmark of the other water fountain sources when observed at high angular resolution. The extreme red- and blue-shifted masers are found in distinct regions at the ends of a bipolar jet-like structure. In addition, by using published (single-dish) spectra of the masers over $\sim$ 17 years, Boboltz & Marvel find (for the first time in a water fountain PPN) that the water masers in OH12.8 are accelerating at a rate of 0.63 km s^{-1} yr^{-1}.

3 IRAS19190+1102

The water masers in IRAS19190+1102 (I19190 hereafter) were first discovered by Likkel [11], who found masers spread in LSR velocity over 70 km s^{-1}. Given this source's colder IRAS color temperatures than the rest of her survey and the peculiar 1612 and 1667 MHz OH maser profiles, Likkel suggested that I19190 was an energetic molecular cloud source, although she did not rule out a "relationship to evolved objects with high-velocity water maser emission". Indeed, the other water fountain PPNe have similar color temperatures to I19190. Claussen, Sahai, & Morris [3] re-observed the water maser emission from I19190 in a survey of cold OH maser sources (candidate PPNe) using the NRAO 100-m Green Bank Telescope (GBT), finding maser emission over a range of LSR velocities exceeding 100km s^{-1}.

Recent VLBA observations [4] of I19190 show that the high velocity masers are separated into a bipolar structure of red- and blue-shifted features as in the other water-fountain PPNe observed with the VLBA. Figure 2 shows two VLBA epochs of the high-velocity water masers separated by approximately two years. Proper motions of the water masers over this time show that the two groups of masers are moving away from each other at 2.7 mas yr^{-1} (in the plane of the sky), translating to a velocity of 26 km s^{-1} assuming a distance of 2 kpc. The calculated three-dimensional expansion speed (one-sided) is 51.7 km s^{-1} . Thus it appears that I19190 should join the class of bona fide water fountain PPNe.

4 IRAS16342-3814

One of the most extreme members of the water fountain PPN class is I16342. This source has water masers spread over a range of radial velocities encompassing 270 km s^{-1}, the largest spread of velocities known, until recently (see Table 1), in the handful of water-fountain nebulae. In the discovery single-dish spectra [12] and subsequent single-dish observations [13] (hereafter LMM92), the spectra show two main groups of masers: one at radial LSR velocities from approximately 150 to 180 km s^{-1}, and one at radial LSR velocities from -90 to -60 km s^{-1}. In the LMM92 multi-epoch study, no water maser emission was found in the intervening range of the central velocities, i.e. approximately -60 to $+150$ km s^{-1}. LMM92 suggested that the water masers appeared to be reflection symmetric about a central velocity and analyzed red/blue pairs of features (e.g. $\sim +170$, -85; $\sim +145$, -55 km s^{-1}) which were thought to be symmetrically situated about a single centroid velocity. In their analysis, they found that the central velocity was $+43.2$ km s^{-1} with respect to the LSR. LMM92 also suggested that the members of the red/blue pairs presumably arise on opposite sides and at similar distances from the star.

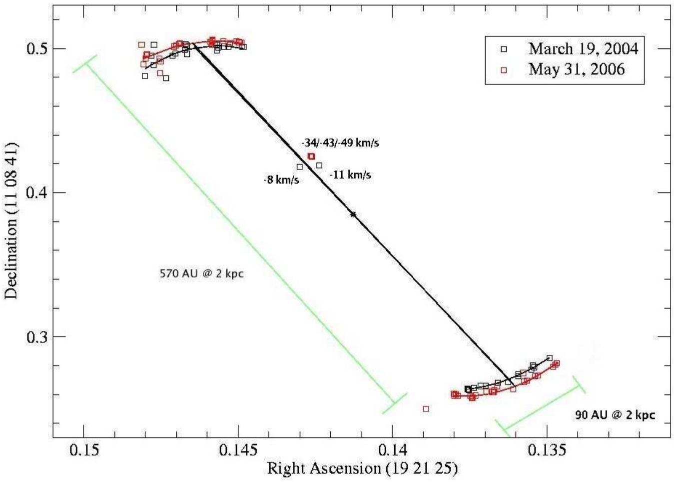

Fig. 2. Map of the water masers of I19190 for two epochs: black/white symbols for March 19, 2004, colored symbols for May 31, 2006. The angular expansion rate between the NE and SW groups of masers is 2.7 mas yr^{-1} or 26 km s^{-1} for a distance of 2 kpc.

Sahai et al. [16],[14] studied I16342 in some detail in the optical and near-IR using HST and the Keck Adaptive Optics (AO) system, and OH emission using the VLA. A bipolar nebula with lobes separated by a dark equatorial waist is seen in the HST images. The morphology implies that the lobes are bubble-like reflection nebulae illuminated by starlight escaping through polar holes in a dense, dusty obscuration of the central star. The AO observations reveal a remarkable corkscrew-shaped structure apparently etched into the lobe walls, which is inferred to be the signature of the underlying precessing jet. The VLA maps of the OH masers show features with the largest red- and blue-shifted velocities concentrated around the bright eastern and western polar lobes, respectively, while intermediate-velocity features generally occur at low latitudes, near the dark waist region. Figure 3 shows the HST images overlaid with the OH emission (and the water masers, see below).

VLBA multi-epoch observations of the high-velocity water masers in I16342, reported in Claussen, Sahai, & Morris [2] (hereafter CSM07) show that the red- and blue-shifted masers lie at opposite ends of a bipolar structure 2975 mas in extent, at a position angle of 66.1° east of north. The -66.0 and $+153.0$ km s^{-1} velocity groups form a velocity-symmetric pair in the sense of LMM92 and shows a proper motion of their separation vector of 11.0 mas yr^{-1}. This corresponds to a tangential velocity of 105.0 km s^{-1} if it is assumed that both members of the pair equally share their separation velocity (see Figure 4). The total three-dimensional speed (one-sided) of material in the collimated fast outflow, based on these measurements, is thus $151.9 \mathrm{km\,s}^{-1}$.

CSM07 perform an analysis based on the change in velocities of their velocity groups as compared to LMM92. They find that the radial velocity outflow speed has increased by roughly 5 - 6 km s^{-1} over a period of about 14 years (from 1988 to 2002), implying 1) that momentum has been added to the water maser emitting

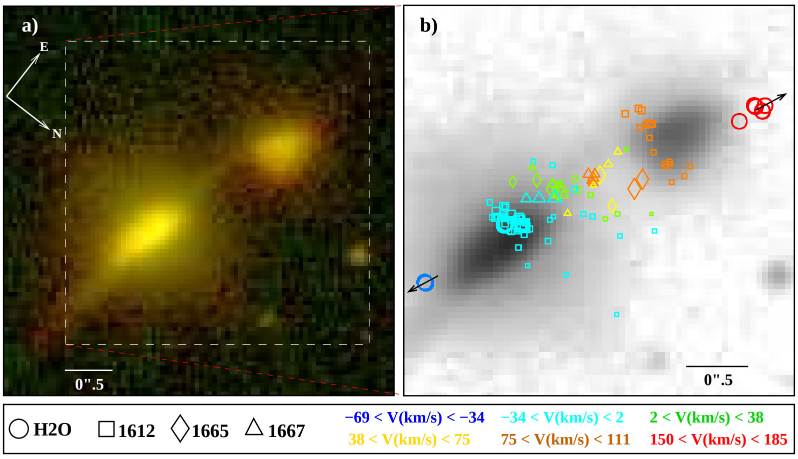

Fig. 3. (a) A color image of I16342, made of exposures taken with WFPC2/HST through the F814W filter in red and F555W filter in green. (b) VLA OH 1612, 1665, and 1667 MHz maser features, overlaid on the F814W image. VLBA water masers are also show. Water masers in the velocity range $V_{LSR} = -20$ to -33 km s^{-1} are co-located with the blue-shifted OH masers.

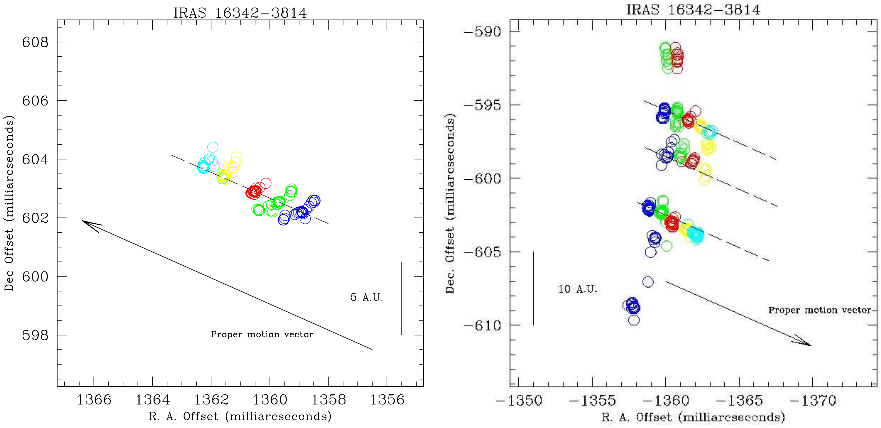

Fig. 4. Water masers in I16342. *Left.* Masers in the northeast part of the outflow, at +153.0 km s^{-1} radial velocity. Colors depict different epochs of the observations in 2002, separated by 1 month intervals. *Right.* Masers in the southwest part of the outflow, at -66.0km s^{-1}radial velocity. These two groups form a velocity-symmetric pair (LMM92).

material by the jet, and thus that the jet in I16342 has remained active, and 2) that the average acceleration is $\sim 0.4 \mathrm{km\,s^{-1}yr^{-1}}$. This is very similar to that found by Boboltz & Marvel for OH12.8. Measuring the acceleration of the gas in the collimated fast outflow provides an additional observable for constraining hydrodynamic models of the interaction between the jet and circumstellar envelopes. Although the acceleration of the wind is sensitive to model parameters (e.g [10]), it has not been used as a constraint in such models, as the observational data has not, until recently, been available.

5 Summary

High angular resolution observations of the water masers in water fountain PPNe have confirmed the suggestion by LMM92 that the red- and blue-shifted masers lie on opposite sides of a bipolar outflow. Comparison with optical HST images show that, in two cases, a small bipolar nebula is likely being formed by the collimated fast outflow (as indicated by the water maser jet) interacting with the circumstellar gas, evacuating material and allowing stellar light to reflect from the walls of the cavities thus created. An accurate distance measurement has been obtained for one water fountain PPN by absolute astrometry of the water masers. Careful comparison between spectra over many years has suggested that the gas traced by the masers is accelerating in two objects. Although not reviewed here, the motions of the water masers in W43A are well fit by a precessing jet model [8], suggesting the presence of a binary companion of the central star. Finally, the measurement of the three-dimensional velocities of the jets and the extent of the maser emission give an estimate of the lifetime of the collimated fast outflow traced by the water masers. These lifetimes, listed in Table 2, are very short (≤ 100 years), and thus confirm the rapid evolution from the AGB towards the PN phase. Further high angular resolution observations of candidate water fountain sources will confirm the bipolar nature of these sources. Repeated VLBA observations of water fountain sources will allow direct distance measurements, as well as determine the spatial evolution of the water maser structures. High sensitivity and high velocity resolution spectral monitoring, with the GBT, will permit a careful measurement of the acceleration or deceleration of the radial velocity of the masers, and add the acceleration in many water fountain sources as an observable constraint on the models of the outflows which shape their circumstellar environments.

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