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"Water Fountain" Masers in Proto-Planetary Nebulae

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Abstract:

Some very old, Asymptotic Giant Branch (AGB) stars exhibit strong collimated maser emission from their circumstellar envelopes. A small number of these form a group known as “Water Fountains,” (WFs) for their H_2O masers with a very broad velocity distribution. These arise during the formation of a Planetary Nebula (PN), and are thought to contribute to the varied and intricate morphologies found in Planetary Nebulae (PNe). The theory is that an AGB star exhibits bipolar rotating episodic jets that carve out the dusty circumstellar envelope, and in doing so decides the shape of the PN to come. Much work has been done on astronomical masers of other kinds, but due to the rarity of these WFs, they remain an elusive target of study, with only 16 observed. Even now, the theory is changing, and with the arrival of more WF observations, we can gain significant insight into this mysterious period in a star’s lifetime.

1. Introduction:

1.1 Planetary Nebulae:

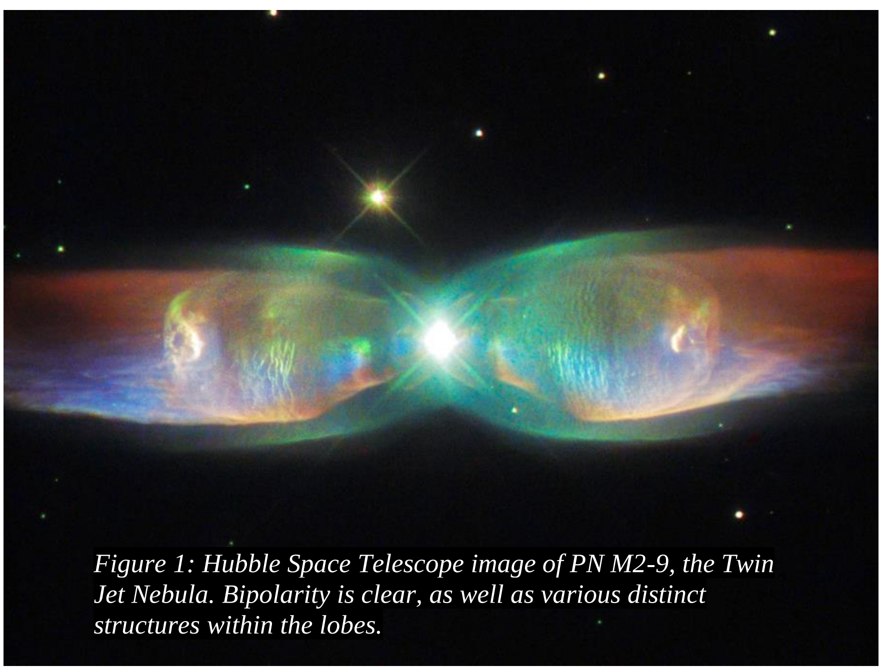


Figure 1: Hubble Space Telescope image of PN M2-9, the Twin Jet Nebula. Bipolarity is clear, as well as various distinct structures within the lobes.

When Planetary Nebulae (PNe) were first observed 250 years ago, our understanding of astrophysics was drastically different, hence the rather unfortunate misnomer. The history of Planetary Nebula (PN) research tells a fascinating story of discovery following the advent of modern astrophysics, see Kwok (2012) for review. We now understand PNe to be a transitional phase in a star’s lifetime between the AGB and White Dwarf stage, when fusion in the star dies and it sheds its outer material, leaving behind its compact core. The bright emission from PNe is part of the remnant of the AGB star’s ejected circumstellar shell, ionized by the hot central star. Although the accepted quantitative theory for PNe was developed in 1970, the varied and intricate morphologies of these objects remain mysterious in origin. The many studies on the subject generally agree that PNe can be classified as round, elliptical, or bipolar, as in Balick (1987). Most of these studies point out that only 15% of PNe are bipolar, though Kwok (2010) posits that the fraction could be significantly higher due to the inherent limits of observational classification. Balick and Frank (2002) present an excellent review of PN and Proto-Planetary Nebula (PPN) shapes and structures. They highlight that AGB mass-loss is isotropic, Post-AGB PPNe can exhibit high-order axisymmetry, and there exists compelling evidence for cold dusty disks and tori around post-AGB stars. Due to the wide set of shapes in mature PNe, it is difficult to deduce a single formation mechanism. Thus, we would like to look specifically at PPNe, particularly the point at which symmetry changes from spherical to something more complex. First, however, it is helpful to discuss AGB stars and the phenomenon of maser emission.

1.2 AGB stars

After a star runs out of hydrogen in its core to fuel fusion, it becomes a red giant, and the core begins to fuse heavier elements. As the star gets older, it joins the Asymptotic Giant Branch (AGB), which refers to a specific region on a graph of luminosity vs temperature. AGB stars are known to have high mass-loss rates, up to 10^{-4} solar masses per year. This results in a large circumstellar envelope (CSE) featuring various shells of interesting molecular chemistry. One phenomenon that arises in these shells is maser emission, wherein certain molecular populations are excited and pumped in such a way that they emit collimated coherent emission at specific frequencies. This is analogous to the common laser, with parallel monochromatic photons being emitted and amplified without destructive interference, the difference being that masers emit in radio frequencies. Astrophysical masers have been observed since the 1960s, and have a great many applications, as detailed by Elitzur (1992). Maser emission from late-type stars manifests as a spectral double-peak, due to emission from the near and far sides of the circumstellar shell. These peaks illustrate the expansion velocity of the envelope, as the emission from either side of the expanding spherical shell is doppler shifted to different frequencies. The most notable molecules in AGB stars are SiO, H_2O, and OH, listed in order of distance from the central star. Shell masers like this are pumped radiatively (Elitzur, 1992), and after the AGB stage, disappear from the inside out, with SiO the first to go. However, OH and H_2O masers can remain active into the PPN or even PN phase, giving us clues about the dynamics of those systems (Desmurs, 2012). It also should be noted that because these only arise in oxygen-rich stars, there exists a strong selection bias against carbon-rich AGB stars.

Historically, PPNe research has been difficult due to the large extinction from the dust around post-AGB stars. When the Infrared Astronomical Satellite was launched in 1983, astronomers were given a new catalogue of sources bright in the Infrared to study and classify. Many of these are known to be AGB/Post-AGB stars, emanating strong IR emission from their dust envelopes. Those that have strong emission at 1612 MHz, so containing OH maser activity, are known as OH/IR stars.

1.3 Water Fountains

Some PPNe show water masers that have an abnormally large velocity range, causing them to be dubbed "Water Fountains" (WFs). These are the focus of this paper, as they can give crucial insight into the morphological shift that occurs in PPNe. First observed by Likkel and Morris (1988), WFs are named for their very fast jets that house the H_2O maser emission at 22 GHz, with velocities typically greater than 75 km/s, and up to 500 km/s (Gómez, 2011). They are believed to be pumped by the energy from shock fronts, as the jet slams into the surrounding Circumstellar Envelope. This causes the molecules to be excited, causing photon emission upon de-excitation. Due to the great dynamical speeds observed, WFs have an exceptionally short lifetime of on average 100 years (Imai, 2007). This fact, coupled with the difficulty in identifying candidate targets, means that only 16 sources have been confirmed as WFs (Gómez, 2015). By finding and studying WFs, we can better understand the processes that change a spherically symmetric AGB star into bipolar and asymmetric PN.

2. Previous Work:

2.1 The Importance of Jets

Any theory of PPN dynamics must explain the presence of bipolar, multipolar, and point-symmetric morphologies in PNe, as well as explain the advent of asymmetry in the AGB circumstellar envelope. In 1978, Kwok et al proposed a detailed magnetohydrodynamic model which was developed further by Kwok (1982) and Balick (1987) to become the "Generalized Interacting Stellar Winds" (GISW) model. They assume a slow equatorial wind during the AGB period, creating a toroidal CSE, followed by a fast equatorial wind that slams into the existing envelope, except for at the poles where the envelope is considerably less dense. The second wind is thought to be powered by the contraction of the central star as it becomes a white dwarf. This model can successfully account for bipolar PNe with cylindrical symmetry and reflection symmetry about the equatorial plane, but fails to predict the multiple bubble-like structures with point symmetry observed in many PNe and PPNe. An additional failing of the GISW is that it doesn't include an accepted explanation for its assumption of an equatorially dense CSE, though multiple mechanisms have been considered. Possible solutions to this problem include binary effects, disk-forming planetary destruction, magnetic fields, and chaotic or nonradial pulsations. (Sahai, Trauger, 1998)

A simple explanation for the aspherical symmetries in PNe is bipolar rotating episodic jets. While these were already known to exist in PNe, it was thought that they occurred well into the PN phase, and added structure to the GISW-established nebula. However, the now-accepted mechanism of PN formation is high-velocity collimated outflows, or jets. The model assumes a spherical CSE at the end of the AGB phase, which is consistent with theory and observation of AGB stars. Jets begin to carve out the CSE, which decides the morphology of the PN to come. A fast, hot stellar wind then begins to flow, filling in the imprinted space around the star. It is this that becomes the optically emitting portion of the PN (Sahai, Trauger, 1998). The jets that cause this structure are thought to be traced by the high-velocity masers we observe in Water Fountains, thus WFs provide the observational evidence that bolsters this theory.

2.2 The illustrative case of IRAS 16342-3814

Work with WFs began with the peculiar discovery by Likkel and Morris (1988) of extremely fast 22 GHz H_2O masers around IRAS 16342-3814. They originally detected an "amazing 259 km s^{-1} velocity range between the highest and lowest velocity emission features" (Likkel & Morris, 1988). Since, the object has been observed many times and is a prime example of a PPN (see Claussen, 2009; Sahai, 1999; Sahai, 2005; Sahai, 2017; Imai, 2012; among others). HST images show it to be a small bipolar nebula, with a dusty equatorial waist obscuring all but the two lobes, interpreted to be reflection nebulae illuminated through polar holes in the dusty CSE. Further near-IR imagery was found by Sahai et al, (2005) with the Keck Adaptive Optics system. They showed corkscrew-like structures in the lobe, implying a precessing jet. Figure 2 on the next page from Claussen (2009) shows the maser emission from OH and H_2O, and illustrates the vast difference in velocities. It also uses the optical and IR images from the Sahai papers, overlaid with the maser locations to show their distribution. The corkscrew structures can be made out in image (d). In the case of IRAS 16342-3814, the maser emission matches the optical imagery, and it has been shown that this remains true when circumstellar extinction is low enough that we can detect optical emission.

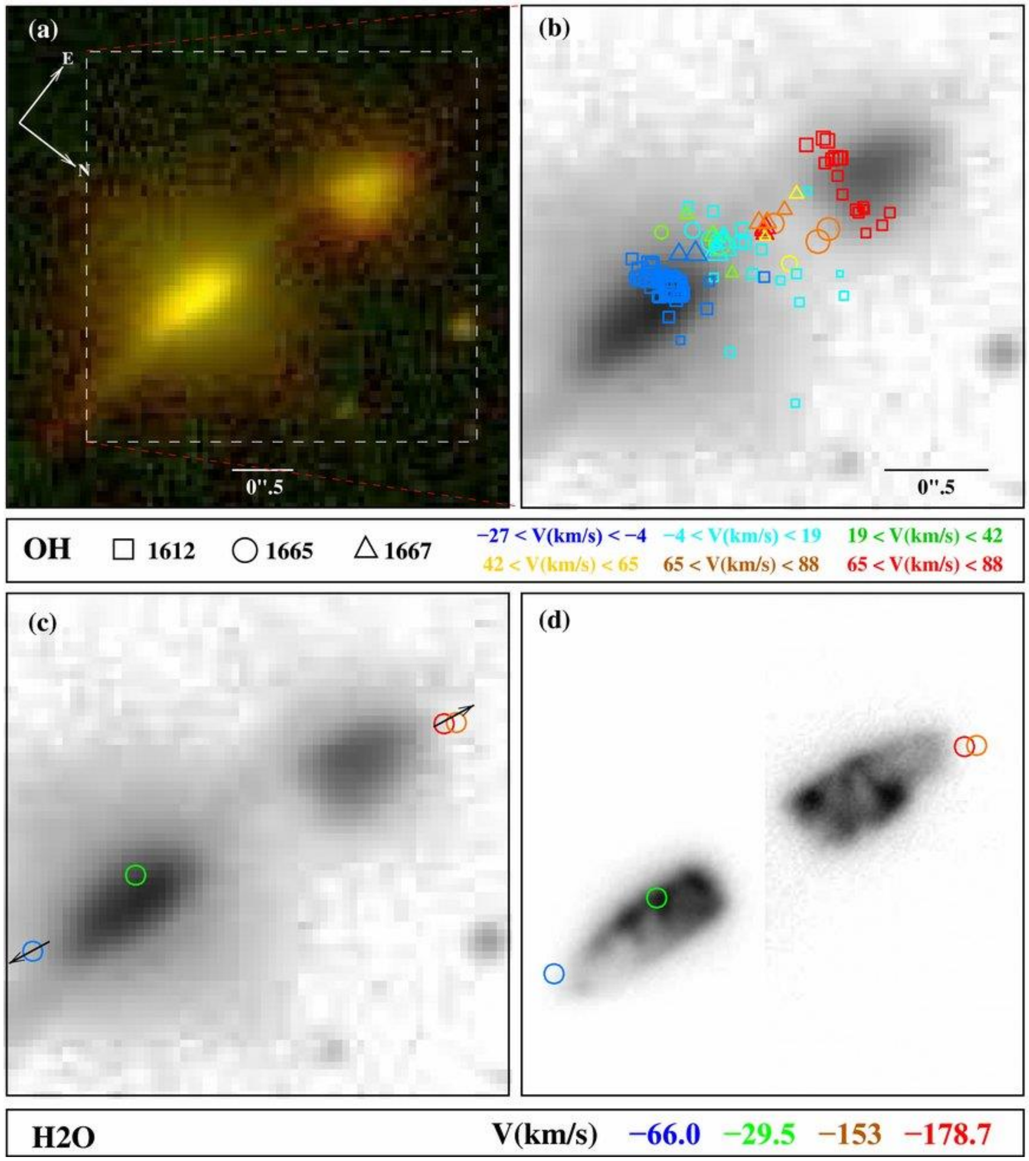


Figure 2: IRAS 16342-3814 maser data overlaid on optical and IR images. See Claussen et al, 2009 for details.

One technique for examining structure is looking for dusty structure is to look at emission lines from molecules excited by the random collisions due to the dust temperature. Carbon Monoxide (CO) is one of these molecules, with two different isotopes (^{12}CO and ^{13}CO) that help give insight into the chemical and thermal conditions in a star's envelope. The first group to examine thermal lines in a WF was He et al (2008), who searched for and detected in IRAS 16342-3814 the ^{12}CO $J = 2 - 1$ and ^{13}CO

$J = 2 - 1$ lines. They found that the mass loss rate for ^{12}CO is an order of magnitude lower than that for OH/IR stars, and that the $^{12}CO/^{13}CO$ line intensity ration is quite small (1.7). This implies a cold, thick, Oxygen-rich CSE. They also concluded that the CO emission region is at the base of the bipolar lobes. Further observation by Imai et al (2012) yielded notably different velocity profiles between the two isotopes, with ^{13}CO displaying a narrow gaussian, with much less overall intensity than the ^{12}CO, which had wide wings. Opacity effects were realized to be the main cause of the disparity. Using the infrared image from image (d) in figure 1, they were able to draw the conclusion that there exists a bipolar cavity embedded in a larger spherical halo of dust and CO. Models using that geometry accurately matched the observed CO emission, for both isotopes.

2.3 Jet Collimation and Magnetohydrodynamics

To understand the forces at work inside and on the surface of stars, physicists need to consider the fluid nature, as well as the magnetic properties of the electrically charged material in stars. The study of this has come to be known as magnetohydrodynamics (MHD). A great amount of work has gone into modeling and understanding the MHD of post-AGB stars, so much so that another whole paper would be required to present a fair review of the field. We will discuss some conclusions, however. García-Segura (1997) presented a three-dimensional model of PNe, to try to match our physical understanding to jets and point-symmetry. It was shown that magnetic fields can produce jets with speeds matching observational data. However, a single rotator cannot exhibit precession, which is observed in at least two PPNe (Imai, 2002; Yung, 2011), and understood to be an important part of the shaping process. A binary system, (such as with a close star or a large planet) is thought necessary to achieve precession. One peculiar WF is W43 A, which displays SiO and OH maser emission, as well as a precessing H_2O jet. The SiO and OH velocities are consistent with Mira variables (a kind of pulsating star named for the first one observed) and OH/IR stars still undergoing stellar mass loss, before becoming a PPN (Imai, 2005). Analysis of the magnetic field shows strong values, reinforcing the role magnetic fields play in the CSE and in the collimation of jets. (Amiri, 2010)

2.4 Special Cases

W43A is also notable because it seems to still be in the AGB phase, what with SiO masers still present, and flux variation in the OH maser due to envelope pulsation (Imai, 2002). Another WF, IRAS 15103-5754 is confirmed to be in the PN phase, yet still has water jets. It differs from other WFs in that it presents a linear increase in velocity with distance from the central star, which is known as a Hubble Flow. This phenomenon suggests an explosive event. IRAS 15103-5754 is also unique in that it has maser emission in a line through the center star, as opposed to the separated groups of emission in other WFs. These observations, made by Gómez et al, (2015a) led them to propose that PPNe pump their water masers with shocks in the jets, whereas water masers in PNe trace singular explosive events.

Of the 17 confirmed WFs listed in table 1, fifteen are in the transitional PPN phase, not correlating strongly with either AGB stars or PNe. The existence of W43A and IRAS 15103-5754 force us to expand our understanding of WFs. Whereas the theory up to this point has been that WFs arise during, and are indeed the cause of the symmetry shift in the Post-AGB phase, we may be wrong. It is serendipitous that we can see emission from this mysterious period, but there is a lot more going on than we know about.

Table 1: Confirmed WFs, from Desmurs (2012) with modifications

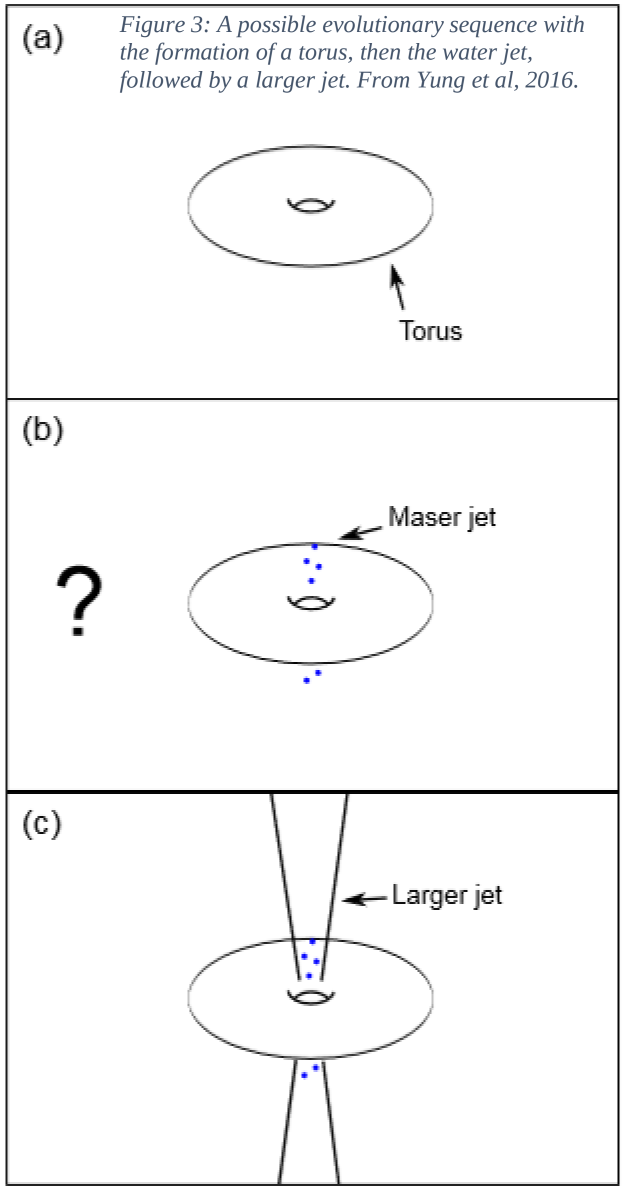
PN	Other name	OH Velocity range [km/s]	H_2O Velocity range [km/s]	Primary Reference
IRAS 15103-5754			75	Gómez et al. (2015a)
IRAS 15445-5449	OH 326.5-0.4		90	Deacon et al. (2007)
IRAS 15544-5332	OH 325.8-0.3		74	Deacon et al. (2007)
IRAS 16342-3814	OH 344.1+5.8		260	Claussen et al. (2009)
IRAS 16552-3050	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 18455+0448		12	38	Vlemmings et al (2014
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)

3. Future Research:

A recent study by Yung et al (2016) continues to cast doubt on the idea that WFs are at the beginning of the morphological transition. They performed a study of the Spectral Energy Density (SED) profiles of 17 WFs, and suggest that the masers could be objects from multiple stages of the metamorphosis. The main idea of their argument is that the masers we observe are not telling the whole story. We have been calculating the dynamical ages of WFs assuming that the maser emission is coming from the tip of a small jet, but it could well be that the masers are simply encased in a larger jet of other non-emitting material. This is plausible because the shell in which water is situated is at an intermediate distance, so it's likely that material on both sides of a water maser will get swept up in the jet. Figure 3 from Yung et al, (2016)

Figure 3: A possible evolutionary sequence with the formation of a torus, then the water jet, followed by a larger jet. From Yung et al, 2016.



shows a possible evolutionary sequence, though it remains unclear if the smaller jet must exist before the larger, or if they can form at the same time.

Clearly, more observation and theoretical work is required to complete our theory of PPNe. The pool of confirmed WFs is yet woefully small, and thus hard to perform any kind of real statistical analysis on. Yung (2016) suggest that the simple one-dimensional radiative transfer model they used will be helpful in the future to analyze WF data as it comes in.

As our telescope technology increases, resolution will get steadily better and we will be able to see considerably more structure in PNe and PPNe. In terms of magnetohydrodynamics, being able to resolve binaries in these systems would give vital information, as the theory doesn't currently allow for precessing jets (moving in a tight circle, forming a corkscrew of outflow) from a single-point system. Better resolution will give us greater insight into the dynamics of the CSE as the system undergoes its morphological shift. As of yet, we have only been able to resolve small-scale corkscrew structure in the closest PPN, and even then just slightly. Better observations will put significant bounds on our theories.

4. Conclusion:

Stellar evolution on the whole is a fairly well-understood process, but our theories are not perfect, or even complete. The specific mechanisms by which a spherically symmetric AGB star undergoes a drastic and unique morphological shift are yet unknown. Observational difficulty has led to a dark stage in stellar evolution, causing the beautiful and mysterious Planetary Nebulae. The work on this problem has given us a number of helpful clues and red herring alike. Water Fountains, as a window through the dust, may be the key to unraveling the true nature of PPNe.

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