Astrophysical Masers:
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Water masers as signposts of extremely young planetary nebulae

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Abstract. Only five planetary nebulae (PNe) have been confirmed to emit water masers. They seem to be very young PNe. The water emission in these objects preferentially traces circumstellar toroids, although in K 3-35 and IRAS 15103-5754, it may also trace collimated jets. We present water maser observations of these two sources at different epochs. The water maser distribution changes on timescales of months to a few years. We speculate that these changes may be due to the variation of the underlying radio continuum emission, which is amplified by the maser process in the foreground material.

Keywords. masers, stars: AGB and post-AGB, planetary nebulae: general

1. Introduction

Planetary nebulae (PNe) represent one of the last stages of evolution of low and intermediate mass stars ($\simeq 0.8 - 8$ M$_\odot$). The PN phase takes place after the Asymptotic Giant Branch (AGB) and a short ($10^2 - 10^4$ yr) transitional post-AGB phase. During the post-AGB phase the central start contracts and increases its temperature until it is hot enough to photoionize the circumstellar envelope expelled in previous evolutionary stages. This photoionization marks the entrance of a source to the PN phase.

Maser emission of different molecules (e.g., OH, H_2O, SiO) is widespread in oxygen-rich AGB stars (Lewis 1989), mainly tracing the (roughly spherical) expansion of the circumstellar envelope. Masers tracing collimated jets are observed in post-AGB stars, as in the case of "water fountain" stars (Imai 2007). However, maser emission is rare in PNe. So far, only 7 and 5 sources have been confirmed to harbor OH emission (Uscanga *et al.* 2012, Qiao *et al.* 2016) and H_2O masers (Miranda *et al.* 2001, de Gregorio-Monsalvo *et al.* 2004, Gómez *et al.* 2008, Uscanga *et al.* 2014, Gómez *et al.* 2015), respectively. No SiO maser has ever been detected in a PN.

In the particular case of water masers, those seen in AGB stars are expected to fade out in 100 yr after the end that phase (Lewis 1989). This timescale is shorter than the duration of the post-AGB phase. Therefore, the detected water masers in PNe are not the remnant of those pumped during the AGB, but are related to later outflow events. The scarce number of water-maser-emitting PNe (H_2O-PNe) and their tendency to be optically obscured (Suárez *et al.* 2009), strongly suggest that this emission is produced only during the short time period in the early stages of PN evolution.

Photoionization in PNe is a key differential factor with respect to sources in previous evolutionary phases that, in turn, can have a fundamental effect on maser emission. The presence of ionized material implies the emission of free-free radiation at radio wavelenghts. This emission can be strong, and favors the presence of maser emission since it acts as a background that can be amplified by foreground parcels of gas with inverted populations. Thus, maser emission can be present in PNe under physical conditions that would not produce it in the AGB or post-AGB phases. This complicates the interpretation of the morphology and kinematics of maser emission in PNe, since maser spots would tend to be distributed with the morphology of the background ionized region, but with the kinematics of the foreground molecular gas. Moreover, radio continuum emission in PNe is expected to significantly vary, as the photoionization proceeds along the envelope. This implies variation in flux density and distribution of the observed maser emission.

All H_2O-PNe have clear bipolar morphologies in radio, optical, and or/infrared images (Miranda *et al.* 2001, Gómez *et al.* 2008, Lagadec *et al.* 2011, Uscanga *et al.* 2014). Moreover, water masers in these sources tend to trace equatorial (toroidal) structures (with the noticeable exception of the two sources discussed below). This suggest that these particular sources are the result of the evolution of binary systems.

2. Monitoring water maser emission in PNe

We have observed water maser emission at 22 GHz in several H_2O-PNe over different epochs, using radio interferometers. Here we present some results for two of them.

2.1. *IRAS 15103-5754*

This is probably the youngest PN known. It is the only one whose water maser emission is spread over a large velocity range ($\simeq 75$ km s^{-1}, Suárez *et al.* 2009, Gómez *et al.* 2015), significantly larger than expected from the expansion of a circumstellar envelope. Therefore, it is the only water fountain that has already entered the PN phase. Moreover, it is the first PN in which non-thermal radio continuum emission has been confirmed (Suárez *et al.* 2015). This radio continuum emission shows a significant variability both in flux density and spectral index, and it has been interpreted as synchrotron emission being suppressed by a growing ionized region.

The maser distribution observed in 2010-2011 (Gómez *et al.* 2015) was dominated by a blueshifted jet to the northeast, nearly aligned with the infrared nebula (Lagadec *et al.* 2011). It showed a linear velocity gradient with highest velocities farther away from the star, which suggest an explosive collimated mass-loss event.

We have monitored the water maser emission in IRAS 15103-5754 with the Australia Telescope Compact Array (ATCA). The spatial and kinematical distribution changes significantly in timescales < 1 year (Fig. 1). While it shows an elongated distribution, suggestive of a jet, its orientation changes gradually with time. It is still roughly aligned with the infrared nebula in August 2014, but is almost perpendicular to it in May 2016. This could indicate a large precession of a jet, but the well-defined orientation of the innermost region of the infrared nebula does not seem consistent with a such a precessing jet. We speculate that the changes in the emission are due to changes in the background radio continuum emission. In this scenario, the radio continuum would trace shocks in a collimated jet in the first epochs. A growing ionization of a circumstellar torus would induce an increasing contribution of free-free emission in the equatorial direction. This change in background continuum would produce a change in the masing areas of the foreground surrounding medium. A continuing monitoring of the maser emission would help to ascertain whether we are witnessing the transition of maser distribution from tracing a jet (as in post-AGB water fountains) to a toroid (as in other water-maser-emitting PNe).

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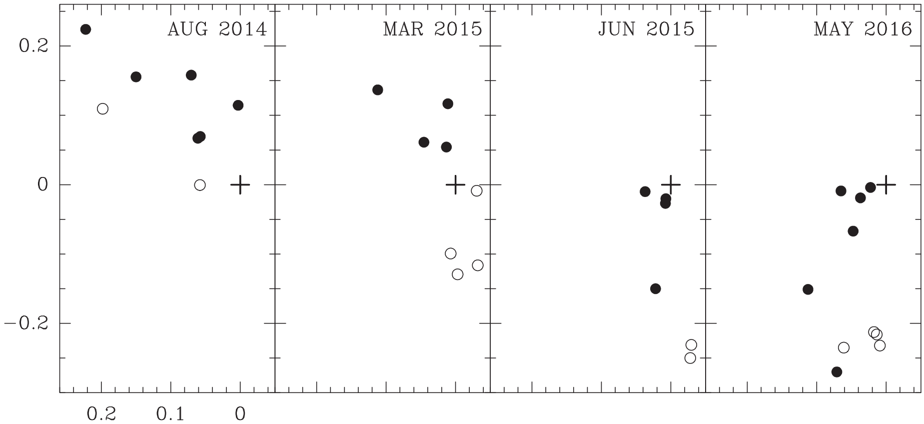

Figure 1. Distribution of water maser components in IRAS 15103-5754 in different epochs. Filled and open circles represent blue- and redshifted components, with respect to the central LSR velocity of the system (-33 km s^{-1}, Gómez *et al.* 2017). The cross marks the centre of the radio continuum emission at 22 GHz. Axis coordinates are offsets (in arcseconds) with respect to the radio continuum position.

2.2. *K 3-35*

K 3-35 was the first PN in which the presence of water maser emission was confirmed (Miranda *et al.* 2001). This emission traces an equatorial torus in the central region, similar to other H_2O-PNe. However, some maser components are located at the tip of the ionized nebula traced by the radio continuum emission.

The water masers also show an interesting short-time evolution, which we have studied with observations with the Very Large Array (VLA). Regarding the masers at the central core of the object (Fig. 2, left), those observed in 1999 can be fitted to an expanding and rotating toroid, with velocities 1.4 and 3.1 km s^{-1}, respectively (Uscanga *et al.* 2008). However, later observations show a distribution that is not consistent with the masers tracing the same spatial and kinematical structure (de Gregorio-Monsalvo *et al.* 2004). Our newest VLA observations (carried out in 2015) still show an equatorial structure, but extending over a larger extent ($0.07'' = 290$ AU, at a distance of 3.9 kpc, Tafoya *et al.*2011) than expected from the expansion velocity determined by Uscanga *et al.* (2008). A possible explanation is that the changes of the maser distribution are not due to motions of the masers themselves, but to changes in the excitation conditions in the gas and/or in the background continuum. In this scenario, the masers could be tracing shocked regions progressively farther away from the central star, as the ionization front progresses along a circumstellar toroid. Alternatively, it could be foreground gas that produces detectable maser emission as it amplifies a growing ionized region in a toroid.

In addition to these central water masers, the observations in 1999 revealed some components on both sides of the bipolar nebula, at the tips of the radio continuum emission, which coincide with bright optical knots in optical images. This bipolar maser distribution did not appear in the observations in 2002, nor in the VLBI observations of Tafoya *et al.* (2011). However, it reappeared in our latest 2015 observations (Fig. 2, right), at positions close to, but not exactly coincident with those seen in 1999. The most straightforward explanation would be that these masers are tracing shocks at the tips of a bipolar jet. However, a proper interpretation depends on an accurate determination of the velocity of the central star. As discussed in Qiao *et al.* (2016), it is unclear whether the central LSR velocity is 23 or 10 km s^{-1}, although these authors favored the later, which is

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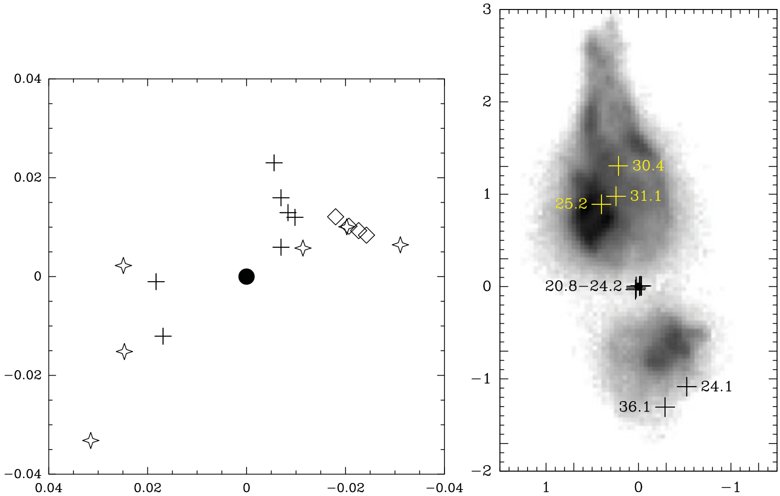

Figure 2. Water maser distribution in K 3-35. Left: maser components in 1999 (crosses, Miranda *et al.* 2001), 2002 (squares, de Gregorio-Monsalvo *et al.* 2004) and 2015 (starred polygons) at the central part of the nebula. The filled circle represents the center of the radio continuum emission. Right: Water maser components in K 3-35 (crosses) observed in 2015, overlayed on a Hubble Space Telescope Image in the F658N filter (which mainly covers the [NII] 6583 Å emission line). The labels represent the LSR velocity of the maser components. Axis coordinates in both panels are offsets (in arcseconds) with respect to the radio continuum position.

based on optical spectroscopy (Miranda *et al.* 2000). If this is the case, all water masers in K 3-35 are redshifted, which challenges any easy explanation. Assuming a velocity of 23 km s^{-1} seems easier to reconcile with the central structure being a circumstellar toroid, but the masers at the lobes are still redshifted on both sides of the nebula. A possible explanation could be that the masers at the lobes are tracing shocks of a wind with a large opening angle, and that only the rear side of the wind is exciting masers, due to an asymmetric density distribution in the circumstellar gas.

These results suggest that short-time variations of the distribution of water masers may be a specific differential characteristic of H_2O-PNe.

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