*Cosmic MASERs: From Protostars to Blackholes*
*IAU Symposium, Vol. 206, 2002*
*V. Migenes and M. J. Reid, eds*

# Interferometric observations of OH and $H_2O$ masers in protoplanetary nebulae imaged with HST - A unique diagnostic of their spatial-kinematic structure

Raghvendra Sahai

*Jet Propulsion Laboratory, California Institute of Technology, MS183-900, 4800 Oak Grove Drive, Pasadena, CA 91109*

Mark J. Claussen

*NRAO, Socorro, NM 87801*

Mark Morris

*University of California, Los Angeles, CA 90095*

**Abstract.** One of the most exciting challenge facing theories of post-main sequence evolution today is to understand how Asymptotic Giant Branch (AGB) stars transform themselves into aspherical planetary nebulae (PNe). Recently, high-resolution imaging surveys of young planetary nebulae and protoplanetary nebulae (PPNe: objects in transition between the AGB and PN phases) have revealed that the majority of these objects are characterised by multipolar bubbles distributed roughly point-symmetrically around the central star. These data strongly suggest that the current model for the shaping of PNe is no longer adequate. High angular-resolution kinematic information is sorely needed to complement the imaging data in order to test new hypotheses, such as our proposal that episodic high-speed jet-like outflows, operating during the protoplanetary or very late-AGB phase, are the primary agent.

We have therefore begun a program of using interferometric mapping of OH (and $H_2O$, when feasible) maser emission in order to trace the kinematics of the structures discovered in protoplanetary nebulae with *HST*. These masers provide a unique and crucial probe of the kinematics of the circumstellar material in PPNe, because of the lack of other emission-line diagnostics. Although our work is still in its infancy (only two objects have been studied in detail), we find that the OH masers indicate the presence of multiple low-latitude outflows and an increase of outflow velocity with latitude. This paper summarises our progress so far, the state of current studies, and future prospects.

## 1. Introduction

Ordinary stars undergo extraordinary deaths, enriching the ISM with material – dust grains, carbon and nitrogen – necessary for the formation of a new



https://doi.org/10.1017/S0074180900222705 Published online by Cambridge University Press

generation of Sun-like stars and planets, and life. Planetary nebulae (PNe) evolve from such stars (with masses $\sim 1 - 8\,M_\odot$), following intense mass loss ($10^{-5}$–$10^{-4}$ $M_\odot\,\mathrm{yr}^{-1}$) during the Asymptotic Giant Branch (AGB) phase of stellar evolution. Ground–based imaging surveys have shown that, even though PNe evolve from AGB stars with mostly spherically–symmetric circumstellar envelopes (CSEs), the vast majority ($\sim$ 80%) of PNe deviate from spherical symmetry (e.g. Schwarz, Corradi, & Melnick 1992); a result that has been dramatically confirmed by Hubble Space Telescope (*HST*)/Wide Field & Planetary Camera 2 (WFPC2) imaging (Sahai & Trauger 1998).

The challenge before us is to determine the physical mechanisms responsible for the dramatic transformation in the symmetry of the ejected matter as the central star evolves from the AGB to the nucleus of a PN (i.e. a white dwarf). Recently, *HST* imaging surveys of young planetary nebulae and protoplanetary nebulae (PPNe: objects in transition between the AGB and PN phases) have revealed that the majority of these objects are characterised by multipolar bubbles distributed roughly point-symmetrically around the central star. These surveys have wrought a virtual renaissance in our understanding of PN formation. We have proposed that hydrodynamic sculpting of the progenitor AGB envelope by episodic high-speed jet-like outflows, operating during the protoplanetary or very late-AGB phase, is a significant mechanism for shaping PNe (Sahai 2000).

In order to test this and other hypotheses for the shaping of PNe related to binarity, accretion disks, and magnetic fields (e.g. Mastrodemos & Morris 1998; Livio 1993; Garcia-Segura 1997), it is necessary to carry out high angular-resolution ($\sim$50 mas) observations of both the morphology and kinematics of young PNe and PPNe. Although many *HST* imaging studies of such objects have been made, spectroscopic observations to determine the kinematics with comparable resolution have been sorely lacking. Fortunately, for young PNe and PPNe which show OH and/or $H_2O$ maser-line emission, ground-based interferometric observations with large arrays (e.g. the VLA) can provide such complementary, high velocity-resolution ($\sim\mathrm{km\,s^{-1}}$) kinematic data. Here we review results from a recently-begun effort to combine *HST* images and interferometric OH maser-line data in order to unravel the detailed structure of PPNs.

## 2. The morphology and kinematics of PPNe

The "Water-Fountain Nebula", IRAS16342-3814 (hereafter IRAS1634) is a PPN belonging to a small class of unusual evolved stars with high velocity outflows traced in either or both of radio $H_2O$ and OH maser line emission (Likkel & Morris 1988; te Lintel Hekkert et al 1988). IRAS16342 has a very red IRAS LRS spectrum suggesting that it has evolved off the AGB in the last few hundred years (Sahai et al. 1999a). Roberts 22 is a bipolar reflection nebula around a more evolved central star (which is not visible, but a spectral type of A2 I is inferred from the spectrum of scattered starlight from the nebula), and has broad H$\alpha$ emission with wings extending to $\pm$450 $\mathrm{km\,s^{-1}}$, showing the presence of a high-speed outflow (Allen, Hyland & Caswell 1980). The *HST* images of these PPN clearly show bipolar nebulae with two bright lobes separated by a dark waist (Sahai et al. 1999a,b). In IRAS1634, the high-velocity OH features (with projected outflow velocities up to $\sim$70 $\mathrm{km\,s^{-1}}$) are clustered around the base of the lobes and low velocity features are found near the waist (Fig. 1). Using the OH data, we estimate an inclination of the nebular axis relative to the line-of-sight, of $\sim$50°, implying that the deprojected outflow velocities of the OH maser spots are as high as $\sim$110 km s$^{-1}$. In Roberts 22, the OH masers are of relatively low velocity and found mostly in the vicinity of the dark waist (Fig. 2). The **spatial-kinematic** distribution of the OH masers relative to the optical structure in these objects is consistent with the hypothesis that the optical lobes are produced as a result of fast collimated outflows interacting with the dense, slowly expanding AGB wind to produce a radial velocity which increases from the equator to the poles. The fast outflow is more complex than a single collimated outflow along the polar direction, and is likely to be constituted of multiple outflows with different axes, with the most dominant of these being clustered around the polar direction. A possible evolution of such outflows is indicated by the differences between Roberts 22 and IRAS1634 – in the former, the total velocity extent of the OH masers is significantly smaller and much more confined to low latitudes. However many more objects need to be observed in order to establish and understand this evolution.

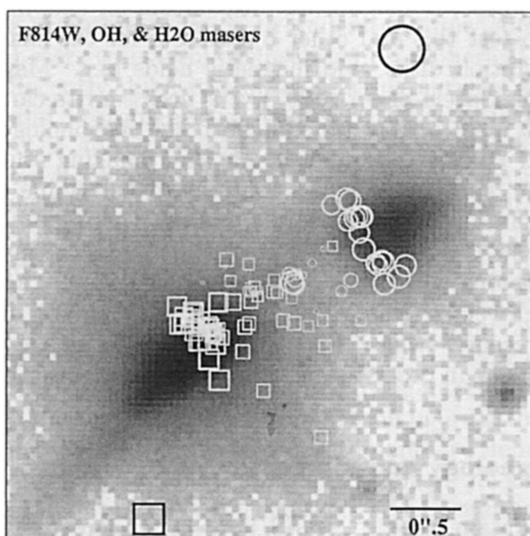


Figure 1. HST/WFPC2 scattered-light image (reverse grey-scale) of IRAS16342-3814 overlaid with locations of OH 1612,1665, & 1667 MHz maser emission features measured with the VLA. Blue (red)-shifted OH (white symbols) & $H_2O$ (black symbols) features, covering a range of 135 (246) km s$^{-1}$ are shown as squares (circles) with sizes proportional to the velocity offset from the systemic velocity (partly adapted from Sahai et al. 1999a)

Water masers are also present in several of the systems under study, but they apparently sample a different (probably faster) component of the outflow. In IRAS1634, the extremely high-velocity $H_2O$ masers, at $\pm$130 km s$^{-1}$, are expected to arise in the post-shock region where the highest velocity portion of the polar jet strikes the prior AGB wind (Likkel & Morris 1988). Recent data from our program of VLA/ VLBA observations of the $H_2O$ maser emission in IRAS1634 and related PPN appears to confirm this expectation; surprisingly, we find that the axis defined by the $H_2O$ maser spots is, astonishingly, not aligned with the optical axis, but inclined to it at ~30°(Fig. 1), strongly indicating that the high-velocity jets which created the lobes change their direction. (We have *assumed* that the geometrical centers of the $H_2O$ maser emission and the optical nebula coincide because of currently unresolved uncertaintes in the absolute position of the $H_2O$ maser spots.)

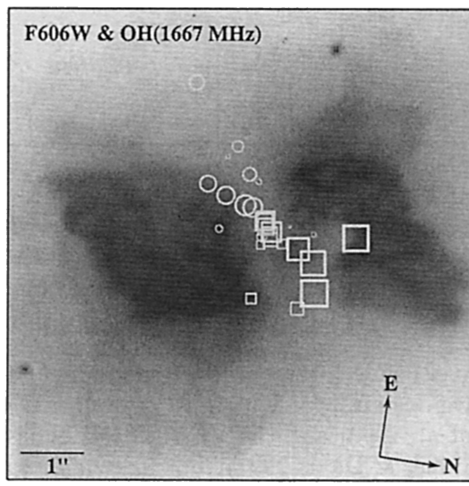


Figure 2. HST/WFPC2 scattered-light image (in reverse grey-scale) of Roberts 22, overlaid with the locations of the OH 1667 MHz maser emission (observed with ATCA). OH features, covering a range of $54\,\mathrm{km\,s^{-1}}$, are coded as in Fig. 1 (adapted from Sahai et al. 1999b)

The G-type evolved star HD179821 (also AFGL2343) has nearly the coldest colors of any evolved star, very large systemic ($100\,\mathrm{km\,s^{-1}}\,V_{LSR}$) and outflow velocities ($V_{exp}$=$32\,\mathrm{km\,s^{-1}}$), a large detached dust shell and a high mass-loss rate ($\sim 10^{-4}\,M_{\odot}\mathrm{yr}^{-1}$). Although it has been argued that HD179821 is a massive red supergiant based on its kinematics (Jura & Werner 1999), we believe that it is more likely to be a low-mass post-AGB star from its chemical composition (Thevenin, Parthasarathy, & Jasniewicz 2000). The *HST* scattered-light image of HD179821 shows several distinct, roughly concentric (but with noticeable distortions from circularity) brightness edges and at least four prominent lobe-like protrusions. Much of the OH 1612/1667 MHz emission is distributed in a ring-shaped structure (Fig. 3). The spatial-kinematic structure of the OH emission clearly shows that the nebula does not have a spherical shell geometry because the decrease of the OH ring radius from the line-center to the line-wings is much slower than expected for a spherical shell. A prolate pole-on geometry is the simplest model which provides a good fit to the data.

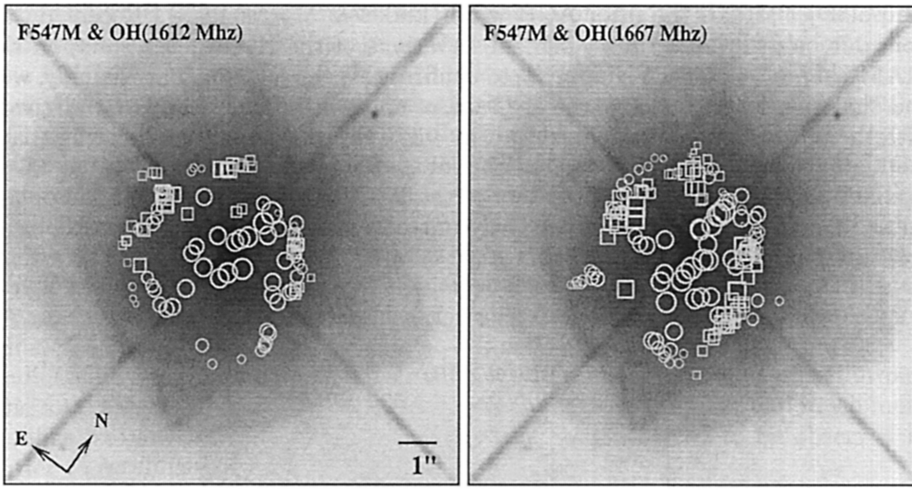


Figure 3. HST/WFPC2 scattered-light image (reverse grey-scale) of the protoplanetary nebula HD179821 overlaid with locations of OH 1612 & 1667 MHz maser emission features measured with the VLA. OH features, covering a range of 60 km $s^{-1}$, are coded as in Fig. 1

There are two other well-studied protoplanetary nebulae – He 3-1475 and M 1-92 – which have been imaged with *HST* (Borkowski, Blondin, & Harrington 1997, Bujarrabal et al. 1990) and the VLA (in OH emission) (Bobrowsky et al. 1995, Seaquist, Plume, & Davis 1991), but for which a detailed comparison of the VLA and *HST* data has not been made.

## 3. Future Prospects

We aim to extend the combination of *HST* and interferometric radio-wave OH (& $H_2O$) imaging as described above, to a significantly larger sample of PPNe. This work will include those PPNe which have already been imaged with one, but not both of the above, techniques. We have obtained observing time on the HST to carry out a SNAPshot imaging survey of 17 PPNe which have been detected in OH maser line emission. We are (and will be) requesting VLA/MERLIN/ATCA and VLBA time to map the latter in the current and upcoming proposal cycles. For selected objects (like IRAS1634) we intend to obtain multi-epoch VLBA data in order to measure the *vector proper motions* of the masers, enabling us to locate the central outflow sources in, and better constrain the very poorly known distances to, these objects. Many of these PPNe are detected (or potentially detectable, based on their relatively strong IRAS fluxes) in millimeter-wave maser and non-maser lines of molecules like CO, SiO, HCN, & HCO+. The *HST*/radio observations discussed in this paper will provide us a list of ideal targets for study with future large millimeter-wave interfrometers (e.g. the ALMA facility in Chile).

*Acknowledgments*: R.S. and M.M. have been partially supported for this work by NASA through a Long Term Space Astrophysics grant (no. 399-20-61-00-00).

## References

Allen, D.A., Hyland, A.R., & Caswell, J.L. MNRAS, 1980, 192, 505

Bobrowsky, A., Zijlstra, A.A., Grebel, E.K., Tinney, C.G., te Lintel Hekkert, P., Van de Steene, G.C., Likkel, L., & Bedding, T.R. 1995, ApJ, 446, L89

Garcia-Segura, G. 1997, ApJ, 489, L189

Jura, M. & Werner, M.W. 1999, ApJ, 525, L113

Likkel, L., & Morris, M. 1988, ApJ, 329, 914

te Lintel Hekkert, P., Habing, H.J., Caswell, J.L., Norris, R.P., & Haynes, R.F. 1988, A&A, 202, L19

Livio, M. 1993, in IAU Symposium No. 155, "Planetary Nebulae", (Kluwer Academic Publishers: Dordrecht) eds. R. Weinberger & A. Acker, pp. 279

Mastrodemos, N. and Morris, M. 1998, ApJ, 497, 303

Sahai, R. & Trauger, J.T. 1998, AJ, 116, 1357

Sahai, R., te Lintel Hekkert, P., Morris, M., Zijlstra, A., Likkel, L. 1999a, ApJ, 514, L115

Sahai, R., Zijlstra, A., Bujarrabal, V., te Lintel Hekkert, P. 1999b, AJ, 117, 1408

Sahai, R. 2000, in *Asymmetrical Planetary Nebulae II: From Origins to Microstructures*, Eds. J.H. Kastner, N. Soker & S.A. Rappaport, ASP, 199, 209

Schwarz, H.E., Corradi, R.J.M. & Melnick, J. 1992, A&AS, 96, 23

Seaquist, E.R., Plume, R., & Davis, L.E. 1991, ApJ, 367, 200

Thévenin, F., Parthasarathy, M., & Jasniewicz, G. 2000, A&A, 359, 138