

# Unraveling the histories of pre planetary nebulae

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**Abstract.** HST images of pre planetary nebulae (pPNe) show a mesmerizing array of highly symmetric bi-lobed morphologies with pinched waists. I shall review the results of detailed Hydrodynamical model studies that nicely match the observed structures and reveal the outflow histories and the geometry of the nuclear outflows of two prePNe.

## 1. Introduction

The general shaping processes of mature planetary nebula have been very thoroughly investigated starting with [1] and continuing with the exquisite 1-D radiation hydro models of the Potsdam group and the two-dimensional simulations of Adam Frank, Vincent Icke, Garcia-Segura, van Marle, many other people and their many collaborators. This field of research has matured very nicely in recent years. With apologies to authors not mentioned, space limitations prevent me from a suitable literature review.

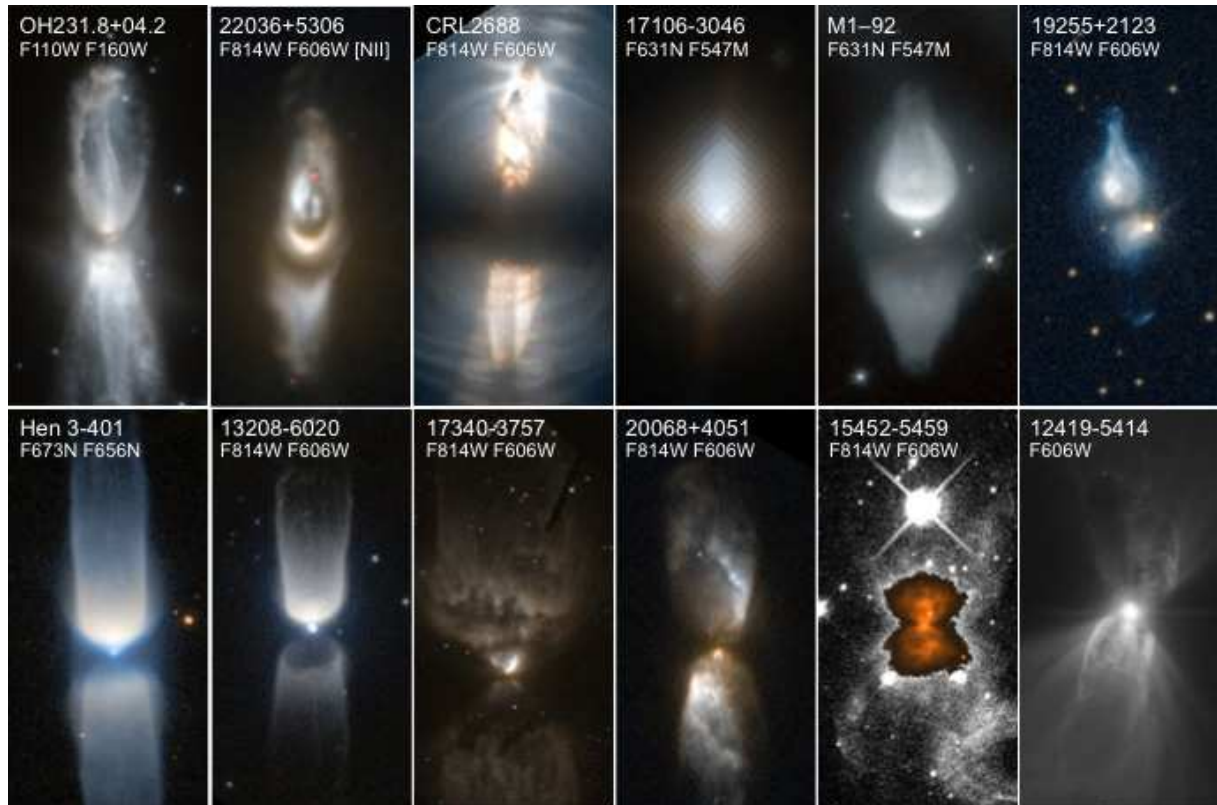
However, in the past decade it has been possible to probe the precursors or planetary nebulae, called pre planetary nebulae, or simply pPNe in this paper. These provide us with a powerful opportunity to trace the evolution of PNe in their infancy and prior to the disruptive effects of ionization, fast and sustained stellar winds, and the shocks and pressure waves that reverberate through the structures of more mature counterparts. This is vital since the underlying astrophysical question is how the stellar outflows of highly evolved stars are formed and collimated to shape the bi-polar pPNe.

Bipolar pPNe pinched waists and generally dark equatorial waistbands comprise the largest single segment,  $\approx 50\%$ , of the prePN population. Owing to their highly symmetric and articulated structures they are also the most opportune targets for understanding collimation processes in post-AGB stars, processes which have remained enigmatic despite a decade of talks, meetings, MHD simulations, and a new generation of very elaborate 3-D hydro simulations of outflows in close binary stars (Huarte-Espinosa et al., 2014[2], and refs within). That is, we are yet to find a flow paradigm that nicely encompasses the essential features of detailed observations of the structure and flow dynamics of pPNe. Indeed, we still don't know whether the equatorial disks and waistbands actively shape the polar outflows or are mere bystanders in the story of late stellar evolution and lobe formation.

Along with Adam Frank, Martin Huarte-Espinosa, Baowei Liu, and several students I have recently endeavored to match details HST images of some bipolar pPNe with the results of hydro simulations (without magnetic fields). A montage of the best-resolved bipolar pPNe is shown in Fig. 1. The subjects of this study are, for now, constrained by the images and by 2-D observations of their projected flow patterns (that is, images of the density as well as Doppler shifts). That is,



the observational data give a reasonably complete picture of the essential hydro state variables, the density and momentum distributions. In a few cases localized radiation from shocks that lie between important parts of the lobes have been used to inform the models of radiative energy losses. The thermal pressure distribution within the flow is not directly measurable at this time since the most omnipresent line ratios that might reveal the temperatures arise in localized shocks or in the cold molecular gas that girds the lobes. However, the images are better fitted by models in which the thermal pressures are less than ram pressures, but not vice-versa.



**Figure 1.** Examples of bright and well-resolved pPNe from HST images in scattered starlight. The colors arise from superimposing images of various filters (indicated) into image planes in Photoshop and adjusting the contrast until that stars are white.

## 2. General conclusions

There are some very important general conclusions to be made before describing the detailed models. For starters, most lobes that are seen in reflected starlight and molecular emission appear to be hollow (strongly edge-brightened), so that the vital medium that flows through them is not an observable. Rather we see their edges, generally in starlight that is reflected from their flow-compressed boundaries. It is these edges, their loci, and their Doppler shifts that we fit with models.

In addition the innermost portions of flows driven by sustained winds are also the youngest, most recently emerged gas and dust. Furthermore, the density structure of the environment is a vital part of the shaping story. That is, once the densities in the diverging flows drop to about the density of the ambient gas they begin to slow down as they accrete upstream gas of low specific momentum. Such lobes will have thin leading edges where the upstream gas is being accreted and “pushed” forward to “plugs”. Shocks will lie on both sides of the plugs.

The forward shock has a speed of the plug speed (which declines with time). The speed of the reverse shock will be the difference of plug and wind speed and will increase with time. The fastest shock will appear along the leading (trailing) edge of the plug when the flows are young (old).

As a rule, we also find that the ambient medium falls off in density as about radius squared. Highly collimated (slowly diverging) flows can penetrate far into the ambient medium at steady speed, much more so than very divergent flows of the same initial momentum flux. In contrast, the edges of blunt flows are impeded and decelerated by the accumulation of the far slower ambient medium.

Finally, after a lengthy parameter study, we have learned that *diverging flows in which the low momenta are concentrated to the polar axis* (more specifically, fall off in zenith angle with a Gaussian form; e.g., [3]) *are the only way to match the flame-like shapes seen in Fig. 1*. We shall use the term “centrally concentrated sprays” for this type of flow to distinguish it from wide-angle flows of uniform density and speed that produce simple pie-wedge-shaped lobes. Pencil-jet flows never fit the HST images.

Another very important result for observers is the flow speed. Many observers have found that their Doppler images show a pattern of linearly increasing Doppler shift with distance from the flow origin. From this they (wishfully) conclude that the flow is ballistic (aka “Hubble-like”), as if the outflow is the result of a brief eruption and not the work of steady winds of roughly constant speed. (Appearances can be deceiving!) However, outbursts inject clumps, and the hydrodynamic evolution of clumps is quite different than that of steady flows.<sup>1</sup>

Our simulations in which the outflow is a centrally concentrated spray show something quite different. In such cases the hot, fast from the advancing tip of the candle-shaped lobe generates a backflow of steadily decelerating speed as it continually mixes with very slow ambient gas. The inevitable, robust result is a thermally cooling zone in the stagnation zone or pocket that trails the leading edge and where gas in the winds mix with slower ambient gas. Emission lines in this zone will display a steady speed gradient with distance behind the head of the lobe.

### 3. A case study

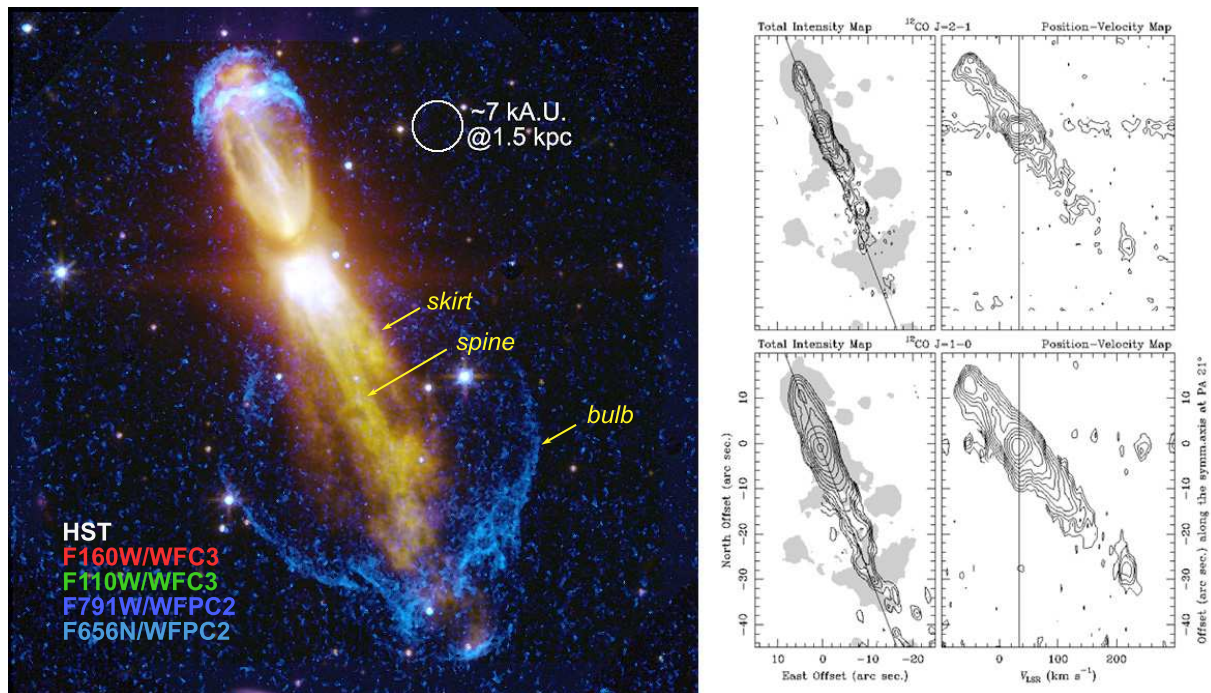
I presented three case studies in my talk. However I will only present one such study here owing to space limitations. The target is the pPN associated with intensively studied southern lobe of OH231.8+04.2, an OH-IR star. To save space I will list the references but not cite specific results. The optical and IR images are extracted from the Hubble Legacy Archive.<sup>2</sup> The maps of the kinematics that I will use here are <sup>12</sup>CO observations from Alcolea et al. 2001, hereafter A+01[4]. Note that the CO emission is restricted to the narrow spine of reflecting dust on the symmetry axis. Our first goal is to simulate the spatial and kinematic structure of the southern lobe. We will consider the bulb separately.

We have successfully simulated the structures of both lobes of OH231 by launching clumps of two types into a stationary ambient medium whose density declines as radius<sup>-2</sup>. We will report the work for only the southern lobe (Fig. 3). The mass in the external medium is 0.1 M<sub>⊙</sub>. The momentum flux and speed of the flow match the results of A+01. Since the tip of both lobe tips have a diameter of 7AU we ran models of a cold clump of that radius and a hot clump model in which the clump thermally expands to that size. Both clumps are launched with core densities of  $\approx 10^{4.5} \text{ cm}^{-3}$ .

Observationally the two sets of models give nearly indistinguishable results. Both leave “contrails” that match the observed shape of the lobe. Both have dense axial spines, and both

<sup>1</sup> While eruptions and clumps might be viable, as they are in  $\eta$  Carinae and OMC-1, theory and the examples of spiral flows favor less exotic modes of continuous mass loss for AGB stars. However, the jury is out.

<sup>2</sup> The HLA is a joint project of the Space Telescope Science Institute (STScI), the Space Telescope European Coordinating Facility (ST-ECF), and the Canadian Astronomy Data Centre (CADAC).



**Figure 2.** Left: Color overlay of images taken using the WFC3 camera on HST. The color code is indicated in the legend. The lobes (shown in yellow) consist of dust-scattered starlight. The bulb is outlined only in shock-excited H $\alpha$ . Right: spatial (left panels) and kinematic images (right panels) in  $^{12}\text{CO}$   $J = 0 - 1$  (top) and  $J = 2 - 1$  (bottom) from [4]. The linear kinematic pattern is not that of a jet (constant speed with radius). The kinematic age of the P-V slope is 770y at a distance of 1.5 kpc.

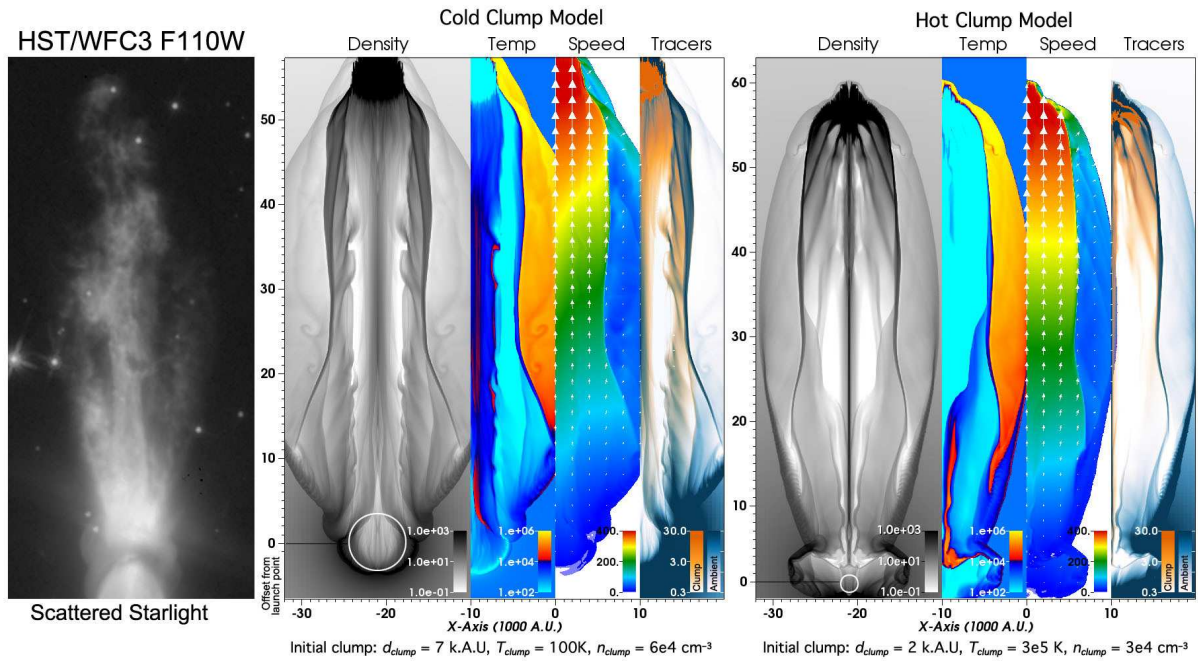
show linearly decreasing speed changes with offset that match the position-velocity pattern of  $^{12}\text{CO}$  observations. One problem with the large cold clump is that its radius exceeds the width of the core seen in HST images. One nice feature of the hot clump is that the simulations match the bowl” at the base of the flow better than does the cold clump model. Both show hot leading tips ( $\approx 10^6$  K) that expand laterally into the ambient gas as the tip advances onward. However, these hot backflows do not mimic the dimensions of the bowl. If we reduce the external density to “fatten” the bulb then other problems arise. In particular, the lobe also fattens unacceptably.

The bulb is easily simulated using the same ambient gas parameters as before, a spray of initial density of  $10^5 \text{ cm}^{-3}$ , and an initial outflow speed that matches that of the clump. These parameters are consistent with the CO observations of A+01. However, the lobes and the bulb really must be modeled as a single, interacting dynamical system. We are pursuing this now.

#### 4. Conclusions

The characterization of outflows is our ultimate goal. Of course, case studies are of interest since they can demonstrate whether the physics of simulations are appropriate, provide feedback on the choice of outflow paradigm, and help to interpret detailed observations. However, we intend to simulate a variety of other well-studied pPNe in order to develop a general sense of the outcomes of the flow collimator, an important feature that is too small to be directly observed. So far we have successfully simulated CRL618 [5] and are close to finishing models for PN M2-9. We will report on these and other models in due course.

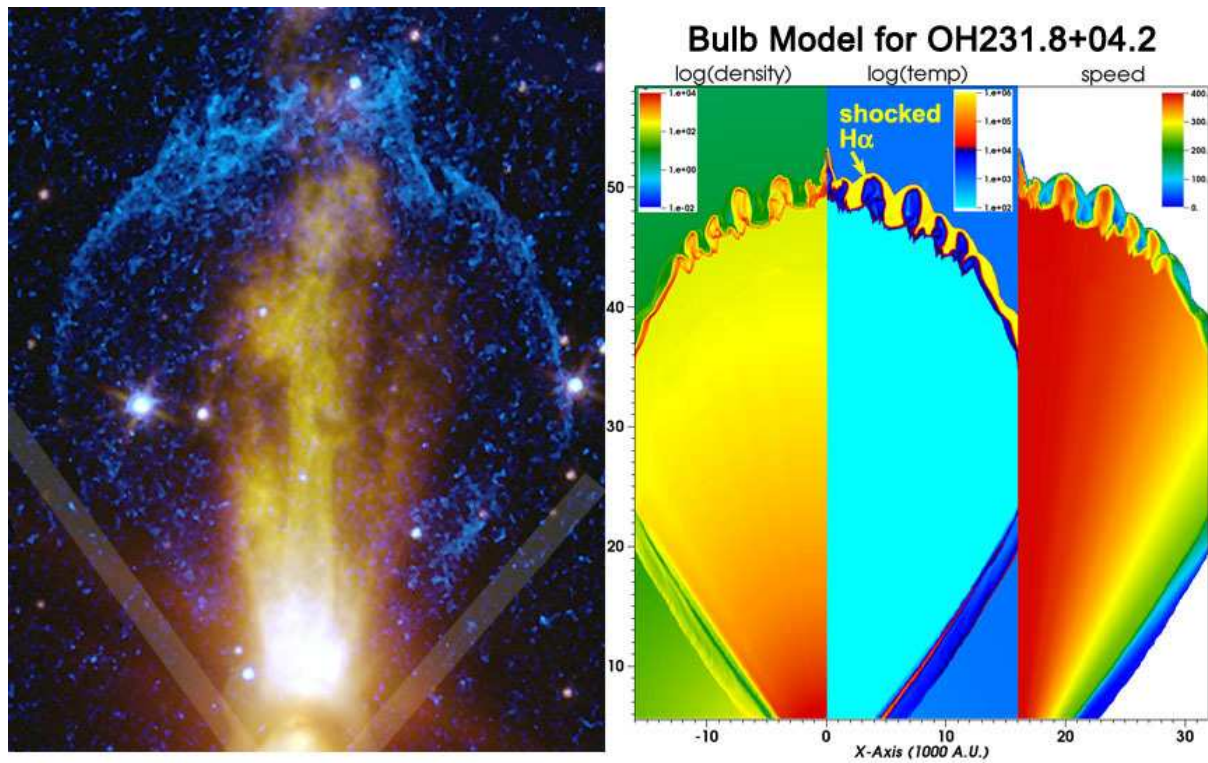




**Figure 3.** Left: F110W image of the southern lobe of OH231. Right: models of cold and hot clumps at the same spatial scale as the HST image (note the small vertical offsets). The four subpanels are, from left to right, log density, log temperature, flow speed, and tracers that show the location of the gas initially located in the ambient medium (blue) and clumps (orange).

## References

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**Figure 4.** Left: Composite image of the southern bulb, much as in Fig. 2. Right: the hydro simulation that matches the shape of the bulb. The outflow is a centrally concentrated spray with a full opening angle of  $40^\circ$  within which the flow momentum is tapered by a Gaussian of  $1/e$  width of  $60^\circ$ . This matches the straight bulb edges in the lower half of the image while providing the round, ruffled shape of the leading part of the bulb.