Models of the Mass-ejection Histories of Pre-planetary Nebulae. III. The Shaping of Lobes by Post-AGB Winds

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Abstract

We develop a physical framework for interpreting high-resolution images and kinematics of pre-planetary nebulae ("prePNe"). We use hydrodynamical models to infer the historical properties of fast collimated nuclear flows ("jet") that successfully form hollow, candle-shaped lobes over ≈103 yr, including the density, momenta, and geometry of the jet and its environment. Next we vary the most influential parameters of this "baseline" model to investigate how changes in the flow parameters affect the model outcomes after 900 yr. Several generic conclusions emerge, such as the injected flows that create the hollow lobes must be light, "tapered," and injected considerably faster than the lobe expansion speed. Multipolar and starfish prePNe probably evolve from wide-angle flows in which thin-shell instabilities corrugate their leading edges. We show how the common linear correlation of Doppler shift and position along the lobe is a robust outcome of the interaction of tapered diverging streamlines with the lobes’ curved walls. Finally, we probe how modest toroidal magnetic fields added to the fast flow affect the outcome of the baseline model. We conclude that the light, field-free, tapered baseline flow model is not only a successful and universal paradigm for unraveling the histories of lobe formation in prePNe, but also provides a comprehensive, inclusive framework for understanding the details of the shapes, sizes, and internal kinematics of their edges.

Key words: ISM: jets and outflows – planetary nebulae: general – stars: AGB and post-AGB – stars: winds, outflows

1. Introduction

Pre-planetary nebulae ("prePNe") are a formed shortly after the end of the AGB evolutionary phase. We presume that prePNe are formed by fast, collimated outflows, or "jets," that are injected into very slow, isotropic "winds" from an AGB star (Höfner & Olofsson 2018) at speeds of 100 km s−1 or more. The jets steadily displace ambient gas downstream to excavate hollow, candle-flame-shaped lobes.

A gallery of the brighter and most representative prePNe are shown in Figure 1. Their kinematics and sizes suggest that prePNe such as these have ages ≈103 yr. The hollow lobes in these images require that the jet is invisible, even in scattered light from embedded dust. The lobes’ widths, lengths, and rounded edges place strong constraints on the geometry and momentum flux of the collimated flow that shaped them.

New hydro- and magneto-hydrodynamic ("HD" and "MHD," respectively) simulations, coupled with new observational tools coming on line in the next 10 years (Figure 2), will be providing an exciting opportunity to recreate the formation and shaping mechanisms of collimated post-AGB mass loss. Our simulations—all of which are heavily constrained by recent measurements of prePNe—are intended to bridge the gap in knowledge from the present to within ≈102 yr after shaping began.

To that end we will use realistic using data-constrained hydrodynamic models that match present observations of the lobes to predict the evolving geometry, density, and speed of the shaped lobes at a resolution of 1 kau (1000 au, or 2× at a distance of 2 kpc). The basic model (Section 2) and the parameter studies (Sections 3 and 4) provide a foundation of reference images for new observations as new observing facilities come on line over the next decade.

The current ideas of PN formation date back to Morris (1987) and took their present forms by about 2000 (see the review by Balick & Frank 2002). Many hydrodynamic simulations of prePNe have appeared (see the summary or recent models by Akashi & Soker 2018) after this review was published. Based on patterns gleaned from the outflows of OH/IR stars, Zijlstra et al. (2001) developed the first analytical description of bipolar lobes formed by fast flows into AGB winds. Since then, various numerical simulations of bipolar prePNe have appeared. Here we mention a few with the greatest impact. Soker (2002) and Lee & Sahai (2003; hereafter “LS03”) ran hydrodynamic models of lobes created by collimated fast winds that penetrate into the slower and denser AGB wind surrounding the nucleus. LS03 showed that low-density “tapered” conical steady flows, similar to a spray, injected at constant speed will encounter and shock the displaced ambient gas and develop a quasi-linear Doppler speed versus distance relation along the lobes’ walls. (This important result has not been appropriately recognized.)

Akashi & Soker (2008) examined short-duration jets (aka “bullets” and “clumps”) using a very general numerical methodology. Their paper contains some significant insights into large-scale shapes and the onset of surface instabilities that appear along the outer boundaries of lobes. They were also the first to define the concepts of “light” and “heavy” collimated flows. A light (heavy) flow is one in which the flow density is less than (greater than) that of the local ambient medium. Light flows produce hollow lobes bordered by dense walls of displaced gas. They interact strongly with the inertial pressure...
downstream and can be influenced by the density distribution of their surroundings. Eventually, the lobes grow homologously once they effectively become heavier than the dilute outer regions of the ambient gas.

Hydrodynamic models of specific nebulae are appearing frequently. For example, our group has used numerical simulations like those reported in this paper to account for the detailed structures and to retrace the evolution of three prePNe, CRL2688 (Balick et al. 2013), OH231.8+04.2 (Balick et al. 2017), and M2-9 (Balick et al. 2018).

In this paper we are able to generalize beyond these case studies. In Section 2 we develop a synthetic and generic “baseline” model that nicely characterizes most of the images of Figure 1 and matches the commonly observed patterns of kinematics of prePNe (Section 5). In doing so, we define a set of fundamental descriptive model parameters, including the flow density, speed, opening angle, and toroidal magnetic fields, and so on. These parameters are varied to assess how changes in these parameters influence the evolution and shapes of the baseline model (Section 3) and the evolving effects of moderate toroidal magnetic fields embedded in the outflow (Section 4). In Section 6 we draw general conclusions about the character of the flows that shape the lobes and identify some important issues that lie beyond the reach of our methodology, at least for the present.

2. Baseline Model

2.1. Methodology

The highly versatile code AstroBEAR (Cunningham et al. 2005, 2009) was used for all of the present simulations. In our case, AstroBEAR solves the Eulerian equations of fluid dynamics in a 2D plane using an adaptive-mesh-refinement (“AMR”) method. The kernel of AstroBEAR is a versatile 3D hydrodynamic solver that can be applied in a wide variety of circumstances, including magnetized/cooling flows and rotating coordinating systems (Huarte-Espinosa et al. 2012b). Radiative energy losses are calculated using the coronal cooling rates by Dalgarno & McCray (1972). The code does not contain facilities for simulating emission-line images, predicting an emergent spectrum, or following the transfer of emitted radiation through dusty zones.

We performed the computations in one quadrant of a $16 \times 32 \text{kau}$ plane in which the injected gas is launched along the $\gamma$-axis into an isotropic and much slower AGB wind (Ivezić & Elitzur 2010). The grid cells are $\delta r = 500 \text{ au}$ in size at time $t = 0$. The wind is presumed steady (i.e., its speed is constant and its density drops as $r^{-m}$, where $r$ is radius from the nucleus and $m \approx -2$). For convenience, the downstream gas is presumed to be cold and stationary. The grid size, $\delta r = 500 \text{ au}$, was dynamically decreased by the AMR algorithm by factors up to four powers of two ($\delta r = 31 \text{ au}$) in regions where the state variables exhibit steep gradients. (We will justify this choice of grid resolution in Sections 2.3 and 2.5.)

2.2. Design of the Baseline Model

Our aim is to develop a generic flow, or “baseline” flow model with the geometry and momentum flux needed to create lobes like those of Figure 1 with the appropriate shape, size, and observed kinematics at 900 yr.\footnote{We choose a final time of 900 yr for convenience. At later times, the flow exceeds the computational grid, $16 \times 32 \text{kau}$.}

The fast flow consists of a Gaussian “tapered” conical “jet” in which both the density and the speed of the injected collimated flow along the nozzle surface fall off as Gaussians with polar angle. We adopted this flow geometry used earlier by LS03 (resembling the structure of magnetocentrifugally driven outflows by Shu et al. 1995) because it is a robust way to produce hollow, candle-flame shaped lobes with curved walls of appropriate dimensions and shock speeds along their walls that are largest near the lobes’ tips (please see the note added in proof at the end of this article). (The Gaussian taper adds only one additional free parameter.) The opening angle of the flow, $\theta_{\text{flow,0}}$, is its $1/e$ width.

Table 1 shows the full set of adopted descriptors for the ambient environment and the fast collimated flow used for the AstroBEAR simulations of the baseline model. Choices of parameter values for the fast collimated flow are chosen to fit the typical images of prePNe in Figure 1. The choice of values is discussed in the next section. More than 100 simulations were run before we found a suitable baseline flow model.

Hereafter we use the term nozzle to refer to the interface where the collimated fast outflow first encounters the isotropic ambient environment. The nozzle’s surface is that of a round
### Table 1

Parameters and Baseline Model Values

| Parameters | Value |
|------------|-------|
| Ambient gas (isotropic “slow AGB winds”) | |
| Particle density at nozzle \(n_{\text{amb,0}}\) (cm\(^{-3}\)) | \(10^4\) |
| Density radial power law \(m\) | \(-2\) |
| Launch speed \(v_{\text{amb,0}}\) (km s\(^{-1}\)) | static |
| Temperature \(T_{\text{amb,0}}\) (K) | \(10^2\) |
| Grid window width \((\Delta x, \Delta y)\) | \((16, 32)\) au |
| Initial total mass on the grid \((M_\text{e})\) | \(\sim 0.01 M_\odot\) |
| The “fast injected flow” leaving the nozzle | |
| Nozzle radius \(r_\text{f}\) (au) | \(10^2\) au |
| Particle density \(n_{\text{flow,0}}\) (cm\(^{-3}\)) | \(310^3\) |
| Injection speed \(v_{\text{flow,0}}\) (km s\(^{-1}\)) | 300 |
| Temperature at launch \(T_{\text{flow,0}}\) (K) | \(10^2\) |
| Gaussian 1/\(e\) taper angle \(\phi_{\text{flow,0}}\) | \(25^\circ\) |
| Injection duration \(\Delta t_{\text{flow}}\) (yr) | 900 |
| Mass injection rate \(M_{\text{flow}}\) \((M_\odot \text{ yr}^{-1})\) | \(8 \times 10^{-7}\) |
| Total injected mass \(M_{\text{flow}}\) \((M_\odot)\) | \(710^{-4}\) |
| Total injected momentum \((\text{g cm s}^{-1})\) | \(410^{37}\) |

**Note.**

* Bold: parameters that are specified in AstroBEAR simulations.

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### 2.4. AGB Wind Density

The total mass and the distribution of the ambient density on our initial grid are determined by its inverse-square form, \(n_{\text{amb}}(r) = n_{\text{amb,0}} \times (r/r_\text{f})^{-2}\), and the chosen value of \(n_{\text{amb,0}}\). The latter is estimated from the total observed wind masses based on \(^{12}\text{CO}\) and \(^{13}\text{CO}\) measurements (see Höfner & Olofsson 2018) and then scaling them to the much smaller volume of a sphere that encloses the adopted grid size. This is difficult to do accurately since the dimensions of the AGB wind are only poorly known and the \(^{12}\text{CO}/^{13}\text{CO}\) ratio may well vary with stellar type and time. We estimate a total mass of the very slow ambient AGB “wind” is \(0.014 M_\odot\) within a radius of 32 au and \(n_{\text{amb,0}} \approx 10^4\) cm\(^{-3}\). (The mass of the ambient gas within the cylinder defined by our grid is about \(0.01 M_\odot\).)

### 2.5. Descriptors of the Fast Injected Flow

Choices of parameter values for the fast collimated flow in the baseline model are chosen for a good fit to the typical images of prePNe in Figure 1. The flow density at the nozzle is set to \(n_{\text{amb,0}}/3\). This results in a flow momentum well within the range of observed values (Bujarrabal et al. 2001). Thus the mass injection rate \(M_{\text{flow}} = 8 \times 10^{-7} M_\odot \text{ yr}^{-1}\), or at total injected mass \(\sim 7 \times 10^{-4} M_\odot\) after the duration, \(\Delta t_{\text{flow}}\), of 900 yr.

The choices of flow speed, \(v_{\text{flow,0}}\), and taper angle, \(\phi_{\text{flow,0}}\), are empirical: our adopted values lead to outcomes that match the lengths and aspect ratios of the lobes of typical prePNe. We adopted a flow temperature at the nozzle, \(T_{\text{flow,0}}\), of 100 K. This value is chosen because it is consistent with typical molecular excitation temperatures; however the divergence (i.e., expansion) of the fast flow rapidly drives that temperature lower as the flow diverges. As it turns out, the choice is immaterial since thermal pressure is negligible compared to ram pressure throughout the entire lobe unless the flow is hotter than \(10^5\) K at launch.

### 2.6. Salient Features of the Baseline Model

As shown in Figure 3, the outcomes of the baseline simulation at time \(t = 900\) yr include a pair of hollow lobes with curved walls of aspect ratio of about 4:1 (Figure 1). Highlights of the baseline simulation are listed as follows.

1. The radial streamlines of the flow stream freely through the lobe interior until they encounter and shock the displaced gas at the nebular reverse shock.
2. The stationary ambient gas at the head of the lobe almost immediately slows the leading edge of the lobe to speeds of \(\approx 140\) km s\(^{-1}\) or \(\leq 50\%\) of the flow speed at the nozzle.
3. Leading and reverse shocks are separated by a slowly advancing contact discontinuity (“CD”).
4. Gas upstream (downstream) side of the CD consists almost exclusively of gas from the injected fast flow (ambient AGB gas) with relatively little mixing.
5. The freely streaming fast gas reaching the front (top) of the lobe overtakes and shocks the thin rim of displaced gas, forming prominent “thin-shell” instabilities\(^5\) at high latitudes.
6. Shock-excited emission lines and very soft thermal X-rays can arise near shocks where temperatures are large. However, the emission measure of hot gas is small.

\(^5\) Thin-shell instabilities are even more important in analogous models without a taper imposed on the injected flow and in 3D models.
Hence the shock-excited emission may not always be detectable proximate to the shocks.

7. The thin-shell instabilities create zones of relatively low density in the walls into which the hot post-shock gas penetrates. One or more expanding “fingers” will form between denser zones along the corrugated lobe edge. A multipolar or “starfish” shape can develop; see Section 3.

8. Axial knots of dense gas develop near the y-axis when the streamlines outside of the inner shock strongly converged in the first $\sim 10^3$ yr (when the inertia of the densest static ambient gas is most influential). They may be artifacts of the 2D model’s idealized geometry and easily repressed by flow turbulence or spatial irregularities.

9. As found by LS03, streamlines entering the lobes’ side walls at oblique angles retain their transverse speed while their forward speeds rapidly slow. As a direct result, streamlines of the post-shock gas follow lobe walls, especially at high latitudes.

10. The lateral edges of the outer portions of the lobe walls (beyond the CD) are driven into the ambient gas by thermal pressure (expansion) of gas. The heat between the CD and the outer walls was originally generated at the tip of the flow as it progressed into the ambient gas.

11. As the lobe tip moves onward, the gas at the sides of the lobes’ leading edges interacts with slower ambient gas and falls behind. This gas thermally expands and cools adiabatically in place. Its expansion is constrained to the lateral direction.

12. The axial ratio and overall shapes of the lobes change little after 100 yr. This is the result of the inertial resistance of the rapidly declining density of ambient gas upstream.

13. The choices of temperature of the AGB and flow medium are not influential in the outcomes. That is, the thermal pressure of the injected gas is negligible compared to its ram pressure. Thermal pressure only dominates outside the lobe where the gas is static. However, the inertia of the ambient gas is vital for shaping the lobes’ geometries.

14. Note the locus of the reverse shock in the second panel of Figure 3. The speed of the gas from the nucleus that crossed the reverse shock increases steadily with lobe height (i.e., a monotonic speed gradient in the y direction; see Section 5).

Only marginally light and tapered injected flows of speed $\approx 300 \text{ km s}^{-1}$ produce closed lobes with shocked, curved walls within which Doppler speeds increase with distance from the central star. (Untapered—i.e., uniform—flows produce open conical lobes with a round leading surface and straight, unshocked walls.)

As first discussed by Frank et al. (1996), Canto et al. (1988), Tenorio-Tagle et al. (1988), and in more detail in LS03, the fast gas streams along the lobe walls after crossing the inner shock. The speeds of the converging flow increase steadily with height (the flow kinematics will be described in detail in Section 5). The hot post-shock flow converges to the symmetry axis where it encounters the mirror-image flow coming from the adjacent quadrant. Thus a highly disturbed zone of complex kinematic and thermal structure forms along the forward edge of the flow that changes in shape as the lobe moves forward. This process is especially important at first when the flow is most influenced by its denser surroundings. Soon thereafter thin-shell instabilities may amplify the structural complexities in this zone.

The paradigm of a steadily injected flow is not necessarily the only one that serves to fit the basic properties of the lobes of prePNe. Akashi & Soker (2008), showed that pulsed injections can also form hollow closed lobes.

Accordingly, we reran the baseline model with pulsed flows of duration $\Delta t$ and equal injected masses, momentum fluxes, and speeds. The density of the injected gas and the duration of injection were $\rho_{\text{inj}} = 1 \times 10^5 \text{ cm}^{-3}$, 300 yr) and $2.7 \times 10^4 \text{ cm}^{-3}$, 100 yr). A comparison of lobes formed by steady and pulsed winds are shown in Figure 4. The outcomes differ primarily by differences in the thicknesses of the lobe walls but not their aspect ratios. The kinematics of the gas within the lobe walls is similar in all cases. The lobes of pulsed flows are slightly longer than their steady-flow counterparts since the more percussive initial impact of pulsed flows allows them to initially penetrate further before swept-up gas slows their progress.

2.7. Limitations and Reliability

Constructing numerical models requires a variety of compromises involving limitations of computational speed and model accuracy. We reran the baseline model run with three, four, and five grid refinement levels (cell sizes $\delta r = 500 \text{ au}/2^i$, where $n = 3, 4,$ and 5; i.e., $\delta r = 63, 31,$ and 16 au, respectively). The relative run times are 0.18, 1.0, and 1.8. Nonetheless the large-scale structures of all three models are similar (Figure 5). The major difference is the complexity of the thin-shell instabilities in the upper quarter of the lobe. Note that $\delta r = 31 \text{ au}$ at 1–2 kpc corresponds to $\sim 0''02$.

However, running all of the models with the resolution needed to fully characterize the flow emerging from some sort of close binary star system, $\delta r = 1 \text{ au}$, is not feasible at this
time. Any study at that level of detail requires the incorporation of turbulence, time variations (on the order to the binary period) within the injected fast flow (such as turbulence and variability on shorter scales than the binary period).

More relevant here is that the large-scale flow patterns of the baseline model after 900 yr are the essentially the same for $\delta r = 63, 31$, or 16 au. So the results presented throughout this paper are generally robust. Even so, the pixelation of the nozzle’s surface introduces subtle artificial striations of the propagating flow as it emerges from the nozzle. Such striations can be seen as radial rays in the density structure inside the lobes in Figure 5. These striations trigger small irregularities at lobe boundaries that slowly grow, depending on the spatial resolution of the simulations.

2.8. The Formative Years

The most rapid transition from initial post-launch to final lobe geometry occurs in the first 50–100 yr when the light wind is most effectively influenced and deflected by the ram pressure of the dense ambient gas in the former AGB wind. Details of the rapid changes in lobe structure and flow patterns are illustrated in the left panel of Figure 6 at $t = 25$ and 50 yr. These frames are computed at a spatial resolution $\delta r = 2$ au (0.2% of the launch radius). Shear instabilities rapidly form along the lobe walls and slide upwards as the lobe grows. They incite numerous and highly localized ripples in flow direction. The ripples slide upward and diminish in amplitude while maintaining their relative spacings as the lobe grows (not shown).

However, the small shear instabilities have no effect on the large-scale structure of the lobe’s edges after $\Delta t = 900$ yr. We find that the aspect ratio of a lobe quickly approaches its same final value in simulations of resolutions, $\delta r$, from to 2 to 64 au for all nozzle opening angles near 25°. That is, the side walls of the lobes continuously push outward at about $10–15$ km s$^{-1}$. At the same time, the forward speed of the lobe tips at 50 yr, $\sim120$ km s$^{-1}$, barely changes as the lobes grow. The large-scale shape of the lobe is predictably established by $t \approx 50$ yr even. Only the thicknesses of the lateral walls are poorly represented in models calculated with $\delta r = 31$ au. Otherwise all of the results presented in the next section are robust.

3. Parameter Variations

We now present how the outcomes of the baseline model are affected by variations of the parameters that describe the ambient gas and fast flows. All models are run for 900 yr using a resolution of $\delta r = 31$ au for the first 200 yr and $\delta r = 64$ au thereafter. The resolution change is benign.
3.1. Variations in the Properties of the Ambient Gas

3.1.1. Variations in $n_{\text{amb},0}$

We first investigate outcomes in the baseline simulation as the properties of the ambient gas are varied. First, note that untapered and heavy diverging flows will both create a lobe shaped like a pizza wedge with a dense leading edge that is formed as displaced ambient gas retards its forward progress. A light tapered interacts strongly with denser ambient gas and develops lobes until it reaches regions where the local density is smaller than that of the gas plowing into it. Gas at the edges of the tapered flow displaces less of the ambient medium at slower speeds than gas near the flow symmetry axis. This is how the wall curvature develops. For a given taper the density contrast $n_{\text{flow},0}/n_{\text{amb},0}$ is the key to understanding the length and curvature of the walls.

Identical tapered flows are injected into external media of larger densities and smaller density contrasts from left to right in Figure 7. Lobes are shorter and more curved as the contrast increases in this sequence, as expected. The lobe lengths in the sequence of the four models are in the ratios of approx. $4/3, 1, 3/4$, and $1/2$, respectively. The lobe aspect ratio is only marginally affected along the sequence. Thus the aspect ratio is a poor diagnostic of the density contrast.

3.1.2. Variations in Density Power Law $m$

Changes in the radial power law $m$ of the ambient density distribution $n_{\text{amb}}(r) = n_{\text{amb},0}(r/r_0)^m$ from the standard baseline value $m = -2$ have mimic changes in $n_{\text{amb},0}$ (see Figures 7 and 8).

For a fixed value of $n_{\text{amb},0}$, $m$ determines where the flow transitions from light (at the nozzle) to a heavy state where the ambient density is smaller. The length and curvature of the lobe vary accordingly. The total mass of ambient mass is also affected by the value of $m$.

3.1.3. Variations in the Radial Speed and Sound Speed of the Ambient Gas

For computational convenience we assumed that the ambient gas is static. However, we ran baseline models in which its flow speed, $v_{\text{AGB}}$, is $10$ and $20$ km s$^{-1}$, as indicated by dozens of CO spectral observations. This has no appreciable effect on the outcome (not shown). Similarly, the outcomes are very similar so long as the sound speed of the ambient gas is far less than that of the collimated gas ($T_{\text{amb}} \lesssim 10^5.5$ K).

3.2. Variations in the Properties of the Injected Gas

Next we show how changes in key flow parameters $n_{\text{flow},0}$, $v_{\text{flow},0}$, momentum flux $(n_{\text{flow},0}v_{\text{flow},0})$, and opening angle $\phi_{\text{flow},0}$ affect the model outcomes.

3.2.1. Variations in $n_{\text{flow},0}$

All else being equal, denser flows carry more momentum and serve as more effective pistons in displacing the ambient gas. This is illustrated in Figure 9, in which the density contrast increases from left to right. Interestingly, the overall dimensions, shapes, and wall thicknesses of the lobes are strikingly similar to those in Figures 7 and 8. All of them are difficult to distinguish observationally.

Figure 6. Left: details of the early density and flow patterns for the baseline model with $\delta r = 2$ au at $t = 25$ and $50$ yr. Left: ambient (injected) gas is indicated in orange (blue). Flow velocities are indicated by the lengths and colors of the arrows. Rapid changes in velocity within the lobe walls are shown in an inset. Right panel: logarithm of the ram-to-thermal energy density ratio. Thermal pressures are ignorable within the lobe walls, except at the perimeter where both pressures are comparable.

Figure 7. Models for ambient densities of $3 \times 10^3, 10^4$ (baseline) $3 \times 10^4$, and $10^5$ cm$^{-3}$ at the inner edge of the nozzle, $n_1 = 10^7$ au.
3.2.2. Density Variations That Preserve the $n_{\text{amb},0}$: $n_{\text{flow},0}$ Ratio

Figure 10 shows that the lengths and axial ratios of models with the same density contrast are all about the same at $t = 900$ yr. However, the structure in the upper half of the lobe depends on the density of the ambient gas that the fast flow displaces. The differences become evident at early ages. At lower densities the flow tends to spread more quickly after launch. The spread diffuses the ram pressure along the leading edge of the lobe. The spreading is less effective at higher ambient densities.

3.2.3. Variations in $v_{\text{flow},0}$

As expected, faster flows penetrate further into and displace more of the ambient gas (Figure 11). The lobes formed by faster flows are increasingly longer and wider, much like the outcomes in Figures 7–9. Note that the lobe length is not proportional to the initial speed of the flow, as one might naively expect, because the wider lobes formed by faster inflows displace more AGB gas. Note also that thin-shell instabilities are strongly enhanced by higher flow speeds.

3.2.4. Variations in Flow Opening Angle

Finally, we present a series of simulations with opening angles of $15^\circ$, $25^\circ$ (the baseline), $35^\circ$, and $45^\circ$ (Figure 12).
Each fast flow has the same momentum flux per steradian at the nozzle launch radius \( r_0 \). Thus each injected flow makes lobes of about the same overall length. However, the total injected flow mass and momentum scale with the surface area of the orifice.

The tapered flow used in this section (and throughout the rest of the paper) is marginally light: at launch the peak launch density of the tapered flow on its symmetry axis is one-third that of the adjacent ambient gas. This ratio of flow-to-ambient density decreases with polar angle. Thus, the outer, lower-density, and slower portions of the tapered light flow interact with and are strongly deflected by the denser surrounding stationary gas. As a consequence the edges of the lobes develop a cup-shaped base with curved upper walls.

The leading plug is very susceptible to the formation of thin-shell instabilities that can cause it to wrinkle and corrugate (Figure 12). The wrinkles eventually fragment into fingers. This forms “multipolar” prePNe in which each finger is driven by thermal pressure of shock-heated gas from the reverse shock upstream. The ultimate outcome is a “starfish” (Sahai & Trauger 1998). It is useful to compare the respective leading edges of the narrow opening-angle flows of IRAS 19255+2123 and IRAS22036+5306 with wide-angle flows IRAS1750-3224 and IRAS19024+0044 in Figure 1.

### 4. Magnetic Shaping

#### 4.1. Baseline Models with Toroidal Fields

We reran baseline model of Section 2 after injecting toroidal fields \( B_z \) of \( 10^{-5}, 10^{-4}, 10^{-3.5}, 10^{-3}, \) and \( 10^{-2} \) G into the fast injected flow. Aside from this field, the flow leaving the nozzle is the same as the baseline model. The weakest of fields, \( 10^{-2} \) G, makes no discernible change in the final lobe morphology from the baseline model. The strongest value of the field, \( 10^{-2} \) G, channels the entire injected flow into a very dense and narrow axial cylinder, or “spear,” containing nearly all of the injected gas. Three intermediate outcomes are shown in Figure 13, along with the nonmagnetized baseline model (leftmost panel).

The toroidal magnetic field carried by the streamlines initially collects in the compressed walls of the lobe between the reverse shock and the CD. Immediately beyond the reverse shock the flow is essentially parallel to the walls so the flow is deflected vertically toward the upper lobe (as in the baseline model). The local influence of the field on the flow is therefore marginal at first.

Shortly thereafter, the lobe becomes truncated where the pressure of the compressed magnetic pressure within “nose” of the lobe dominates the local ram pressure. This transition occurs at \( y \sim 20 \) (15) kau in the third (fourth) panel of Figure 13. In every simulation displayed in Figure 13, the field yokes the streamlines toward the symmetry axis. They converge to form a dense, thin, lumpy, and highly magnetized “spear.” The upper tip of the spear steadily pulls away from the top of the lobe over time.

The spear is one of the most conspicuous features in our simulations in which \( B_z \gtrsim 10^{-4.5} \) G at the surface of the
nozzle. Within the spear, the flow speeds vary from 300 km s\(^{-1}\) at the base to about 200 km s\(^{-1}\) at the midway point to 250 km s\(^{-1}\) at the tip. It is clear that the complex structure within the spear is not well resolved in the present 2.5D models (in which \(\delta r = 16\) au) where various MHD instabilities are likely to arise.

The third panel of Figure 13 \((B_z = 10^{-3.5})\) nicely exemplifies the influence of the toroid field on the outcomes. We show the details of this simulation in Figure 14 at \(t = 900\) yr. We cannot describe the structure of the spear in detail since we do not adequately resolve it. Figure 14 is directly comparable to the baseline model of Figure 3.

The early evolution of this model is shown in Figure 15. The density, flow pattern, and magnetic field distribution are shown at 25 and 50 yr at high spatial resolution (\(\delta r = 2\) au). (This figure is analogous to field-free baseline model of Figure 6 in Section 2.5.) The spear is visible in nascent form at 25 yr and in a rapidly advancing and maturing state at 50 yr. The flow convergence pattern that forms it is highlighted in the inset of the left panel. The complexity of the spear is obvious. Moreover, the present results and the formation of shear instabilities inside of the inner shock will need to be confirmed in fully 3D MHD simulations. Nonetheless, field thickens the lobe walls and quite possibly suppresses flow instabilities along the lobes’ outer edges.

In general, toroidal fields produce 900 yr outcomes that are less satisfactory fits to the images of Figure 1 than the corresponding unmagnetized baseline model. The inclusion of the field serves to add complexity to the structure of the nonmagnetized baseline model of Section 3.

4.2. Comparison with Previous Models

Pioneering studies of the shaping of hot, ionized PNe by magnetized flows with toroidal fields were published by
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García-Segura et al. (1999, 2005), Dennis et al. (2009), and Steffen et al. (2009a), of which the latter is most directly comparable to the present models. Steffen et al. (2009b) considered fast (10^4 km s^{-1}), uncollimated, and toroidally magnetized winds blowing into slow AGB winds of two different forms that were ejected from a rotating AGB star with a dense equatorial disk (~10^7 cm^{-2} in the midplane).

Other than the injection of a toroidal field into the fast flow, the structure of initial conditions, computational methodology, and spatial resolution adopted by Steffen et al. (2009b) are all quite different from those used here. Nonetheless, the presence of the toroidal magnetic field in the wind produces basically the same basic outcomes: thin, fast, dense spears form along the symmetry axis, behind which trailing wakes form (compare the side-by-side model images in their Figure 1).

Ciardi et al. (2013), Albertazzi et al. (2014), and van Marle et al. (2014) examined how external poloidal fields (parallel axial field lines) affect the shapes of PNe formed by steady isotropic fast winds from a central star. The growing bubble of gas takes on an increasingly elliptical form with thin axial protrusions, not unlike our results.

However, poloidal shaping requires 10^4–10^5 yr before the field energy density successfully competes with the diverging kinetic energy density of the fast stellar wind so that realistic structures form in typical interstellar fields of \( \lesssim 5 \mu G \) (van Marle et al.; Haverkorn 2015). By that time, the field-induced structures lie a full parsec from the central star.

Comfortingly, all of these models end up at about the same morphological endpoint since they share one key process: the energy density of the diverging shaping winds declines more rapidly than the wind-compressed magnetic energy density in the walls of the lobe (depending on the field geometry in the flow).

### 4.3. Possible Examples

Thin leading, magnetically formed axial jets are uncommon in observations of prePNe. Nonetheless, possible examples of prePNe shaped by magnetized flows include Hen 3-1475 (Fang et al. 2018), M1-92 (Figure 1 and Bujarrabal et al. 1998a, 1998b), and IRAS 19255+2123 (K3-35).

NGC 7009 is an example of a more mature and ionized PN that may have been shaped by a toroidal field (Steffen et al. 2009a) or by a poloidal field (Albertazzi et al.). Its shape is a good match to the poloidal model, but its size is not. Other examples include the axial jets in Hen 2–104 and NGC 7354, and possibly the ansae of Fleming 1, Hen 2–90, Hen 2–111, Hubble 4, IC 4593, K4-47, M1-16, M1-66, M2-48, NGC 3918, NGC 6543, NGC 6751, and NGC 6881.

### 5. Kinematics

Models of prePN shaping are tightly constrained by observed kinematic patterns (usually from molecular aperture synthesis, long-slit, or fiber-fed spectrographs).

#### 5.1. Common Linear P–V Outflow Pattern

PrePNe often exhibit a linear correlation in Doppler shift with distance along the lobe symmetry axis (that is, a tilted position–speed outflow pattern on a position–velocity (“P–V”) diagram. \( P–V \) diagrams also show line splittings indicative of lateral lobe expansions of 10–20 km s^{-1}. Illustrative \( P–V \) data can be found for Hen 3-401, IRAS16594-4656, Roberts 22 (Hrivnak et al. 2008), M1–92 (Alcolea et al. 2008), M2–56 (Castro-Carrizo et al. 2002; Sánchez Contreras et al. 2010), and OH231.8+04.2 (Sánchez Contreras et al. 2000, 2015, 2018; Alcolea et al. 2001).

M2–9 is an outstanding example since there are a diverse set of spatial and kinematic observations (Balick et al. 2018). M2–9 is unique in that long-slit spectra show two distinct patterns: the usual split and tilted linear \( P–V \) pattern in optical lines and [Fe II] \( \lambda 1.64 \mu m \) from the inner shocks of the lobes along with a distinct \( P–V \) diagram in \( H_2 \) \( A2.12 \mu m \) of split lines of constant Doppler shift from the outer shocks along the lobe walls (Smith et al. 2005). Balick et al. (2018) incorporated all these disparate kinematics into one comprehensive model based on the same paradigm as the baseline model of Section 2.

#### 5.2. Explaining the Pattern

The kinematic pattern of gas that is predicted by the baseline model is shown in the second and fifth panels of Figure 3 and the left panel of Figure 6. The gas from the nozzle flows freely until it strikes the reverse shock obliquely. The forward component of its momentum is largely arrested in the shock where the associated decrease in the flow’s kinetic energy is converted into heat. On the other hand, the transverse component of momentum is continuous across the shock. (The physics of oblique streamline-wall interactions can be found in Canto et al. 1988, Frank et al. 1996, and LS03.)

The net result is that the streamlines of the flow in the post-shock zone are nearly parallel to the lobe walls. The post-shock gas flows toward the lobe tip (LS03). The flow speed of this gas increases rapidly along the lobe walls for two reasons: at small polar angles the speed of the tapered flow is fastest and the obliquity of the streamline impact on the walls is greatest. As a result, emission lines in the hot post-shock gas exhibit a monotonic (almost linear) gradient in Doppler shift in y direction.

We stress that the tilt of the \( P–V \) diagram is a direct and necessary result of the tapered speed of the collimated flow at the nozzle and the candle-flame-shape walls formed by light flows. Tilted \( P–V \) diagrams can be expected in all prePNe with hollow lobes with curved walls, such as those in Figure 1.

Until recently, the tilted \( P–V \) pattern seen along the walls of the lobes of prePNe was interpreted in terms of ballistic outflows, as if the lobe was mystically created in a brief, energetic event and flung outward without any further change in shape (see Alcolea et al. 2001, 2008; Corradi et al. 2001; Akashi & Soker 2008).

The ballistic paradigm nicely accounts for the tilt of \( P–V \) diagrams, but it is directly conflicts with the candle-flame shapes the lobes of typical bipolar prePNe. The results apply to all of our simulations whether or not magnetic fields are not present.

The tilt of the \( P–V \) diagram pattern changes as the lobe grows such that its general slope (length/proper-motion speed) is always a good measure of its age (like 1/\( H_0 \), where \( H_0 \) is the cosmic Hubble slope). The low ambient density upstream assures a uniform, almost ballistic expansion of lobe shape after a few hundred years. The results are much the same when the fast wind is pulsed rather than steady (Section 2.5 and Figure 4).

We note that a tilted \( P–V \) trend is often seen in mature fully ionized PNe where thermal pressure dominates the dynamics of the nebula (Huarte-Espinosa et al. 2012a). The tilt is largely
vestigial. On the other hand, some bipolar PNe also show $P-V$ diagrams with an overall tilt that suggests highly collimated nuclear flows are (or have been) active in the histories of shaping their lobes. Hen 2-104 (Corradi et al. 2001) and NGC 6302 (Santander-García et al. 2015) are probably the most compelling cases. Bipolars with very round lobes, such as Hubble 5, Hen 2-428, NGC 650-1, and NGC 2440, may be cases where persistent thermal pressure of continuously re heated photoionized gas is dominant.

5.3. Kinematics of Magnetic Models

Magnetic models result in a stunted lobe formed by fast, collimated winds plus a thin, dense, jet-like protrusion, the "spear," where the fields dominate the local energy density. The internal characteristics of the stunted lobes formed by light tapered flows are the essentially same as the unmagnetized model. Long-slit observations of the lobe edges will show the normal linear $P-V$ pattern.

However, the kinematics of the spear downstream of the lobe will not have a tilted $P-V$ s. The strong surrounding toroidal field squeezes and guides that gas entering the base of the jet to higher speeds (up to $\approx 300$ km s$^{-1}$) before the flow slows near its outer tip (Figure 14).

6. Conclusions

6.1. The Lobes of Light Field-free Outflows

This paper is one in a series of hydrodynamic studies of the evolution of the lobes of prePNe intended to probe their histories, as constrained by high-quality images and high-dispersion spectra of their lobes. All of the simulations in our studies produce lobes formed by marginally light and tapered flows of various geometries and ejection speeds as they interact with slow AGB winds.

In Section 2 we developed a specific “baseline” model that fits the attributes of common prePNe. We discussed the major features of the baseline model (Figures 3–5) and how the outcomes may change for pulsed (non-steady) flows (Figure 6). In Section 3 we varied the parameter values at the surface of the nozzle to see how the lobe geometry and kinematics are affected (Figures 7–12). Lobe widths are primarily functions of the flow opening angle, density, and speed. Their lengths are differentiated largely by flow speed, the ratio of flow to ambient density at the surface of the nozzle, and the nozzle opening angle. In addition, kinematic ages are determined from lobe length to growth-rate ratio, $\theta/\theta$. In Section 5 we showed that the patterns of kinematics observed in most prePNe are well explained by the paradigm of Section 2.

We explored the effects of toroidal magnetic fields embedded in the flow in Section 4. The fields degrade the fit of the models to typical prePNe seen in Figure 1.

6.2. Major Findings

We exploit this opportunity to compile the major findings of this paper and to merge them with others from our previous case studies. These findings pertain only to simulated lobes that are similar to the baseline model of Section 2, including an ambient density that is central concentrated. The (nonmagnetized) flow paradigm of Section 2 is the best basis for understanding the evolutionary histories of the formation of prePNe. Accordingly, we ignore magnetized flows in this section.

1. Hollow, closed lobes are formed by collimated super-sonic light flows (“light jets”; $n_{\text{flow},0}/n_{\text{amb},0} \approx 0.1-0.3$ to the cold and much slower AGB winds into which they are injected).
2. Lobes with curved walls are most readily formed by “tapered” flows (“tapered jets”) in which the momentum flux of the flow falls off with polar angle at the injection nozzle.
3. The low specific-momentum gas that they displace quickly retards the growth rate of the lobe tip by 40%-60% for such light flows. The retardation scales with the density contrast $n_{\text{flow},0}/n_{\text{amb},0}$.
4. The leading edge of a light flow effectively becomes heavy once it reaches the outer, lower-density regions of the AGB winds. In the baseline model, this occurs within about the first 100–200 yr.
5. The lobes retain their large-scale shapes (i.e., aspect ratios) once this occurs.
6. The lobe tip formed by a steady jet can slowly speed up as the density of the upstream gas declines; however, it never regains its initial speed.
7. Flows of limited duration but the same injection geometry and total momentum as a steady flow produce lobes that are very similar in appearance and most likely not distinguishable observationally.
8. The radial streamlines of the injected fast wind flow freely until they reach the walls of swept-up and displaced ambient gas at the lobe perimeters.
9. The streamlines of tapered flow are deflected at the compressed, shocked gas in the inner walls of the lobes where they produce slower flows that follow the curved lobe walls (LS03). This produces walls within which the flows converge at the lobes’ tips.
10. Shear instabilities along these walls produce local K-H instabilities within which flow and ambient gas do not effectively mix. The vortex-like instabilities spread apart but do not affect the lobe width, length, shape, or speed after they form.
11. Under most conditions thin-shell instabilities quickly arise within the rim of swept-up ambient gas at the leading portions of the lobe.
12. These instabilities continue to grow in amplitude once the rims enter the sparse stratified outer regions of the slow AGB winds.
13. The leading edges of wider-angle flows fragment into families of growing fingers that will resemble starfish and multipolar prePNe.
14. The walls of the lobes are bounded by leading (outer) and reverse (inner) shocks separated by a contact discontinuity through which no mixing occurs. However, the CD slowly drifts outward allowing very small amounts of ambient and injected gas to share the same very local volume.
15. Lines of shock-excited species such as [Fe II] $\lambda 1.64$ Å and low-lying levels of optical forbidden may arise in the recombination zone at the reverse shock where the post-shock temperature $\gtrsim 10^4$ K. Soft X-rays may arise near the front edge of the lobe in extreme cases.
16. The Doppler shifts of these emission lines along the lobe walls formed by tapered flows will rise steadily with...
distance. As a result, the $P-V$ diagrams of Doppler shifts from the lobe walls are tilted and approximately linear. 17. Gas in the walls outside the CD consists of ambient gas flows that was initially heated to $\sim 10^5$ K by the leading shock. This hot at the lobe edges expands in place as the lobe tip moves beyond it. The expansion is laterally outward (into the ambient medium), owing to the dense gas in the lobe walls.

6.3. The Lobes of Magnetized Outflows

We found in Section 5 that fast winds containing a toroidal field produce hybrid lobe-jet outcomes (Figures 13–15). When the energy density of the field at the nozzle is modest ($10^{-3.5}$ G for the baseline model), stunted but otherwise ordinary lobes form above the nozzle (where the local energy density is dominated by the ram pressure of the flow from the nozzle). However, the kinetic energy density of the diverging collimated wind falls off as $r^{-2}$. In contrast, the energy density of the magnetic field declines as $r^{-1}$ or slower. So at some point the toroidal field takes over, recollimates, and confines the gas at the leading end of the stalled lobe. A thin, very dense, lumpy, and magnetically confined narrow “spear” forms. The gas flowing into the base of the spear starts out at $\sim 300$ km s$^{-1}$. It then encounters and shocks slower gas downstream, beyond which the confined gas flows slows down. Magnetic models produce spears that are not generally observed in prePNe. In Section 4.3 we identified a few prePNe and ionized PNe in which magnetic shaping may have been significant.

6.4. Challenges
6.4.1. Tapered Flows

As we have seen, light tapered flows are a natural way to account for two of the basic attributes of the lobes of prePNe: curved lobes and tilted $P-V$ diagrams.

How does tapering arise? The roots of the concept (whose form we adopted from LS03) go much further back to magnetocentrifugally driven outflows (see Section 2.2 and Blackman et al. 2001; Frank & Blackman 2004; Matt et al. 2006; Huarte-Espinosa et al. 2012b). Unmagnetized flows from accretion disks in binary systems can also be tapered, as illustrated by the recent simulations by Chamandy et al. (2018), Hen2-104 (2018), Chen et al. (2018), Frank et al. (2018), and García-Segura et al. (2018). In many cases, the jet-like ejecta of close binaries morph into tapered flows as they plow into dense environmental material near the binary. However, in some cases these outflows are much slower than hundreds of km s$^{-1}$ that are typically observed in prePNe.

6.4.2. Molecular Kinematics

In Section 5.2 we listed a variety of the most detailed spatio-kinematic studies of prePNe, many if which are based on the lines from cold molecular gas near the lateral edges of lobes. Although the baseline model is consistent with the characteristic morphologies and kinematics of molecular observations, the large disparity of the predicted and observed gas temperatures of the molecular tracers and the model raise questions about the model (as noted by the referee).

The post-shock zone outside the reverse shocks of the side walls is the only one in which the observed kinematical patterns of the shocked optical-IR ($T_{\text{col}} \gtrsim 10^4$ K) and the more gently collisionally excited molecular tracers ($T_{\text{col}} \lesssim 10^2$ K) might be located. The problem is that the cold molecular temperatures strongly conflict with the predictions of the baseline model in that zone (Figure 3).

Moreover, the baseline model predicts that the gas in the post-shock zone originates in the fast collimated flow. Thus the molecules within that flow must have survived and cooled during passage through the shock (or were somehow formed in situ in a cold state). This is unlikely.

AstroBEAR does not have the capability to follow changing molecular chemistry and excitation or to investigate possible non-equilibrium line formation. It also employs the coronal cooling function of Dalgarno & McCray (1972) that is inappropriate for cold molecular gas. (These limitations may soon be corrected; see Hansen et al. 2018, 2019.) Thus a reconciliation of the temperature differences of the molecules and other tracers lies beyond the scope of this paper.

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Facility: HST (WFPC2).

Note added in proof: Additional evidence for the shaping of bipolar prePNe by tapered flows is found in new multi-filter HST images of the Hen2-104 (STScI-2019-15). The images show that the nebular ionization increases with distance from the nucleus. Note that extraordinary (deprojected) Doppler speeds of $\pm 500$ km s$^{-1}$ have been found in the lobe tips (Redman et al. 2000). The same ionization trend has been known in the bipolar nebula Menzel 3 for many years (Hubble Heritage Program STScI-P01-05, PI: B. Balick, V. Icke, R. Sahai, and J. T. Trauger). In this case the tips of the lobes are also soft X-ray sources (Kastner et al. 2003) suggestive of very fast flow speeds very close to the lobes’ symmetry axis. The increase in nebular ionization with distance from the CSPN is consistent with shocks generated by a tapered flow. However, this trend cannot be reconciled with any models of photoionization by a central star.

Appendix

The many significant successes of the baseline model include hollow lobes with curved, candle-shaped edges and a common flow pattern inside the edges of the lateral walls with a linear (or nearly linear) radial gradient of flow speed up to $\approx 50\%$ of the speed of the injected gas. The curved walls are the direct result of streamlines that strike the walls obliquely. Here we argue that uniform, untapered cylindrical or diverging flows from the nozzle
fail to account for these highly characteristic shapes and flow patterns.

Untapered cylindrical or diverging flows, whether light or heavy, cannot appear hollow.

In an isotropic external medium, untapered flows produce lobes with purely columnar (cylinders) or radial edges (diverging flows) parallel to the outermost streamlines. (Very small shear instabilities may arise at the flow boundary, as in Figure 6.) Thus the lateral walls are not compressed, shocked, or especially conspicuous in scattered starlight. The ambient gas plays an entirely passive role in constraining the walls of the lobes except in the thin, dense rim along the lobes’ leading edges.

Obviously there is no mechanism by which ambient gas adjacent to the lateral edges of the lobes can be accelerated to create a $P$–$V$ diagram that differs in form from that of the AGB wind.

Also, the untapered flows leave behind a wake of previously shocked gas at $10^4$–$10^7$ K from the compressed rim at the leading edge of the lobe. This hot and largely ambient gas spills sideways from the outer corners of the rim and falls behind the lobe as it continues to grow. There it adiabatically expands in place at its sound speed ($\approx 10$ km s$^{-1}$) but has little if any radial motion.

Therefore, the $P$–$V$ diagram from the long-slit spectrum will not produce the tilted pattern indicative of a radial speed gradient (unless there are strong geometric projection effects that enhance its slope at low inclination). Instead, the spectrum obtained along a lobe’s symmetry axis will resemble that seen for dense ejected clumps, such as those found in H–H objects (e.g., Raga et al. 2004). The emission lines will flare where the slit crosses the shock-heated rim. Behind the rim, the long-slit spectrum will show the $\pm 10$ km s$^{-1}$ lateral expansions of the front and rear surfaces of the training wake.

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**References**

Akashi, M., & Soker, N. 2008, *MNRAS*, 391, 1063
Akashi, M., & Soker, N. 2018, *MNRAS*, 481, 2754
Albertuzzi, B., Ciardi, A., Nakatsutsumi, M., et al. 2014, *Sci*, 346, 325
Alcolea, J., Bujarrabal, V., & Neri, R. 2008, *ApSS*, 313, 235
Alcolea, J., Bujarrabal, V., Sánchez Contreras, C., et al. 2001, *A&A*, 373, 932
Balick, B., & Frank, A. 2002, *ARA&A*, 40, 439
Balick, B., Frank, A., Liu, B., et al. 2017, *ApJ*, 843, 108
Balick, B., Frank, A., Liu, B., et al. 2018, *ApJ*, 853, 168
Balick, B., Huarte-Espinosa, M., Frank, A., et al. 2013, *ApJ*, 772, 20
Blackman, E. G., Frank, A., & Welch, C. 2001, *ApJ*, 546, 288
Bujarrabal, V., Alcolea, J., & Neri, R. 1998a, *ApJ*, 504, 915

Bujarrabal, V., Alcolea, J., Sahai, R., Zamanov, J., & Zijlstra, A. A. 1998b, *A&A*, 331, 361

Bujarrabal, V., Castro-Carrizo, A., Alcolea, J., & Sanchez-Contreras, C. 2001, *A&A*, 337, 686

Canto, J., Tenorio-Tagle, G., & Rózycka, M. 1988, *A&ARv*, 19, 287

Castro-Carrizo, A., Bujarrabal, V., Sánchez Contreras, C., et al. 2002, *A&A*, 386, 633

Chamandy, L., Frank, A., Blackman, E. G., et al. 2018, *MNRAS*, 480, 1898

Chen, Z., Blackman, G., Nordhaus, J., et al. 2018, *MNRAS*, 473, 747

Ciardi, B., Labropoulos, P., Maselli, A., et al. 2013, *PhRvL*, 110, 025002

Corradi, R. L. M., Livio, M., Balick, B., et al. 2001, *ApJ*, 553, 211

Cunningham, A., Frank, A., & Hartmann, L. 2005, *ApJ*, 631, 1010

Cunningham, A., Frank, A., Varnière, P., et al. 2009, *ApJS*, 182, 519

Dalgaro, A., & McCray, R. A. 1972, *A&A*, 10, 375

Dennis, T. J., Frank, A., Blackman, E. G., et al. 2009, *ApJ*, 707, 1485

Fang, X., Gómez de Castro, A. I., Toalá, J. A., et al. 2018, *ApJ*, 865, 23

Frank, A., Balick, B., & Livio, M. 1996, *ApJ*, 471, L53

Frank, A., & Blackman, E. G. 2004, *ApJ*, 614, 737

Frank, A., Chen, Z., Reichardt, T., et al. 2018, *Galax*, 6, 113

García-Segura, G., Langer, N., Rózycka, M., & Franco, J. 1999, *A&A*, 517, 767

García-Segura, G., Lopez, J. A., & Jose Franco, J. 2005, *ApJ*, 618, 919

García-Segura, G., Ricker, P. M., & Taam, R. E. 2018, *ApJ*, 860, 19

Hansen, E. C., Hartigan, P., Frank, A., et al. 2018, *MNRAS*, 481, 3098

Hansen, E. C., Hartigan, P., Frank, A., et al. 2019, *MNRAS*, 483, 2123

Haverkorn, M. 2015, *ASSL*, 407, 483

Höfner, S., & Olofsson, H. 2018, *A&ARv*, 26, 1

Hrivnak, B. J., Smith, N., Su, K. Y. L., et al. 2008, *ApJ*, 688, 327

Huarte-Espinosa, M., Frank, A., Balick, B., et al. 2012a, *MNRAS*, 424, 2055

Huarte-Espinosa, M., Frank, A., Blackman, E. G., et al. 2012b, *ApJ*, 757, 66

Ivezic, Z., & Elitzur, M. 2010, *MNRAS*, 404, 1415

Kastner, J. H., Balick, B., Blackman, E. G., et al. 2013, *ApJ*, 591, 37

Lee, C.-F., & Sahai, R. 2003, *ApJ*, 586, 319

Matt, S., Frank, A., & Blackman, E. G. 2006, *ApJ*, 647, 45

Morris, M. 1987, *PASP*, 99, 1115

Raga, A. C., Beck, T., & Riera, A. 2004, *ApSS*, 293, 27

Redman, M. P., O’Connor, J. A., Holloway, A. J., et al. 2000, *MNRAS*, 312, 23

Sahai, R., Morris, M. R., & Villar, G. G. 2011, *AJ*, 141, 134

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

Sánchez Contreras, C., Alcolea, J., Bujarrabal, V., et al. 2018, *A&A*, 618, 164

Sánchez Contreras, C., Bujarrabal, V., Miranda, L. F., & Fernández-Figueroa, M. 2000, *A&A*, 355, 1103

Sánchez Contreras, C., Cortijo-Ferrero, C., Miranda, L. F., et al. 2010, *ApJ*, 715, 143

Sánchez Contreras, C., & Sahai, R. 2012, *ApJS*, 203, 16

Sánchez Contreras, C., Veillía Prieto, L., Agüinde, M., et al. 2015, *A&A*, 577, 52

Santander-García, M., Bujarrabal, V., Koning, N., et al. 2015, *A&A*, 573, 56

Shu, F. H., Najita, J., Ostriker, E., et al. 1995, *ApJ*, 455, 155

Smith, N., Balick, B., & Gehrz, R. D. 2005, *AJ*, 130, 853

Soker, N. 2002, *ApJ*, 568, 726

Steffen, W., Espíndola, M., Martínez, S., & Koning, N. 2009a, *RMxAA*, 45, 143

Steffen, W., García-Segura, G., & Koning, N. 2009b, *ApJ*, 691, 696

Tenorio-Tagle, G., Canto, J., & Rózycka, M. 1988, *A&A*, 202, 256

van Marle, A. J., Cox, N. L. J., & Decin, L. 2014, *A&A*, 570, 131

Zijlstra, A. A., Chapman, J. M., te Lintel Hekkert, P., et al. 2001, *MNRAS*, 322, 280