

---

# Explosive Shaping of Proto-Planetary Nebulae

Timothy J. Dennis<sup>1</sup>, Andrew J. Cunningham<sup>1</sup>, Adam Frank<sup>1</sup>, Bruce Balick<sup>2</sup> and Sorin Mitran<sup>3</sup>

<sup>1</sup> Department of Physics & Astronomy, University of Rochester, Rochester, NY 14627 [tdennis@pas.rochester.edu](mailto:tdennis@pas.rochester.edu)

<sup>2</sup> Department of Astronomy, University of Washington, Seattle, WA 98195 [balick@astro.washington.edu](mailto:balick@astro.washington.edu)

<sup>3</sup> Department of Mathematics, University of North Carolina, Chapel Hill, NC 27599 [mitran@amath.unc.edu](mailto:mitran@amath.unc.edu)

**Summary.** We present a pair of 2.5D simulations for the purpose of critically examining two alternative models of a collimated proto-planetary outflow. We consider a ballistic clump, and a steady jet, and compare and contrast the morphologies and kinematics that arise in each case. We find that the clump model provides as good or better a description both morphologically and kinematically as does the jet model.

**Key words:** ISM: jets and outflows – planetary nebulae: general – planetary nebulae: individual (CRL-618) – stars: AGB and Post-AGB

## 1 Introduction

Observations over the past decade have revealed an unexpectedly rich variety of morphological classes for proto-planetary nebulae (PPNe) [1]. A new paradigm is needed to account for the point-symmetric, multipolar and butterfly PPN types. The highly collimated outflows associated with these objects have led to the suggestion that high-speed jets operate during the late asymptotic giant branch (AGB) and/or the post-AGB evolutionary phases of the central star [9]. Momentum excesses of as much as  $\sim 10^3$  times that for which radiation pressure can account are observed in these outflows [4], which has led to the suggestion that they are magnetically launched [2, 3, 5, 6]. Magnetic launch mechanisms can operate either in the steady-state, or – as has been suggested for both Supernovae (SNe) and gamma-ray bursts (GRBs) – in the impulsive limit [8]. In this contribution we present simulations of two alternative models for the collimated outflows associated with PPNe: a steady jet and a ballistic clump. We find that ballistic clumps do as well or better than steady jets in accounting for both the morphological and kinematical characteristics of PPN-associated outflows.

## 2 Description of initial conditions

We use the AstroBEAR code which is extension of the BEARCLAW adaptive mesh refinement (AMR) package for solving conservation laws. We present two 2.5D simulations of outflows; one modeled as a ballistic clump, and one as a steady jet, each with an effective resolution of 48 cells per clump/jet radius,  $r_0$ , and parameterized to approximate as closely as possible the conditions present in the circumstellar envelope of a post-AGB star. The number density profile of the ambient environment is modeled in both cases according to:

$$n_a(r) = \min \left( n_0, \frac{n_0 r_0^2}{r^2} \right) \quad (1)$$

The clump number density,  $n_c$  is specified by:

$$n_c(r) = n_a(r) + n_0 \left[ 1 - \left( \frac{|r - r_{c,0}|}{r_0} \right)^2 \right] \quad (2)$$

for  $|r - r_{c,0}| \leq r_0$ , while the jet number density  $n_j$  is taken to be constant. The jet velocity,  $v_j$  is smoothed according to:

$$v_j(r) = v_{j,0} \left[ 1 - (1 - s) \left( \frac{r}{r_0} \right)^2 \right] \quad (3)$$

Radiative cooling is modeled using optically thin atomic line cooling. Numerical values for all relevant parameters are given in table 1.

**Table 1.** Simulation Parameters

Model	Parameter	Value
Jet	Radius, $r_j$ .....	500 AU
	Computational cells per $r_j$ ..	48
	number density, $n_j$ .....	500 $cm^{-3}$
	peak velocity, $v_{j,0}$ .....	100 $km s^{-1}$
	Temperature, $T_j$ .....	200 K
	Nominal ambient density, $n_a$ ..	500 $cm^{-3}$
	Ambient temperature, $T_a$ ..	200 K
	Shear parameter $s$ .....	0.9
Clump	Radius, $r_c$ .....	500 AU
	Computational cells per $r_c$ ..	48
	nominal number density, $n_o$ ..	500 $cm^{-3}$
	velocity, $v_c$ .....	100 $km s^{-1}$
	Temperature, $T_c$ .....	200 K
	Nominal ambient density, $n_a$ ..	500 $cm^{-3}$
	Ambient temperature, $T_a$ ..	200 K

### 3 Results and Conclusion

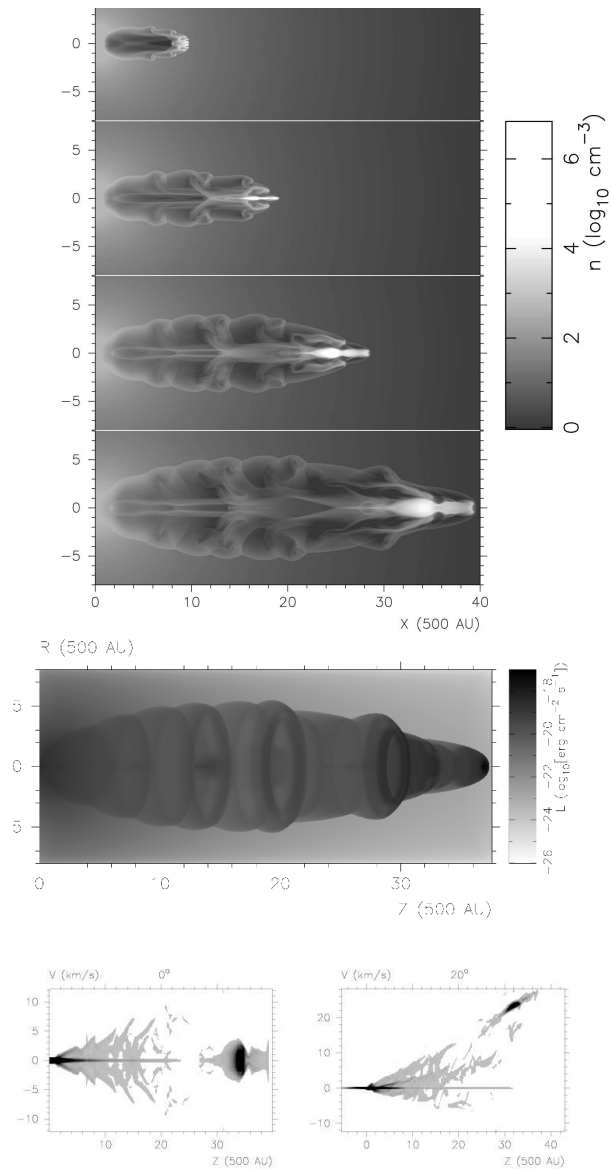
Our results for the clump and jet are presented in figures 1 and 2 respectively. We find that the clumps account as well or better than jets for morphology in two ways. Firstly, we find that over the same distance, the frequency of occurrence of ablation events which lead to structures reminiscent of rings seen in observations, is greater for the case of the clump model than for the jet model. This is particularly evident in the synthetic maps of emission. Secondly – as indicated in the sequences of density maps – outflow collimation is better preserved over the course of the simulation in the case of the clumps.

Additionally, kinematical evidence in the form of synthetic position-velocity (PV) diagrams indicate that clumps preserve “Hubble-Flow”-like kinematics better than do jets in spite of the greater frequency of ablation events. Indeed, PV diagrams for the jet indicate a complete absence of any such behavior, while a clear linear trend is evident in the case of the clump when the angle of projection is taken to be non-zero, so that the contribution of the axial component of velocity to the line-of-sight velocity predominates.

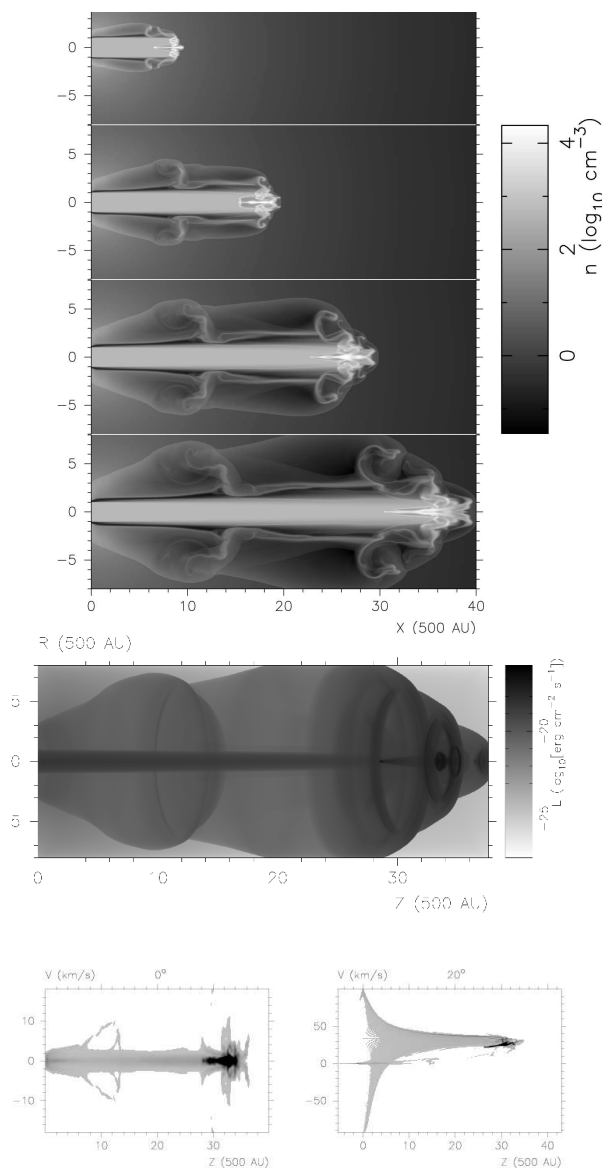
We conclude that Multi-polar PPNe are more easily explained as resulting from the fragmentation of an explosively launched shell. Jet Models of such PPNe would require positing multiple, co-existing, separately-aligned, quasi-stable rotational axes.

### References

1. B. Balick, A. Frank: *Ann. Rev. Astron. & Astroph.* **40**, 439 (2002)
2. E. G. Blackman, A. Frank, J. A. Markiel et al: *Nature* **409**, 485 (2001)
3. E. G. Blackman, A. Frank, C. Welch: *Astrophys. J.* **546**, 288 (2001)
4. V. Bujarrabal, A. Castro-Carrizo, J. Alcolea, et al: *Astron. & Astrophys.* **377** 868 (2001)
5. A. Frank: arXiv:astro-ph0606583v1 (2006)
6. A. Frank, E. G. Blackman: *Astrophys. J.* **614** 737 (2004)
7. S. Matt, A. Frank, E. G. Blackman: *Astrophys. J.* **647** L45 (2006)
8. T. Piran: *Rev. Mod. Phys.* **76** 114 (2005)
9. R. Sahai, J. T. Trauger: *Astrophys. J.* **116** 1357 (1998)



**Fig. 1.** (top) Clump density at times 208, 477, 753, and 1082 years; (center) Synthetic map of Clump integrated radiative emission at time 1082 years assuming optically thin atomic line cooling, and a projection angle of  $20^\circ$ ; (bottom) Synthetic Position-Velocity Diagram of clump at time 1082 years assuming projection angles of  $20^\circ$  (left) and  $0^\circ$  (right) respectively. Note: all images have been produced by revolving the 2.5D simulation data about the symmetry axis and integrating.



**Fig. 2.** (top) Jet density at times 336, 628, 896, and 1165 years; (center) Synthetic map of Jet integrated radiative emission at time 1132 years assuming optically thin atomic line cooling, and a projection angle of 20°; (bottom) Synthetic Position-Velocity Diagram of jet at time years assuming projection angles of 20° (left) and 0° (right) respectively. Note: all images have been produced by revolving the 2.5D simulation data about the symmetry axis and integrating.