Planetary Nebulae in our Galaxy and Beyond
Proceedings IAU Symposium No. 234, 2006
M. J. Barlow & R. H. Méndez, eds.

doi:10.1017/S1743921306004145

The shaping of planetary nebulae through interaction with the interstellar medium

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Abstract. Interaction with the Interstellar Medium (ISM) cannot be ignored in models of PN evolution and shaping. As first pointed out by Villaver *et al.* (2003 ApJ 585 L49), this interaction begins during the AGB phase. We have run extensive sets of 3D simulations, from the beginning of the AGB superwind until the end of the PN phase to study this interaction. We find ISM interaction strongly affects the outer structures. The simulations predict parsec-size shells to be common. The structure and brightness of ancient PNe is largely determined by the ISM interaction during the AGB and the majority of PNe will have tail structures.

Keywords. stars: AGB and post-AGB, circumstellar matter, planetary nebulae: general, ISM: structure, ISM: evolution, stars: mass-loss, hydrodynamics

1. Introduction

Observations of planetary nebulae (PNe) have shown several cases where the outer shell shows the only departure from symmetry and this has been proposed to be an effect of interaction with the interstellar medium (ISM). Recently, Villaver *et al.* (2003) performed 2D hydrodynamic simulations following the full AGB and post-AGB (PN) phases and found that the AGB phase has the predominant PN shaping effect. Observational evidence for the effect of the ISM on AGB wind structures was found by Zijlstra & Weinberger (2002).

We have developed a "triple-wind" model (Wareing *et al.* 2006) using an initial slow AGB wind, a subsequent fast post-AGB wind and adding a third wind reflecting the movement through the ISM into the accepted interacting stellar winds model. We are using a hydrodynamic scheme (Wareing 2005) to investigate the effects of this triple-wind model on the formation of PNe. We have now run a large set of simulations modeling the 500,000 yr evolution on the AGB. Our parameters are detailed in Table 1.

2. Results and discussion

It is clear from our results that the interaction with the ISM strongly influences the environment in which the PN forms (see left panel of Figure 1). Our results reveal a four stage PN evolution. In the first "undisturbed" stage the fast wind shell is initially

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Table 1. Simulation parameters

	$\dot{M}$ [$M_\odot\,yr^{-1}$]	ρ [$H\,cm^{-3}$]	v_{wind} [$km\,s^{-1}$]	T_{wind} [K]
Slow wind	$10^{-7}, 5\times10^{-7}, 10^{-6}, 5\times10^{-6}$		15	10^4
Fast wind	5×10^{-8}		1000	5×10^4
ISM		2, 0.1, 0.01	0–200; steps of 25	8×10^3

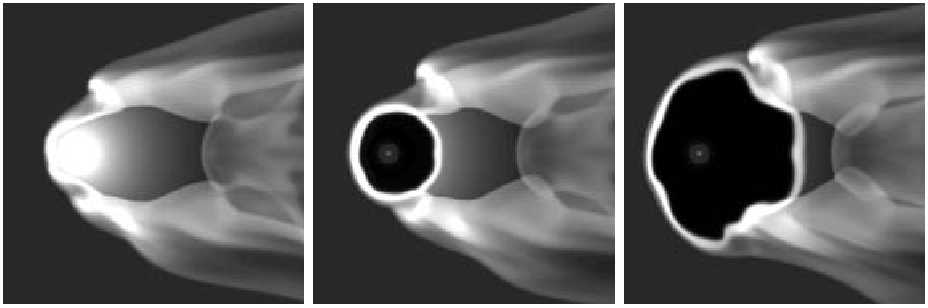

Figure 1. Logarithmic density slices through the centre of the data cube showing the evolution of the PN–ISM interaction with the central star having a velocity of 100 $\mathrm{km\,s^{-1}}$. The images are 1 pc on a side. The left panel is at the end of the AGB phase, the middle 3000 yrs into the PN phase and the right 6000 yrs.

unaffected. In the second "brightening" stage, the PN brightens upstream as the shell interacts with the bow shock (see the middle panel of Figure 1). In the third "deviation" stage, the PN deviates from circular symmetry as the downstream shell portion progresses down the tail (see the right panel of Figure 1) and the central star appears to move upstream of the geometric nebula centre. Finally, in high speed cases ($\geqslant$ 100 $\mathrm{km\,s^{-1}}$) a fourth "swept-downstream" stage occurs where the fast wind has formed a bow shock and the downstream portion of the shell has progressed beyond the tail of undisturbed AGB material. We find that PNe evolve quicker through these stages the faster they move through the ISM. Central star displacement during the third stage can occur early on when the central star has a high proper motion and thus is not an indicator of an old PN. PNe with large AGB wind bow shocks can re-brighten late in life when the PN eventually enters the second stage.

Much of the mass lost during the AGB phase is stripped downstream, from 65% at a proper motion of 25 $\mathrm{km\,s^{-1}}$ to 90% at 175 $\mathrm{km\,s^{-1}}$, providing a possible explanation of the missing mass problem observed in PNe.

3. Conclusions

These conclusions are in agreement with the conclusions reached by Villaver *et al.* (2003) using similar models. PNe observed to be interacting with the ISM are not necessarily ancient, nor require high proper motions or magnetic fields. Our simulations have shown that interaction can become apparent at a young age and that central stars with an average proper motion can show evidence of interaction in their nebulae. A test case comparing simulations of a high speed star to new IPHAS observations of PN Sh 2-188 has given an excellent fit of our model to available data (Wareing *et al.* 2006).

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https://doi.org/10.1017/S1743921306004145 Published online by Cambridge University Press