The interaction of planetary nebulae with the interstellar medium

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Summary. Interaction with the interstellar medium (ISM) cannot be ignored in models of planetary nebula (PN) evolution and shaping. Recent research has shown this interaction begins during the asymptotic giant branch (AGB) phase of evolution. We have run extensive 3D simulations, following the AGB and PN phases, using a "triple-wind" model which includes a slow symmetric AGB wind, fast symmetric post-AGB wind and a third wind reflecting the linear movement through the ISM. A wide range of stellar velocities, constant mass-loss rates and ISM densities has been considered.

We find ISM interaction strongly affects the outer structures. The simulations predict parsec-size shells to be common: previously such shells have been attributed to mass-loss modulations by thermal pulses. The majority of PNe will have tail structures and the structure and brightness of ancient PNe is largely determined by the ISM interaction during the AGB. Cases comparing our simulations to observations of the AGB star R Hya and the PN Sh 2-188 have given an excellent fit of our model to available data.

In some cases, instabilities launched from the bow shock ahead of the star can form vortex structures downstream, enhancing mixing and returning angular momentum to the ISM, essential for the formation of the next generation of stars.

1 Introduction

Planetary nebulae (PNe) display a wide variety of shapes some of which, e.g. round, can be simply understood in terms of the symmetric interacting stellar winds (ISW) model [16]. Many theories have been introduced to explain more complex shapes such as hour-glasses and butterflies e.g. adding an asymmetric slow wind to the ISW model [14, 1] invoking a binary companion to the central star [21] or magnetic fields [11]. Observations of PNe have shown several cases where the only departure from symmetry is in the outer shell. Interaction with the interstellar medium (ISM) has been postulated to be the cause of these asymmetries.

Early studies of the PN–ISM interaction [12, 19, 13] concluded that a nebula will fade away before any disruption of the shell becomes noticeable. In contrast to this, many PNe with large angular extent were found to show signs of PN–ISM interaction, including all with central stars with a proper motion greater than 0.015 arcsec yr^{-1} [3]. Hydrodynamical models [20] of the interaction revealed that the PN shell is first compressed in the direction of motion, then in later stages significantly decelerated with respect to the central star. Both of these studies conclude that the interaction with the ISM becomes dominant when the density of the nebular shell has dropped below a certain critical limit, typically $n_{\mathrm{H}} = 40\,\mathrm{cm}^{-3}$ for a PN in the Galactic plane.

Villaver et al.[23] (hereafter referred to as VGM) pointed out that previous studies of the PN–ISM interaction had ignored the preceding asymptotic giant branch (AGB) stage of stellar evolution. VGM performed 2D hydrodynamic simulations and found that crucially the interaction is defined during this stage where the slow wind is shaped by the ISM; the PN then forms in this pre-shaped environment. Employing a conservative relative velocity of the central star to the ISM of 20 $\mathrm{km\,s}^{-1}$ and a low density of the surrounding ISM of $n_{\mathrm{H}} = 0.1\ \mathrm{cm}^{-3}$, they found that the PN is brightened on the upstream side of the nebular shell and concluded that PN–ISM interaction provides an adequate mechanism to explain the high rate of observed asymmetries in the external shells of PNe. Further, stripping of mass downstream during the AGB phase provides a possible solution to the problem of missing mass in PNe.

VGM found that simple hydrodynamic simulations can reveal much information regarding the PN–ISM interaction. In order to investigate the interaction further, we have developed a 'triple-wind' model including an initial slow AGB wind, a subsequent fast post–AGB wind, and a third wind throughout reflecting the movement through the ISM. Employing a parallel 3D hydrodynamic scheme to simulate our model, we have performed a comprehensive set of 92 simulations investigating the PN–ISM interaction. We have used our simulations to interpret the structure of the extreme PN Sh 2-188 [25], the structure around the AGB star R Hya [26] and investigate vortices launched from the head of the bow shock [27]. In this conference paper, we consider these results and summarize our paper on the generalization of the PN-ISM interaction [28].

2 The hydrodynamic scheme and triple-wind model

The numerical scheme, CUBEMPI, used in our simulations to solve the hydrodynamics equations employs a second-order Godunov method due to [10]. It is posed in 3D Cartesian coordinates, fully parallel and includes the effect of radiative cooling due to [18] above 10^4-K. We have used a numerical domain of 200^3 cells. Full details can be found in [24].

In our 'triple-wind' model, the simulation is performed in the frame of reference of the star, which is placed at cell coordinates $(50, 100, 100)$. Mass loss is effected by resetting the values of the hydrodynamic variables at the start of every timestep in a volume-weighted spherical region of radius $5\frac{3}{4}$ cells at the position of the central star. The wind has been modeled with a spherically symmetric constant mass-loss rate $\dot{M}$ with constant velocity v and temperature T. Density in the source volume has been defined by $\dot{M}/(4\pi v r^2)$ where r is the physical radial distance from the central star. The other hydrodynamic variables are set accordingly. Simulation of movement through the ISM is achieved by flowing ISM material in at the ($x = 1$) boundary with a velocity vector v_x, v_y, v_z = ($v_{\rm ISM}$,0,0). The ISM density and temperature are constant. All other numerical boundaries have conditions allowing material to flow out of the domain freely. Gas pressures in the model are calculated assuming an ideal gas equation of state.

3 Model parameters

We have held the following parameter values constant: for the slow AGB wind a velocity of $v_{\rm sw} = 15$ km s^{-1} and a temperature of $T_{\rm sw} = 10^4$ K; for the fast post–AGB wind a mass-loss rate of $\dot{M}_{\rm fw} = 5\times10^{-8}\ \dot{M}$, a velocity of $v_{\rm fw} = 1000$ km s^{-1} and a temperature of $T_{\rm fw} = 5\times10^4$ K; and for the ISM a temperature of $T_{\rm ISM} = 8000$ K, characteristic of the warm intercloud medium [5]. In the model, the switch between the AGB wind and the post–AGB wind is instantaneous and occurs after 5×10^5 years of AGB evolution. In view of the still considerable uncertainties on the detailed properties and evolution of these winds, more detailed temporal variations have not been modeled.

In our simulations, we have varied three parameters: relative velocity of the star to the surrounding ISM $v_{\rm ISM}$, slow wind mass-loss rate $\dot{M}_{\rm sw}$ and ISM density $\rho_{\rm ISM}$. We have considered a range of $v_{\rm ISM}$ from 0 km s^{-1}, testing the implementation of the triple-wind model and its ability to simulate a spherical nebula, up to 200 km s^{-1}, in 25 km s^{-1} steps in order to fully cover the range of velocities of PN-forming stars in the Galaxy. We have used three constant values of ISM density $n_{\rm H}$ = 2, 0.1 & 0.01 cm^{-3} to investigate the range of densities in and just above the Galactic plane, where most PNe are found. We have used values of the AGB wind mass-loss rate of 10^{-7}, 5×10^{-7}, 10^{-6} & $5\times10^{-6}\ \dot{M}$ up to $v_{\rm ISM} = 75$ km s^{-1}. Above this velocity, we have not used a mass-loss rate of $10^{-6}\ \dot{M}$ due to time and computational constraints.

4 Results and Discussion

This section summarizes work published more fully in [28]. The reader is referred to that paper for fuller details.

4.1 The four stages of interaction

How a PN will interact with the ISM is set during the AGB phase. VGM's work was the first to highlight this important point. During the AGB phase, the expanding AGB wind forms a bow shock ahead of the central star at a point of ram pressure balance against the oncoming ISM. Initially, the PN expands within this bubble of undisturbed AGB wind material and this we define as the first stage of PN–ISM interaction, Wareing-Zijlstra-O'Brien (WZO) stage 1. The PN is as yet unaffected by the ISM interaction which is radially further from the central star. The AGB wind bow shock may be observable as a faint arc around the PN. In the case of a slow-moving star with a large bow shock, this stage can last for the entire lifetime of the PN and it is unlikely a PN–ISM interaction will ever be observed. However, if the central star is moving even at average speed, the PN–ISM interaction can become rapidly apparent. We show this stage in Figure 1(a). Characteristic of this stage is a shell of swept-up ISM, up to a few pc away. This has been called a 'wall' [30]. On sky images, this may also show up as an area of reduced emission around the PN, located within the wall. There is some evidence for such cavities [29, 9].

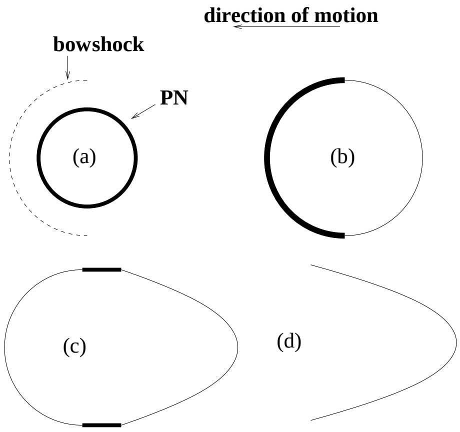

Fig. 1. A simple illustration of the appearance of a PN during the four stages of PN–ISM interaction. The direction of motion is to the left and thicker lines indicate the brightest regions. Panel (a) illustrates stage WZO 1, (b) stage WZO 2), (c) stage WZO 3 and (d) stage WZO 4. The position of letters (a), (b), (c) and (d) indicate the position of the central star at each stage.

Stage WZO 2 is entered when the PN has expanded far enough to interact with the bow shock formed during the AGB phase of evolution. As the PN shock merges with the AGB wind bow shock, driving another shock through it, the density and temperature of the material increase accordingly. This is shown in Figure 1(b). If $v_{\rm ISM}$ is predominantly in the plane of the sky, we would observe part of the nebular shell brighter than the rest. If, however, $v_{\rm ISM}$ is almost all along the line of sight to the PN, the whole structure would brighten and it would be difficult to identify this PN as undergoing a PN–ISM interaction until later in its evolution when distortions of the PN shell may reveal its true nature. This stage is relatively short lived and can be as short as a thousand years or so in our simulations with the largest $v_{\rm ISM}$.

The third stage of interaction, WZO 3, is defined by the geometric centre of the nebula moving downstream away from the central star as shown in Figure 1(c). The shift of the geometric centre due to the deceleration of the PN shell in the direction of motion is guaranteed to occur and provides a measurable effect of this interaction. During this stage, and beginning during the second stage, it is difficult to estimate the age of the PN from its apparent diameter on the sky. The AGB–ISM interaction has cocooned the PN inside the AGB wind bow shock and this considerably inhibits the expansion of the PN shell during stages two and three. Identification of the arc of nebular shell moving downstream yet still inside the AGB wind bubble and the central star would provide an estimate of the radius of the PN as this part of the shell is not yet inhibited by the PN–ISM interaction. This radial distance could provide an estimate of the true PN age. This third stage can be open-ended and only in the higher v_{ISM} cases is the PN affected enough by the interaction to become completely unfamiliar and enter the fourth stage of interaction before it fades away. Even in the highest velocity cases, the third stage lasts at least 10 000 years. It is possible that in the most extreme cases, the PN shell will continue to appear circular as the nebula is swept downstream of the central star. Sh 2-68 is an example of a nebula where the central star is thought to have deserted its PN [15]. The central star has the largest value of proper motion measured via ground-based observations at 53.2 ± 5.5 mas yr^{-1}.

In the fourth and final stage of PN–ISM interaction, WZO 4, the PN no longer appears circular. The fast wind has formed a bow shock ahead of the star and the little remaining AGB material in the vicinity of the star is being swept downstream with turbulent areas of high density and temperature as shown in Figure 1(d). At this time, the observable structure may not be identified as a PN. Further, the central star appears to have long since left these regions.

Central stars of PNe which show evidence of interaction should have a proper motion consistent with the observed distortions across the plane of the sky if the nebula is close enough and the central star is moving fast enough in the right direction to have an appreciable angular motion over time. [3] performed an investigation of PNe with known large angular motion and revealed many show signs of being in WZO Stage 2.

4.2 Missing mass

The interaction with the ISM considerably alters the amount of mass within the observed nebula: the ram-pressure stripping of material downstream during the AGB phase removes mass from the circumstellar region during the AGB phase. Our simulations show that up to 90 per cent of the mass ejected from the star during the AGB phase can be left downstream forming the tail behind the nebula. This effect may provide a solution to the missing mass problem in PNe whereby only a small fraction of the mass ejected during the AGB phase is observationally inferred to be present during the post–AGB phase. Our simulations clearly support VGM's conclusion that PN–ISM interaction at low speeds can provide an explanation of the missing mass phenomenon. Further, we show that this effect is even more pronounced at high speed.

5 Sh 2-188

Sh 2-188 was thought to be a bright one-sided arc-like PN when new observations taken as part of the Isaac Newton Group Photometric Hα Survey of the Northern Galactic Plane (IPHAS) [8] revealed a faint ring-like completion of the arc and a tail stretching away in opposition to the bright arc. Our model revealed this PN to be a strong PN–ISM interaction where the central star is moving at 125 km s^{-1} in the direction of the bright arc relative to the ISM and the nebular shell is interacting with a bow shock formed during the AGB phase between the slow wind and the ISM. In Figure 2 we show the IPHAS observation of Sh 2-188 next to the result of our simulation. We have discussed this comparison elsewhere [25].

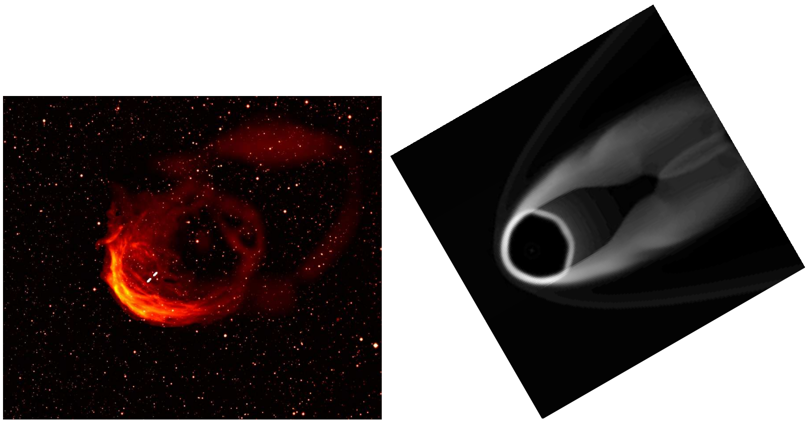

Fig. 2. A figure showing the IPHAS image of Sh 2-188 in the left panel and in the right panel a slice through the density datacube of the simulation at the position of the central star parallel to the direction of motion, 20,000 years into the post-AGB phase of evolution, aligned to the direction of proper motion. For full details, refer to [25].

6 R Hya

Recent IR observations of the AGB star R Hya as part of the MIRIAD programme [22] have revealed an arc-like structure to the North West of the star. We have interpreted this structure to be a bow shock ahead of the star [26]. The existence of this AGB bow shock has confirmed the hypothesis that the major shaping effect for the PN–ISM interaction occurs during the AGB phase of evolution. In Figure 3 we show the MIRIAD observation from [22] next to the result of our simulation. We have discussed this comparison elsewhere [26].

7 Vortices in the wakes of AGB stars

In our simulations, we see instabilities at the head of the AGB wind bow shock forming von-Karman like vortices downstream. Some structure in the bow shock of Sh 2-188 indicates the development of such structures. Further, recent observations [17] have revealed a 4 degree tail behind the Mira system. This tail contains a ring-like structure which can be understood as a vortex moving downstream. When the PN shell expands far enough to interact with these vortices, typically during stage 3 or 4, it is affected and the PN shell would be distorted and brightened accordingly. We have discussed the importance of these vortices for the local ISM elsewhere [27]. Inhomogeneities in the ISM could be expected to seed more instabilities for vortices.

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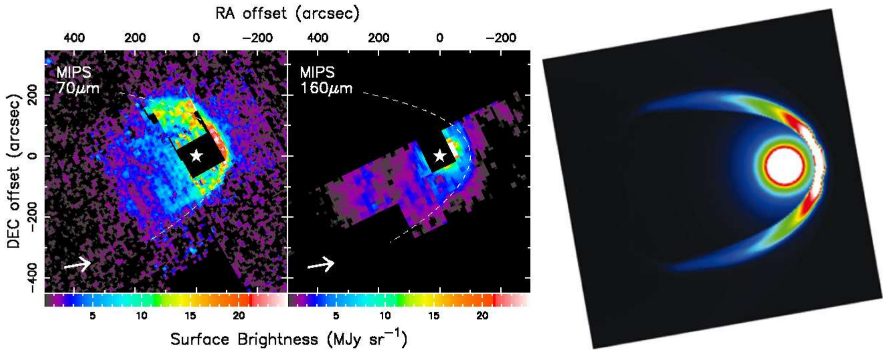

Fig. 3. A figure showing the MIRIAD image of R Hya in the left panel and a slice through the density datacube of the simulation at the position of the central star parallel to the direction of motion, 40,000 years into the AGB phase of evolution, aligned to the direction of proper motion. For full details, refer to [26]

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