RAM PRESSURE STRIPPING IN PLANETARY NEBULAE

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ABSTRACT

We present two-dimensional numerical simulations of the evolution of a low-mass star moving supersonically through its surrounding interstellar medium (ISM). We show that the ejecta of a moving star with a systemic velocity of 20 km s$^{-1}$ will interact with the ISM and will form bow shock structures qualitatively similar to what is observed. We find that, owing to ram pressure stripping, most of the mass ejected during the asymptotic giant branch (AGB) phase is left downstream of the moving star. As a consequence, the formation of the planetary nebula is highly influenced, even at the low relative velocity of the star. The models are based on the predictions of stellar evolution calculations. Therefore, the density and velocity of the AGB and post-AGB winds are time dependent and give rise to the formation of shock regions inside the cavity formed by the previous winds. As a result, the stand-off distance is also time dependent and cannot be determined by simple analytical arguments.

Subject headings: hydrodynamics — ISM: jets and outflows — ISM: structure — planetary nebulae: general — stars: AGB and post-AGB — stars: winds, outflows

1. INTRODUCTION

The process or processes that may cause the departure of spherical symmetry in planetary nebulae (PNs) have been the subject of many studies, e.g., the hydrodynamic collimation of the fast wind by an equatorial density enhancement (Frank & Mellema 1994), the rotation of a single star with a magnetized wind (Różycki & Franco 1996; García-Segura 1997; García-Mellema 1994), and the evolution of a PN in a close binary system (Soker 1996). These mechanisms are able to account for the formation of elliptical, point-symmetric, and bipolar PNs. However, several PNs have been observed in which mainly the external shell shows departure from sphericity (e.g., MA 3, PM 1-295, M2-40). In these PNs, the presence of asymmetries cannot be explained by the physical processes related to the central star (CS), such as rotation, magnetic fields, or binarity. Instead, the interaction with the interstellar medium (ISM) was proposed to be the cause of the observed asymmetries.

The interaction of a PN with the ISM was first suggested by Gurzadyan (1969, p. 235), and the first theoretical study was made by Smith (1976); he assumed a thin-shell approximation and the “snowplow” momentum-conserving model of Oort (1951). Later on, Isaacmann (1979) used the same approximation but considering higher velocities and ISM densities. Both theoretical works arrived at a similar conclusion, namely, that the nebula fades away before any disruption of the nebular shell becomes noticeable. Borkowski, Sarazin, & Soker (1990) analytically, and Soker, Borkowski, & Sarazin (1991) numerically, confirmed the thin-shell approximation originally developed by Smith (1976), concluding that the interaction becomes dominant when the density of the nebular shell drops below a critical limit, owing to the nebular expansion. As a consequence, the interaction should be easily observable during the late stages of the nebular evolution. Moreover, high ISM densities, large relative velocities, or both were needed to explain PN asymmetries due to interaction with the ISM.

This is the scenario commonly accepted nowadays, and as a result, the search for interaction of PNs with the ISM has been mostly restricted to old PNs with large angular extent (Tweedy & Kwitter 1996; Xilouris et al. 1996). Evidence for the interaction has been also reported in the study of some individual objects (e.g., Borkowski, Tsvetanov, & Harrington 1993; Tweedy, Martin, & Noriega-Crespo 1995; Soker & Zucker 1997), and the observations have been interpreted in the light of the available models. As a consequence, high spatial velocities were invoked to explain the morphologies of PNs at large distances from the Galactic plane.

The problem is that in the available models, the PN-ISM interaction was studied by considering the relative movement when the nebular shell was already formed. In this Letter, we demonstrate that when the PN formation is followed by considering the evolution of the stellar wind from the asymptotic branch (AGB), high velocities, high ISM densities, or the presence of a magnetic field is not necessary to explain the observed asymmetries in the external shells of PNs. Moreover, in contrast to what is commonly believed, the interaction is observable even during the very early stages of the PN phase.

2. THE NUMERICAL METHOD

We have carried out the numerical simulations with the fluid solver ZEUS-3D (Stone & Norman 1992a, 1992b; Stone, Midgley, & Norman 1992, developed by M. L. Norman and the Laboratory for Computational Astrophysics. The computations have been performed using a two-dimensional spherical polar grid with the angular coordinate ranging from 0° to 180° and a physical radial extension of 2 pc, which gives a total grid size of 4 × 2 pc. We have adopted a resolution of 400 × 360 zones in the radial and angular coordinates of the grid, respectively. We consider the photoionization of the gas during the PN phase by using a simple approximation to derive the location of the ionization front for arbitrary density distributions (see Bodenheimer, Tenorio-Tagle, & Yorke 1979; Franco, Tenorio-Tagle, & Bodenheimer 1990). This is done by assuming that ionization equilibrium holds at all times and that the gas is fully ionized inside the H ii region. The models include the Raymond & Smith (1977) cooling curve above 10^4 K. For temperatures below 10^4 K, the unperturbed gas is treated adiabatically but the shocked gas region is allowed to cool down with the radiative cooling.
curves given by Dalgarno & McCray (1972) and MacDonald & Bailey (1981). The photoionized gas is always kept at 10⁴ K, so no cooling curve is applied to the H II region unless there is a shock.

2.1. The Boundary Conditions

We assume that the ISM moves relative to the star perpendicular to the line of sight by fixing the position of the star at the center of the grid and allowing the ISM to flow into the grid at the outer boundary from 0° to 90°. On the other hand, from 90° to 180° we set an outflow boundary condition. The temporal evolution of the stellar wind for a 1 M⊙ star during the AGB phase (taken from Vassiliadis & Wood 1993) and the PN stage (Vassiliadis & Wood 1994) has been set within a small (five radial zones) spherical region centered on the symmetry axis, where reflecting boundary conditions are used. The gas evolution in a static configuration as well as the stellar wind inputs for the models are described in detail in Villaver, García-Segura, & Manchado (2002a) and Villaver, Manchado, & García-Segura (2002b).

In order to study the interaction process, we have adopted a purely hydrodynamical scheme, in which we assume that the ISM pressure is simply the standard gas thermal pressure, \( P = nK T \) (where \( n \) is the number of particles per unit volume, \( K \) is Boltzmann’s constant, and \( T \) is the gas temperature). Since the strength of the interaction depends linearly on the ISM density and quadratically on the relative velocity of the star, we have adopted two ISM densities and a very conservative value for the star’s velocity, 20 km s⁻¹. The ISM is assumed to be homogeneous with the characteristics of the warm neutral medium, which is the main observed constituent of the ISM, with temperatures estimated to be in the range 5000–8000 K (Kulkarni & Heiles 1988) and neutral atomic hydrogen densities between 0.1 and 1 cm⁻³ (Burton 1988). We use an ISM temperature of 6000 K and densities of 0.1 and 0.01 cm⁻³, the latter to study the interaction with a very low density ISM.

3. RESULTS

3.1. The Evolution during the AGB through a Low-Density Medium

The logarithm of the gas density during the AGB phase is shown in Figure 1 for a star moving with 20 km s⁻¹ through a low-density ISM (\( n_p = 0.01 \) cm⁻³). Figure 1 shows only half of the \( r-\theta \) plane, the star is fixed in the grid, and the ISM flows in from the top to the bottom.

During the very early stages of the evolution of an AGB star, a free-streaming steady stellar wind with a velocity of 2 km s⁻¹ and mass-loss rate of \( \dot{M} = 10^{-8} M_\odot \) yr⁻¹ reaches ram pressure equilibrium with the ISM at a stand-off distance from the star of 0.13 pc (Fig. 1, first panel on the left). After this, the mass-loss rate and wind velocity are changing continuously in the inner boundary, giving rise to the formation of shocks that develop inside the bow shock cavity formed by the early stationary wind. From then onward, the stand-off distance cannot be computed from a simple ram pressure balance argument between a free-streaming stellar wind and the ISM. The ram pressure of the ISM is balanced by the ram pressure of the stellar wind inside the bow shock cavity, making it a time-dependent problem.

As a consequence of the interaction process, a highly asymmetric shell is formed that grows in size mainly in the downstream direction. The outer bow shock is radiative for the stellar velocity considered, so the density of the swept-up shell is proportional to the square of the upstream Mach number and proportional to the ISM density. As the mass-loss rate continues (highly modulated by the thermal pulses in the star; see Fig. 1 of Villaver et al. 2002a), new shells are subsequently formed inside the structure generated by the previous stellar wind. During most of the AGB evolution (355,000 yr of the ~495,000 yr that the AGB phase lasts), the leading part of the gas is not able to expand far away from the CS. Only the high mass-loss rate periods associated with the last two thermal pulses during the AGB have enough momentum to compete efficiently with the previously developed density structure. It is at this moment that
the leading parts of the outer shell grow in size. The last two panels show the density at the end of the second thermal pulse and in the middle of the third one, respectively. Because of the relative movement, mass is constantly flowing away from the head of the bow shock, forming cometary structures behind the star.

3.2. The Evolution during the AGB through a Higher Density Medium

In Figure 2, we show the gas evolution for an ISM density of \( n_0 = 0.1 \, \text{cm}^{-3} \), lower than the value in the Galactic plane (\( \sim 1 \, \text{cm}^{-3} \)). The snapshots of the evolution have been selected at the same times as those shown in Figure 1. As expected, the effects of the stellar movement are more noticeable, since the ram pressure exerted by the ISM depends linearly on the ISM density. The compression and deformation of the upstream side of this shell is higher than in the case shown in Figure 1. As for the low-density case, the stagnation radius can be computed from a ram pressure balance argument only when the wind is stationary in the early evolution (see the first panel of Fig. 2, where the stagnation radius is a factor of \( 10^{-1/2} \) smaller than in the first panel of Fig. 1). In the present case, the upstream side of the shell does not increase in size until very late in the evolution, and the size is always at least 1.5 times smaller than the one formed when the star evolves in a lower density medium.

3.3. The PN Stage

During the PN phase, the stellar wind increases its velocity, generating an adiabatic shock that forms the brightest shell of the nebula. In principle, this shell should not be affected by the interaction with the ISM, unless other mechanisms such as ambipolar diffusion under the presence of an external magnetic field are invoked to propagate the asymmetry to the innermost regions of the nebula.

In the right panel of Figure 3, we show the gas density when the PN is 2500 yr old\(^5\) and when the ISM has a density of \( 0.1 \, \text{cm}^{-3} \). The simulated region has been reflected around the symmetry axis in order to more clearly show the structure. The left panel shows the PN at the same age but when the star is evolving at rest with respect to the ISM (see Villaver et al. 2002b). Two bright shells are clearly distinguished in both panels of Figure 3. These are a spherical innermost shell shaped by the fast wind and an external shell that shows a characteristic bow shock configuration in the right panel of Figure 3.

The first effect of the interaction, apart from that on the morphology, is that the total size of the outer PN shell (halo) is reduced considerably. The radius of the halo in the left panel of Figure 3 is 1.8 pc, whereas the outer shell of the interacting nebula has a radius of 0.7 pc. The displacement of the CS with respect to the geometrical center of the nebula is 0.1 pc, which corresponds to 20" at a distance of 1 kpc. A less obvious effect is that the formation of the outer shell of the PN takes place in a lower density environment, since most of the mass ejected during the AGB phase is stripped by the ram pressure of the ISM and left in the downstream direction of the stellar movement. The model at rest has 0.7 \( M_\odot \) of gas above the ISM value in the circumstellar envelope \( (0.43 \, M_\odot \) that was lost by the star and \( 0.27 \, M_\odot \) of ISM matter swept up by the wind); only 0.24 \( M_\odot \) of gas is recovered when the star is moving.

4. DISCUSSION

We find that the movement of the CS with respect to its surrounding medium considerably alters the circumstellar gas structure formed during the AGB phase and hence the PN formation. Up to now, it has been generally accepted that the deceleration of the nebular shell due to its interaction with the ISM can be more likely observed during the late stages of the nebular evolution. We find that when the evolution of the stellar wind is properly considered in the simulations, the interaction with the ISM cannot be studied using simple ram pressure balance

\(^5\) That is, 2500 yr after the photoionization has started at the end of the AGB phase.
arguments and plays a major role even during the early AGB evolution.

From an observational point of view, the presence of asymmetries in the halos of PNs that could be related to the interaction with the ISM is a common feature. The high rate of observed asymmetries cannot be explained if all of these PNs are moving at high velocities through high-density media. Instead, it can be understood when the evolution of the stellar wind is taken into account, producing a much higher efficiency in the interaction. Moreover, in agreement with our results, Guerrero, Villaver, & Manchado (1998) show kinematical evidences that the interaction of the external shells of PNs with the ISM are found at all evolutionary stages.

According to our simulations, it may not be necessary to invoke the presence of a magnetic field in the ISM to explain the asymmetries found in the slow-moving (10–20 km s$^{-1}$) PNs Sh 2-216 (Tweedy, Martos, & Noriega-Crespo 1995) and NGC 6894 (Soker & Zucker 1997). For the model parameters assumed in this Letter, no instabilities appear in the nebula, which is in agreement with the analytical results of Dgani & Soker (1994, 1998).

Another important aspect is that the interaction with the ISM considerably reduces the mass of the circumstellar envelope during the AGB and PN phases owing to ram pressure stripping. Stellar evolution calculations predict that stars with initial masses in the range of $\sim 1$–$5 M_\odot$ will end as PN nuclei with masses around $0.6 M_\odot$. Most of the mass is lost on the AGB phase and should be easily observable as ionized mass during the PN stage. However, observations of Galactic PNs reveal on average only $0.2 M_\odot$ of ionized gas. The mass stripped away by the ISM when the star is moving could solve the problem of the missing mass in PNs.

5. SUMMARY

We have studied the effects the relative movement of the CS with respect to the ISM has on the evolution of the stellar ejecta during the AGB phase and on shaping the PN. Under the very conservative conditions assumed for the ISM density and the CS’s velocity (20 km s$^{-1}$), we find that the PN-ISM interaction provides an adequate mechanism to explain the high rate of observed asymmetries in the external shells of PNs. According to our simulations, spherical halos in PNs are expected only if the star is at rest with respect to the ISM or if the star is moving at low angles with respect to the line of sight; otherwise, bow shock–like and cometary structures should be present.

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