FLIERs as stagnation knots from partially collimated outflows

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Abstract. We propose a new model for the formation of fast, low-ionization emission regions (FLIERs) in planetary nebulae that is able to account for many of their attendant characteristics and circumvent the problems on the collimation/formation mechanisms found in previous studies. In this model, Flieres are formed in the stagnation zone of partially collimated stellar winds with reduced momentum flow along the axis. A concave bow-shock structure is formed due to the lack of momentum flow along the axis of a midly bipolar stellar wind. The stagnation knots are formed when the shocked environment medium accumulates at the apex of the outer shell and is compressed to a dense knot in the concave section of the bow-shock. We present two-dimensional hydrodynamic simulations of the formation of a stagnation knot and compare the resultant dynamical properties with those of Flieres in planetary nebulae.

1. Introduction and model description

FLIERs in planetary nebulae were originally identified with the structures previously known as ansae in elliptical planetary nebulae (Balick et al. 1993) though their peculiar characteristics are now recognized in a much wider variety of PNe (e.g. Corradi et al. 1996. Guerrero et al. 1999), and their interpretation has resisted a consistent explanation up to date (Balick et al. 1998). Flieres are characterised by outflow radial velocities of the order of 30-50 km/s; ionization gradients decreasing outwards from the nebular core and ‘head-tail’ morphologies, notably with the tails pointing outwards from the nucleus. More recent observations reveal very high radial velocities for other Flieres (Corradi et al. 1999, Gonçalves et al. these proceedings, Redman et al. 1999). Mainly two types of models have been explored for the formation of Flieres (see Balick et al. 1998 and references therein), namely, ionization fronts (IF) on localized dense knots or bow-shocks of fast knots ramming through the shell of the PN. Recently, Redman & Dyson (1999) and Dyson & Redman (these proceedings)
discuss a model in which FLIERs represent recombination fronts (RF) in mass-loaded jets.

In this work we present a simple hydrodynamic model for the formation of symmetric axial knots with supersonic velocities from a low-density bipolar outflow with reduced momentum flux along its axis. The knots are formed from cooling shocked ambient gas in the stagnation region of the combined outflow. The evolution of a dense knot propagating through a thin ambient medium has been studied by Jones, Kang & Tregillis (1994) using hydrodynamic simulations and by Soker & Regev (1998) from analytic arguments in the specific context of FLIERs. However, those works do not discuss the formation process for the knots. Previously, we introduced the idea of a "stagnation knot" to model the large scale structure of the giant envelope of the PN KjPn 8 (Steffen & López, 1998). The reduced momentum flux around the axis causes the bow-shock to become concave instead of convex in this region. If the bow-shock is non-radiative, the ambient medium passing through the oblique region of the shock is then "refracted" towards the axis, instead of away from it, as it happens in conventional bow-shocks. The accumulated material in the stagnation region may then be held together for sufficient time to cool and be compressed to a dense knot. If the shock is radiative, the compressed post-shock material is later crushed to a single or multiple knots on and around the axis. As long as the central outflow continues and drives the expanding shock, the stagnation knot will move roughly at the same speed as the rest of the bow-shock and remains at the bright rim formed by shocked ambient gas. However, when the outflow ceases the envelope slows down rather quickly whereas the dense knot continues to move outwards at its original speed. As the amount of swept up mass from the ambient medium increases, the knot’s motion is progressively slowed down.

2. Simulations

In order to investigate the dynamical properties of the knots formed in the stagnation region of a partially collimated low-density outflow, we present two cases (A & B) of 2D-hydrodynamical simulations in axisymmetry using the Corali-code (Raga et al. 1995) with a 5-level binary adaptive grid and a maximum of $513 \times 257$ grid cells with a physical sizes of $5 \times 10^{17}$ cm by $2.5 \times 10^{17}$ cm for run A and half of these measures for run B. The cooling was calculated according to the description in Steffen et al. (1997) and references therein. The outflow was initialized on a sphere with a radius of $2.5 \times 10^{16}$ cm ($2.5 \times 10^{16}$ cm), a velocity of $2000$ km/s ($800$ km/s) and a half opening angle $\theta_0 = 15^\circ (15^\circ)$ (the angle of highest momentum flux) for run A (B). The initial number density of the outflow is $30$ cm$^{-3}$ ($40$ cm$^{-3}$) constant on the sphere, whereas that of the ambient medium was assumed to be $120$ cm$^{-3}$. The outflow is switched-off after $1.5 \times 10^{10}$ seconds (473 years) for both runs. The momentum flux was modulated as a function of the angle $\theta$ from the axis arbitrarily using $v(\theta) = v_0(\theta_0/\theta)^2$ for $\theta > \theta_0$ and $v(\theta) = v_0/(1 - 0.25(\theta - \theta_0)/\theta)$ for $\theta \leq \theta_0$. S
3. Results

Key ingredients often found in PNe with FLIERs are observed to form in the models. The outflow creates a low density bipolar cavity with an outer dense and bright rim (see Figure 1) of shocked halo gas which propagates at a few tens of kilometers per second. The rim develops instabilities which produce high density knots propagating at velocities similar to the rim. These knots might be identified as non-axial FLIERs similar to those observed in NGC 7662 (see also Dwarkadas & Balick 1998). In run A (Figure 1a to 1d) after forming a sort of dense "polar cap" at $t \approx 300$ years the stagnation region begins to be compressed to a knot, which we associate with the FLIER. The expansion speed of the rim, the stagnation knot and the instability knots ranges between 60 and 150 km/s at this time. After the stellar wind ceases the expansion speed of the rim and the instability knots rapidly drops to around 50 km/s. The stagnation knot, however, continues its linear motion at a speed of around 150 km/s which drops more slowly. This model leads to representative parameters consistent with observations of PNe with FLIERs.

In the more extreme case of run B (Figure 1e and 1f) the stagnation knot reaches 250 km/s and produces a long feature of fast material far away from the main nebula. The region through which the stagnation knot has propagated shows an outward increase in velocity (Fig. 1d,f). As the dense knot continues, the smaller pieces spread out along the path developing a kinematic pattern of roughly linear increase of speed with distance, as observed in MyCn 18 (Bryce et al. 1997, Redmann et al., these proceedings) and other recent cases (Corradi et al. 1999, and Gonçalves these proceedings).

Within the framework of this model, it would be interesting to search for those young elliptical PNe that show signs of polar caps as likely candidates to develop into compact FLIERs. Full details of this work will appear shortly elsewhere.

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Figure 1. A sequence of density cuts through run A (a-c) and run B (e) as described in the text. Panels "d" and "f" represent the velocity fields corresponding to the densities in "c" and "e".