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The Most Collimated Outflows of Planetary Nebulae

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Abstract. I characterize the common properties of highly collimated bipolar outflows and identify the most plausible mechanisms that create and maintain them.

Keywords. planetary nebulae: general, AGB and post-AGB, hydrodynamics, MHD

Goals: Kinematic observations show that bipolar PNe have the most vigorous collimated outflows, much as the images suggest. The process(es) that collimate large-scale stellar outflows in PNe remain elusive and contentious. The leading contenders are disks or tori formed from mass exchange in a close binary system (Morris 1981, Soker & Livio 1994, Morris & Mastrodemos 1999) and the tension of magnetic fields ejected in the winds of a rotating AGB star (Chevalier & Luo (1994), Blackman *et al.* (2001), Frank & Blackman (2004), García-Segura, López, & Franco (2005), 'G-SLF'). Direct observations to test the viability of collimation by binary interactions and/or magnetic fields are daunting. Fields can only be sampled locally in masers where their energy densities turn out to be high but they cannot yet be traced globally. As for the binary systems, limited spatial resolution and dust obscuration prevent direct or spectroscopic observations of the collimation processes that might operate on scales of the orbital separations.

For now, the best hope of probing the collimation mechanism(s) in post-AGB stars lies in the studies of the morphologies of most extreme examples of highly collimated bipolar PNe where, presumably, the collimation mechanism(s) is(are) dominant and identifiable.

Sample Selection: The well-resolved bipolars Hen 2-86, Hen 2-104, Hen 2-320, Hen 2-437, Hubble 12, Mz 3, M 1-57, M 2-9, M 2-46, M 2-48, M 3-28, MyCn 18, NGC 6302 and NGC 6881 are highly collimated, as demonstrated by their sharply pinched waists. They exhibit other common features, such as hollow lobes (i.e., edge-brightened) and nested structures of similar opening angles. Low-ionization ansae often appear near the symmetry axes. Where their kinematics have been mapped, the outflow patterns exhibit $v_{rad} \propto radius$, implying that their shapes were formed during a fairly brief event.

Collimation by binary interactions: Binary collimation mechanisms are very well suited to explain the axial symmetry of bipolarity and the huge outflow momenta of many bipolar protoPNe (Bujarrabal *et al.* 2001) and the speeds of some of their ansae (Soker 2006). Nonetheless, the extra-nuclear structures seen here show a variety of common details that are simply too complex to be readily understood as the indirect effects of close binary interactions. That is, the collimation process can act only close to the binary system, so we expect that it will be very difficult for good models to account for nested structures, inner and outer lobes, and other common large-scale morphological

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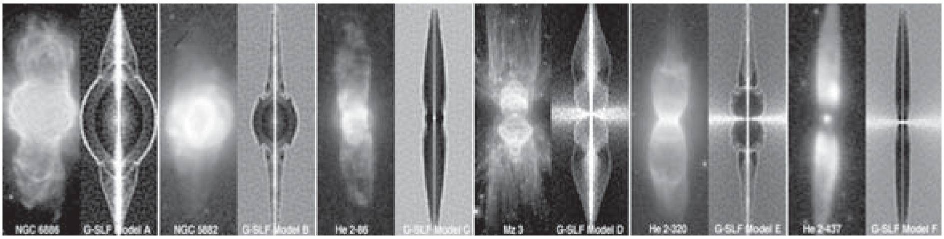

Figure 1. [N II] images of bipolar PNe and closely matching MHD density models adapted from G-SLF.

features of extreme (i.e. pinched-waist) bipolar PNe. No large-scale computational models of the collimation that results from binary interactions with good physics have been published, making morphological tests of the concept impractical at this time.

Collimation by magnetic fields: G-SLF published models of the winds driven by the rapid emergence of a toroidal magnetic field at the stellar surface for weak, moderate, and strong fields (0.1, 1, 5 G). Models AC assume an isotropic wind at the stellar surface and a uniform external environment. Models DF are identical except that the external environment has an imposed equatorial density enhancement. G-SLF show panels of the evolving structure, some of which we reproduce here (Fig. 1). They also find mass outflow speeds as high as 10^3 km s^{-1}, as required to account for the large momenta observed in young bipolars.

Conclusions: Both MHD and binary concepts can explain axisymmetry. However, only MHD models are uniquely capable of accounting for a large range of morphologies found outside the cores of bipolar PNe. However, we caution that models with ionization heating, radiative cooling, and radiation pressure on dust particles are still in their infancy. Also, a duplicity of shaping mechanisms may be at work simultaneously or at different times. Therefore, it is premature and philosophically improper to favor one concept to the exclusion of the others.

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