Planetary Nebulae in our Galaxy and Beyond
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The Dynamical Evolution of Planetary Nebulae After the Fast Wind

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Abstract. In this paper we explore the dynamics of ionization bounded planetary nebulae after the termination of the fast stellar wind. When the stellar wind becomes negligible, the hot, shocked bubble depressurizes and the thermal pressure of the photo-ionized region, at the inner edge of the swept-up shell, becomes dominant. At this stage the shell tends to fragment creating clumps with comet-like tails and long, photo-ionized trails in between, while the photo-ionized material expands back towards the central stars as a rarefaction wave. Once the photo-ionized gas fills the inner cavity, it develops a kinematical pattern of increasing velocity from the center outwards with a typical range of velocities starting from the systemic velocity to ~ 50 km s^{-1} at the edges. The Helix nebula and the Dumbell nebula are clear examples of planetary nebulae at this late evolutionary stage.

The numerical experiment presented here (Figure 1) includes two phases: in the first phase, a typical two-wind model scenario (Kwok 1982) is considered, i. e., a fast wind with $v_\infty = 1000$ km s^{-1} and $\dot{M} = 10^{-7}$M$_\odot$ yr^{-1} sweeps up a slow wind with $v_\infty = 10$ km s^{-1} and $\dot{M} = 10^{-6}$M$_\odot$ yr^{-1} . For simplicity, this phase lasts 1000 yr in the computation, but it could last longer or shorter depending on the particular track of stellar evolution. In the second phase, the fast wind is switched off, and the dynamical evolution is computed for a total of 8000 yr. In both phases the photo-ionization is considered following the approach of García-Segura & Franco 1996 with a central star that emits 10^{45} s^{-1} ionizing photons. A simple expanding spherical morphology is adopted for simplicity (i.e., no rotation, magnetic field, or anisotropic mass-loss events).

The simulations are performed with the hydrodynamical code ZEUS-3D (version 3.4) (Stone & Norman 1992; Clarke 1996), and details about the set up can be found in García-Segura *et al.* (1999), and García-Segura *et al.* (2005) for the self-expanding grid technique.

Keywords. Hydrodynamics — Stars: AGB and Post-AGB — Planetary Nebulae: general — Planetary Nebulae: individual (NGC 7293, NGC 6853)

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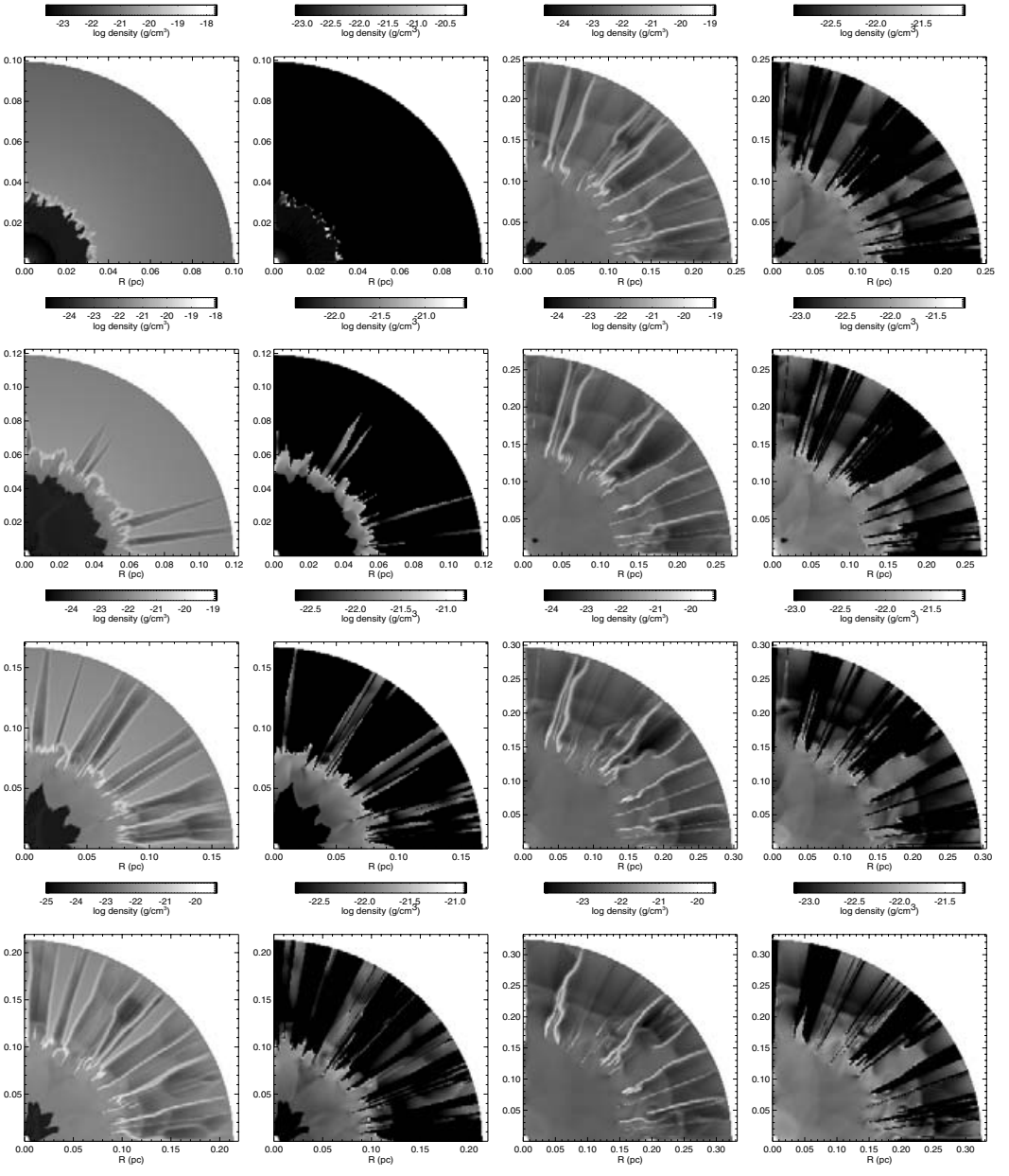

Figure 1. Snapshots of gas densities (left) and photoionized gas densities (right) covering 8000 yr of the evolution, each one separated by 1000 yr.

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