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Disk-Driven Planetary Nebulae: Shapes and Spectra

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Abstract. I have performed numerical hydrodynamical calculations of outflows driven by the evaporation of a pseudo-barotropic ring around a luminous central star. The outflow shapes and internal structures resemble known cylindrical nebulae. Some of the corresponding synthetic spectra show 'Hubble' type outflow.

Keywords. hydrodynamics, protoplanetary nebulae, evaporating disks

1. Introduction

Many bipolar (proto)planetary nebulae (pPN) have a pronounced cylindrical shape, but do not show an anisotropic stellar wind, or magnetic driving. In these cases there is clear evidence of a thick disk at the base of the nebula, and it would be quite remarkable if the outflow did not actually start there. Radiation from the central star is a plausible source of energy. Thus, I have computed a series of hydrodynamical models in which a dense gaseous ring around a luminous star is irradiated so fiercely that the disk surface blows off into space. The model generically produces well collimated cylindrical outflow patterns, with remarkable H-shocks along the axis. The first steps were published in Icke (2022). The present work is a continuation thereof, with emphasis on the velocity field.

2. Hydrodynamics

Single stars probably have planetary systems. When such a star becomes a pPN, its planets will be destroyed, especially if they are gaseous superjupiters. This gas forms an 'excretion disk', and the nascent white dwarf in its centre will fiercely irradiate the disk. The radiative influx energy is equal to the kinetic plus thermal energy of the evaporating gas. The launching conditions of the flow obey

$$\left(\frac{1}{2}\rho v^2 + \frac{1}{\gamma \mathscr{M}_0^2 \sqrt{r}}\right) v = \frac{\mathscr{L}}{\mathscr{L}_0}\,\frac{1}{r^2}\sin\left(\psi - \theta\right) \tag{1}$$

where ρ is the gas density, v the speed perpendicular to the disk surface, γ the adiabatic index of the gas, $\mathscr{M}_0$ the Mach number, $\mathscr{L}$ the luminosity, ψ the local inclination of the disk isodensity surface, θ the polar angle and r the radial distance from the star. In the derivation of Eq.(1), each variable V was replaced by $V_0 \times V$, in which V_0 is a fixed scaling quantity, and V is now dimensionless. The scaling quantities are related by

$$s_0^2 = \gamma P_0/\rho_0 \;; \quad \mathscr{M}_0 = v_0/s_0 \;; \quad \mathscr{L}_0 = 4\pi\rho_0 r_0^2 v_0^3 \tag{2}$$

In my computations, all variables are of order unity, so that the results may be scaled to the observations. For example, using the 'astronomical' units $\rho_A = 10^6$ H/cm^3,

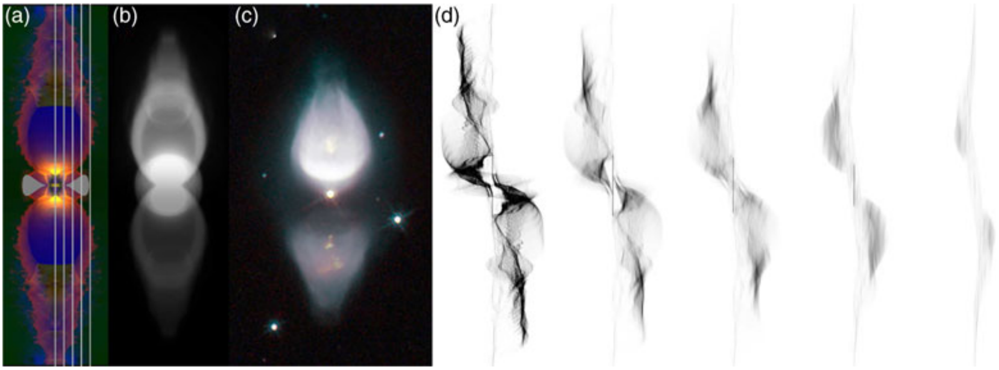

Figure 1. Results from one of my evaporating-disk models compared with M1-92. The mean values in this snapshot: $\rho = 0.66$, $P = 0.35$, $v = 0.71$. Maximum: $\rho = 18.7$, $P = 8.9$, $v = 4.0$. Luminosity $\mathscr{L}_0 = 1.2$. These must be scaled to the observed data (see text). Images, from left to right, **A:** Model Evap220818-d, with positions of the spectrograph slits. Red=density ρ, Green=pressure P, Blue=speed v; **B:** Projected gas density at 50° w.r.t. sky; **C:** M1-92 from Alcolea *et al.* (2022); **D:** synthetic long-slit spectra at the positions indicated in image A.

$r_A = 10^3$ AU, $v_A = 100$ km/s, it follows that $\mathscr{L}_A = 1226\,\rho r^2 v^3\ \mathrm{L}_\odot$. Also, $(4\pi/3)\rho_A\, r_A^3 = 12.4\ M_{\mathrm{Jup}}$, showing that a destroyed superjupiter provides enough matter for the evaporating disk.

3. Results

The overall appearance of my hydro models is encouraging. For quantitative comparison, I use the data assembled by Garcia-Lario *et al.* (1999), Bujarrabal *et al.* (2001), Muthumariappan *et al.* (2006), Hrivnak *et al.* (2008), Fang *et al.* (2018), and Balick *et al.* (2023). The dimensionless units in Eq.(1) make it easy to set up simulations, but the results must be converted into dimensional form for comparison with observations, e.g. the case of M1-92 (Alcolea *et al.* (2022); Figure 1). From their paper I take: speed $v_0 = 170$ km/s, size $r_0 = 3000$ AU and density $\rho_0 = 1.5 \times 10^5\ \mathrm{cm}^{-3}$. Eq.(2) then gives the scaling luminosity $\mathscr{L}_0 = 8100\,\mathrm{L}_\odot$. Because the dimensionless luminosity of the simulation is $\mathscr{L}_0 = 1.2$, my result corresponds to $\mathscr{L} = 9720\,\mathrm{L}_\odot$. This nicely matches their stellar luminosity: $\mathscr{L} = 10^4\,\mathrm{L}_\odot$.

The shapes of the nebulae Hen3-401, Hen3-1475, M1-92, Hen2-437, OH231.8 and V445Pup are reproduced quite well by my models. The axial features in M1-92 and Hen3-1475 agree with the H-shocks that always occur in the simulations, due to the focusing by the concave barotropic disk.

In many of the synthetic spectra, the outflow speed is proportional to the distance to the star, due to the conversion of thermal into kinetic energy downstream of the axial H-shocks. Such $v \propto z$ is in fact observed in some nebulae.

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Supplementary material

To view supplementary material for this article, please visit https://doi.org/10.1017/S1743921324000061

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