The Dynamical Evolution of Planetary Nebulae

D. Schönberner

Leibniz-Institut für Astrophysik Potsdam (AIP)

In cooperation with M. Steffen, R. Jacob, & R. L. M. Corradi

- The physical system & its modelling
- Expansion velocities
  - PNe of the Galactic disk
  - Metal-poor PNe
- Soft X-ray emission
- Summary
Planetary Nebula:
Relic of AGB wind, re-shaped by the steadily changing \textit{radiation field & wind} of the post-AGB (\textit{central}) star while evolving across the HRD towards the WD stage.

Double-shell burning

Last TP cycle: \textit{strong mass loss terminates evolution!}
The physical system (2)

A typical round/elliptical PN –

Central star: \( T_{\text{eff}} \approx 100\,000 \text{ K} \)

Size of PN: \( R_{\text{pn}} \approx 0.2 \text{ pc} \)
\( \Rightarrow \) kinematic PN age: \( \approx 8\,000 \text{ yr} \)

Size of halo: \( R_{\text{halo}} \approx 0.6 \text{ pc} \)
\( \Rightarrow \) kinematic halo age: \( \approx 40\,000 \text{ yr} \)

Halo –

Record of very final loss of stellar matter, enriched by freshly synthesized elements dredged-up from the stellar interior by mixing processes

Planetary Nebula proper –

2 nested shells: Bright RIM & attached fainter, much more massive SHELL, enclosing a “hole/cavity” containing the central star, and expanding into the halo

\( \Rightarrow \) A dynamical system with time-dependent boundary conditions!
Physical structure of a Planetary Nebula

- **fast wind**
- **hot Bubble**
- **10^6 .. 10^8 K**
- **inner wind shock**
- **Contact discontinuity**
- **Shell 10^4 K**
- **Rim 10^4 K**
- **Outer shock**
- **Slow AGB wind**
- **PN shaped by**
  - **photoionization by UV radiation of hot central star**
  - **colliding winds**
    - **fast central star wind**
    - **slow AGB wind**

© M. Steffen, AIP
Historical summary (1)

Early attempts – *Matthews 1966, Ferch & Salpeter 1975*

Expansion of a shell with initially ad hoc constant density and velocity into vacuum, stellar radiation field constant

- No sharp outer boundaries, shells disperse
- Backfill if no stellar wind (or radiation pressure on grains) for support

Authors claim fair agreement with observations, though *no* observables have been computed for comparisons!
**Historical summary (2)**

A breakthrough – Kwok, Purton & Fitzgerald 1978

Birth of the **interacting stellar winds (ISW)** theory

- Fast, tenuous central-star wind sweeps-up slow, dense relic of AGB-wind
- Natural consequence is one nebular shell expanding into and engulfing upstream AGB-wind material (= halo, if ionised)

**Kwok 1982/1983:**
Stellar evolution considered, i.e. time-dependent stellar winds & radiation fields

⇒ Shells expanding with $\approx 20 \text{ km s}^{-1}$ possible

**BUT:**
Analytical solutions, thus hydrodynamics due to ionisation could not be considered properly

**Chu et al. 1987,** based on deep CCD imaging of PNe:

PNe generally with double-shell structure (triple with halo)
Historical summary (3)

Modern simulations –

Schmidt-Voigt & Köppen 1989:
- 1st radiation-hydrodynamics (RHD) study with time-dependent ionisation of H & He, recombination discussed
- Ad hoc initial shells around evolving central-star models (Schönberner), simple wind model
- Ionisation + stellar wind ⇒ double-shell structure, as observed!

Marten & Schönberner 1991: Like above but with better wind model

- Better numerics, evolving & non-evolving stars, 1D & 2D (!)

- 1st consistent RHD simulation up the AGB & across the PN region towards the white-dwarf stage, with a detailed mass-loss prescription
- Time-dependent ionisation, recombination, heating & cooling for

Villaver et al. 2002:
- Consistent RHD simulations based on mass-loss & AGB/post-AGB models of Vassiliadis & Wood (1994)
- No time-dependent ionisation, heating or cooling
Simulations (1a)

Consistent modelling the evolution of Star & wind envelope

1D-hydrodynamics of circumstellar envelope with time-dependent physics

- ionisation, recombination, heating, cooling for 9 elem., 12 ion. stages
- inner boundary condition \( r_i = 5 \times 10^{14} \) cm:
  - Star radiates as a black body with \( T_{\text{eff}}(t) \)
  - \( V_\infty(t) \), \( \rho_i(t) \sim \dot{M}(t)/r_i^2/V_\infty(t) \) from the wind model

Comput. of observables: line strengths & profiles, intensity distributions, X-ray emission (heat conduction incl.)
Simulations (1b)

The post-AGB tracks used for the simulations –

Post-AGB evolution extremely sensitive to remnant masses in terms of luminosity & time scale

Limiting luminosity for a \( \approx 0.6 \, M_\odot \) remnant within 30,000 years: \( \approx 125 \, L_\odot \)

RHD simulations for

- various post-AGB remnants: 0.565...0.696 \( M_\odot \)
- various initial envelope config., e.g. \( \rho \propto r^{-\alpha} \), \( \alpha = 2, \ldots 3.5 \),

& by hydrodynamics of dusty AGB winds
Simulations (2a)

Match between models & real objects – No fits aimed at!

Young model:
0.595 M⊙, age = 3364 yr, $T_{\text{eff}} = 39300$ K

Shell (or I-shell) bright in in Hα or [N II]
Rim (or W-shell) bright in [O III]

PN structure mainly determined by ionisation!

Winds interaction still not dominant!

NOTE: $V_{[\text{N II}]} > V_{[\text{O III}]}$

for young, optically thick PNe!
Simulations (2b)

Doppler-velocities $V_{[\text{N}\ II]}$ vs. $V_{[\text{O}\ III]}$  

Jacob et al. 2013 (Paper VIII)

Objects from the local sample of  

Frew 2008

Open symbols:  

$D \leq 1$ kpc

Filled symbols:  

$D > 1$ kpc

Cool luminous stars

Opt. thick PNe

Hot, faint stars

Opt. thick PNe
Simulations (3)

Match between models & real objects – No fits aimed at!

Middle-aged model:
0.595 M\(_\odot\), age = 6100 yr, \(T_{\text{eff}} = 80\,200\) K

Double-shell structure: rim & shell, despite smooth initial density profile!

Distinct velocities for rim & shell

\(M_{\text{rim}} = 0.07\ M_\odot\), ISW!
\(M_{\text{shell}} = 0.40\ M_\odot\), ionisation!

Again NOT compatible with the Interacting Stellar Winds (ISW) theory!
Expansion velocities (1)

What is the true expansion velocity of a planetary nebula?

The position of the shell’s shock defines the nebular radius, $R_{PN}$

⇒ This shock’s propagation speed, $\dot{R}_{PN}$, is the true PN expansion velocity

However, the shock velocity cannot be measured spectroscopically!

Measurable “expansion” velocities are:
1. Peak separation of Doppler split emission lines ($= V_{rim}$)
2. Half width of emission lines of spatially unresolved objects
3. Post-shock velocity $V_{post} = \dot{R}_{PN}/F$, with $F > 1$, Corradi et al. 2007

Velocities to 1. & 2. may depend (!) on ion used, correspondence to $R_{PN}$?
A typical mean value used in statistical studies is 20–25 km s$^{-1}$

Only velocity to 3. is physically sound, independent (!) of the ion used, correction $F$ depends on shock property, $= 1.25 \pm 0.05$ Jacob et al. 2013

Spectroscop. measured velocity smaller than the true velocity!
Expansion velocities (1a)

Kinematical age ≠ post-AGB age, \( \text{age}_{\text{PN}} \approx t_{\text{post-AGB}} - t_{\text{trans}} \)

Predictions by our model PNe:

Shell radius/post-shock velocity:

\( \text{Reasonable, except youngest PNe} \)

Rim velocity/rim velocity:

\( \text{Underestimated, except youngest PNe} \)

Shell velocity/rim velocity:

\( \text{Overestimated, except oldest PNe} \)

Shell velocity/average velocity:

\( \text{Gesicki et al. 1998} \)

\( \text{Reasonable, velocity field must be known!} \)
Expansion velocities (2)

Post-shock velocity of the shell –

Example NGC 6862, Inflection point of the (outer) shell line profile

good measure of $V_{\text{post}}$:

Robust value of $F = \dot{R}_{\text{out}}/V_{\text{post}}$:
(optically thin models):

$1.25 \pm 0.05$
Expansion velocities (3)

Results for 22 PNe –

Schönberner et al. 2014

- \( V_{\text{post}} > V_{\text{agb}} \) \((\approx 10 \text{ km s}^{-1})\), rapid increase of \( V_{\text{post}} \) from \( \approx V_{\text{agb}} \) to \( \approx 40 \text{ km s}^{-1} \)
- For \( \log T_{\text{eff}} \lesssim 4.7 \):
  - \( V_{\text{rim}} < V_{\text{agb}} \), then increase of \( V_{\text{rim}} \) to \( \approx 25–30 \text{ km s}^{-1} \)
- \( V_{\text{post}}/V_{\text{rim}} \) can be as large as 6!

Theoretical expectations:

SHELL: \( \dot{R}_{\text{PN}} \) (or \( V_{\text{post}} \)) depends on \( T_{\text{e}} \) & upstream density gradient

RIM: \( V_{\text{rim}} \) is constraint by upstream pressure of ionised/heated shell) & hot bubble pressure (winds interaction) –

- first deceleration/stalling due to high shell pressure,
- then acceleration due to increasing wind power
Expansion velocities (4)

Kinematics of shells –

\( V_{\text{post}} \) for a model grid with power-law density profiles, \( \rho \propto r^{-\alpha} \), with \( \alpha = 2 \ldots 3.5 \), \( V_{\text{agb}} = 10 \ \text{km s}^{-1} \), and for \( M_{\text{cspn}} = 0.595 \ \text{M}_\odot \):

*PNe expand into (power-law) environments with initially \( \alpha \approx 2.8 \ldots 3.4 \)*

Observed halo intensity distribution,

\[ \text{SB} \propto r^{-\gamma} ? \]

6 objects in common: 

\[ \langle \alpha \rangle = 3.1 \pm 0.1 \]
\[ \langle \gamma \rangle = 5.2 \pm 0.2 \]

Since \( \gamma \approx 2\alpha - 1 \) \quad \Rightarrow \quad \langle \alpha(\gamma) \rangle \approx 3.1 \]

\( \Rightarrow \) Observed post-shock velocities consistent with measured radial density profiles of halos

\( \alpha > 2, \Rightarrow \) final mass loss on AGB “accelerated”!

(cf. Kwok, Volk & Hrivnak 2002 on density profiles of dusty envelopes around PPNe, \( \alpha \gtrsim 2.5 \))
Expansion velocities (5)

Kinematics of rims –
Sample objects with known \(V_{\text{cspn}}\):

\[
\begin{align*}
0.585 \, M_\odot, \quad \alpha = 2.5 \\
0.595 \, M_\odot, \quad \alpha = 3 \\
0.595 \, M_\odot, \quad \text{Hydro} \\
0.605 \, M_\odot, \quad \text{Hydro} \\
0.625 \, M_\odot, \quad \alpha = 2
\end{align*}
\]

\[
\langle V_{\text{rim}} \rangle \simeq 19 \, \text{km s}^{-1}
\]

\(V_{\text{cspn}} \propto R_{\text{cspn}}^{-0.5}\), and for \(L_{\text{cspn}} = \text{const} \Rightarrow T_{\text{eff}} \propto R_{\text{cspn}}^{-0.5} \Rightarrow V_{\text{cspn}} \propto T_{\text{eff}}\)

*Increasing stellar wind power, \(\dot{M}_c S \times V_{\text{cs}}^2/2\),
\(\Rightarrow \) increase of bubble pressure
\(\Rightarrow \) acceleration of rim, sweep-up of upstream (shell) matter

Theory of radiatively-driven stellar winds predicts correct rim velocities

11th Pac. Rim Conf. on Stellar Astrophys., Hong Kong, Dec. 14–17, 2015 © D. Schönberner, AIP 18/22
Expansion velocities (6)

Metal-poor PNe – Final test against the “universality” of the ISW theory!

We expect:

- $\dot{R}_{PN}$ (\& $V_{post}$) up if metallicity down because of higher electron temperatures
- $V_{rim}$ down if metallicity down because of lower wind power

Observations with VLT/Argus IFU of 4 metal-poor PNe, BoBn 1, M2-29, PRMG 1, Ps 1/K648
Soft X-ray emission from PNe (1)

“Hot bubble” of shocked stellar wind – filling the central cavity

© Ruiz et al. 2013

IC 418:

\[ T_X \simeq 3 \text{ MK} \]
\[ L_X \simeq 9 \times 10^{29} \text{ erg/s} \]

NGC 2392:

\[ T_X = 2.1 \text{ MK} \]
\[ L_X = 1.8 \times 10^{31} \text{ erg/s} \]

NGC 6826:

\[ T_X = 2.3 \text{ MK} \]
\[ L_X = 2.0 \times 10^{30} \text{ erg/s} \]
**Soft X-ray emission from PNe (2)**

Heat conduction – \( T_X \) & increases mean bubble density (hence X-ray emission measure)

**Heat conduction**

Heat conduction reduces characteristic bubble temperature \( T_X \) & increases mean bubble density (hence X-ray emission measure).

**X-ray Temperature (6–41 Å) over wind velocity**

- Adiabatic post-shock temp.

**X-ray luminosity (6–41 Å) over total luminosity**

- **PN X-ray observations**
  - \( M=0.696 \, M_\odot, \, \text{HC2} \)
  - \( M=0.595 \, M_\odot, \, \text{HC2} \)
  - \( M=0.565 \, M_\odot, \, \text{HC2} \)

**PN X-ray observations**

- IC 418
- NGC 2392
- NGC 3242
- NGC 6543
- NGC 6826
- BD+30
- NGC 40
- NGC 5315

**PN X-ray observations**

- **IC 418**
- **NGC 2392**
- **NGC 3242**
- **NGC 6543**
- **NGC 6826**
- **BD+30**
- **NGC 40**
- **NGC 5315**

**PN X-ray observations**

- **IC 418**
- **NGC 2392**
- **NGC 3242**
- **NGC 6543**
- **NGC 6826**
- **BD+30**
- **NGC 40**
- **NGC 5315**

---

SUMMARY

Structure, expansion, & X-ray emission of PNe in general agreement with predictions of full RHD simulations:

- Double-shell structure a natural consequence of ionisation and winds interaction (no distinct mass-loss events necessary!)
- The expansion of a PN is driven by ionisation, not by the central-star wind alone (as the ISW theory assumes)
- Expansion speed of the nebula’s outer edge depends on electron temperature & upstream density profile only, with mean value $\sim 45 \text{ km s}^{-1}$
- Expansion of the rim driven by central-star wind (ISW!), with mean value $\sim 20 \text{ km s}^{-1}$
- Mass-loss rate increases along final AGB evolution, $\alpha \sim 3.1$
- Metal-poor PNe expand faster ($T_e \uparrow$), their bright rim slower ($L_{\text{wind}} \downarrow$) as compared to the metal-rich counterparts
- Winds interaction important in PNe with WR central stars
- Heat conduction responsible for soft X-ray emission