The Dynamical Evolution of Planetary Nebulae

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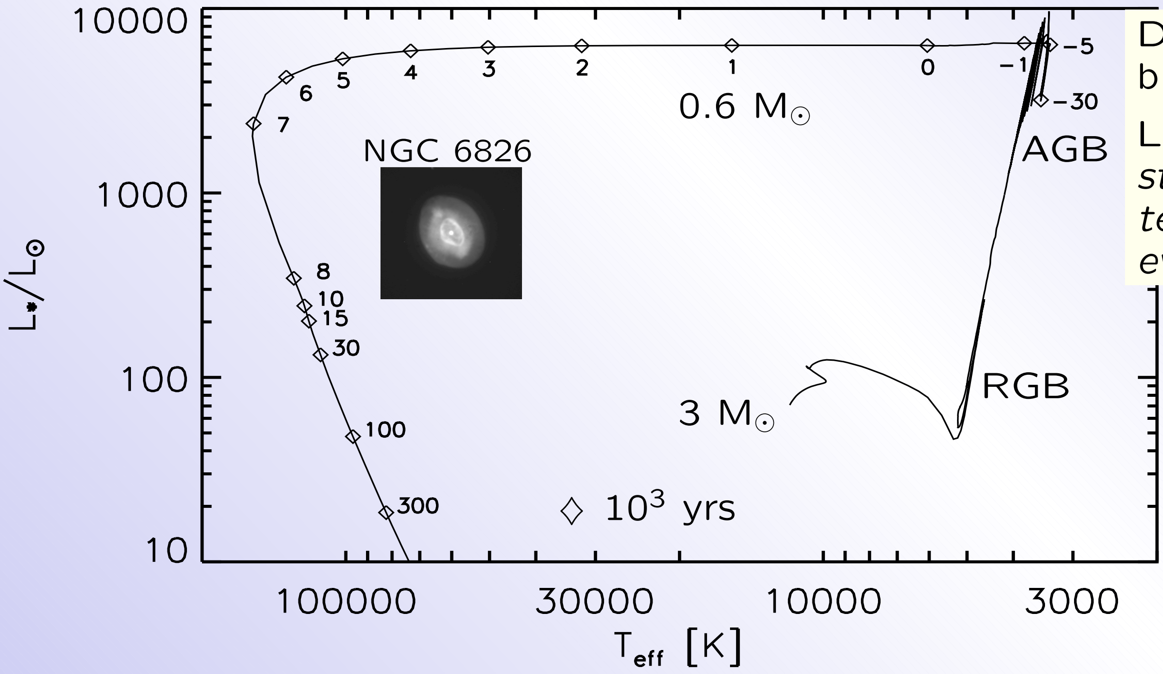
- The physical system & its modelling
- Expansion velocities
  - PNe of the Galactic disk
  - Metal-poor PNe
- Soft X-ray emission
- Summary

The physical system (1)

Planetary Nebula:

Relic of AGB wind, re-shaped by the steadily changing *radiation field & wind* of the post-AGB (= *central*) star while evolving across the HRD towards the WD stage

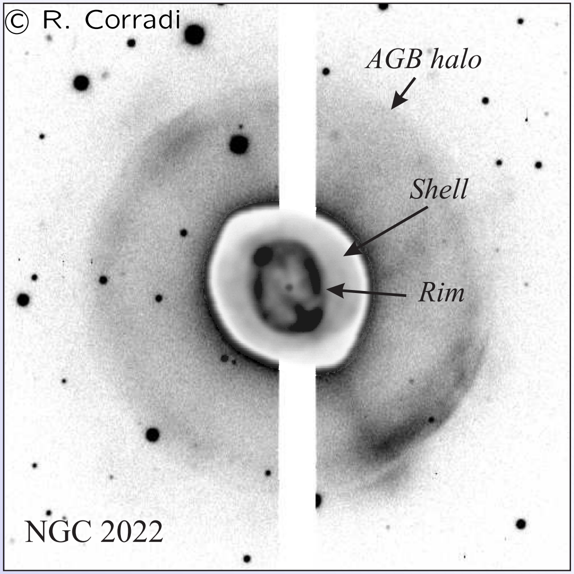


Double-shell burning

Last TP cycle: *strong mass loss terminates evolution!*

The physical system (2)

A typical round/elliptical PN –



Central star: $T_{\rm eff} \simeq 100\,000$ K

Size of PN: $R_{\rm pn} \simeq 0.2$ pc

$\Longrightarrow$ *kinematic PN age:* $\simeq 8\,000$ yr

Size of halo: $R_{\rm halo} \simeq 0.6$ pc

$\Longrightarrow$ *kinematic halo age:* $\simeq 40\,000$ yr

Halo –

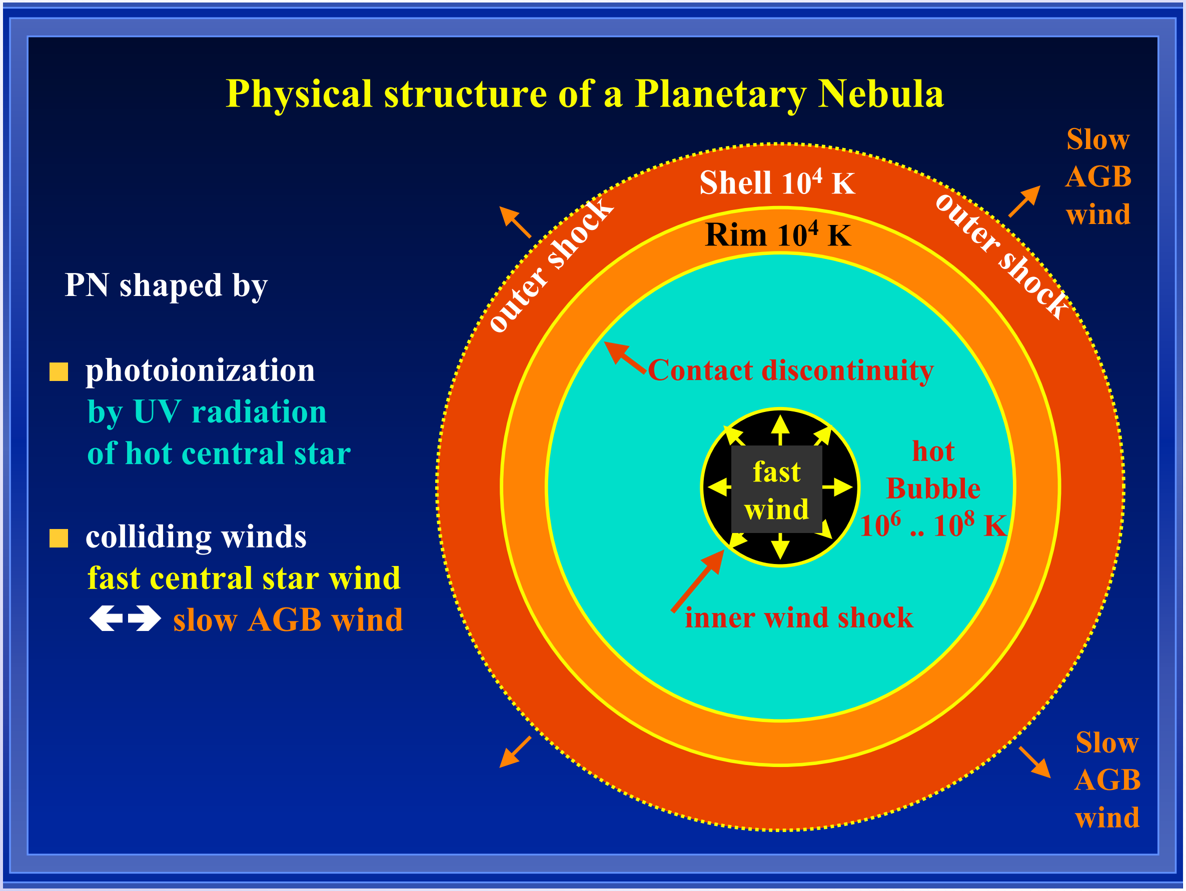
Record of very final loss of stellar matter, enriched by freshly synthesized elements dredged-up from the stellar interior by mixing processes

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*

$\Longrightarrow$ A dynamical system with time-dependent boundary conditions !

The physical system, schematic (3)



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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

$\Longrightarrow$

- 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 $\Longrightarrow$ *Shells expanding with* $\simeq 20\,\mathrm{km\,s^{-1}}$ *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

Mellema 1994/1995 . . . (& coauthors):

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

Schönberner et al. 1997: *& follow-up Papers I–VIII, 2004–2013*

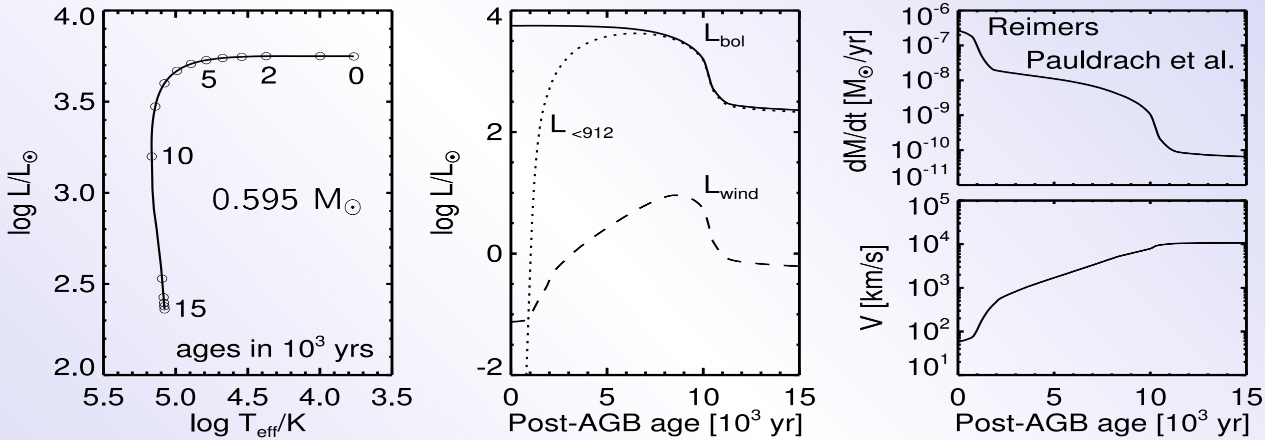
- 1st consistent RHD simulation up the AGB & across the PN region towards the white-dwarf stage, with a detailed mass-loss prescription
- Time-dependent ionisation, recombination, heating & cooling for

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**



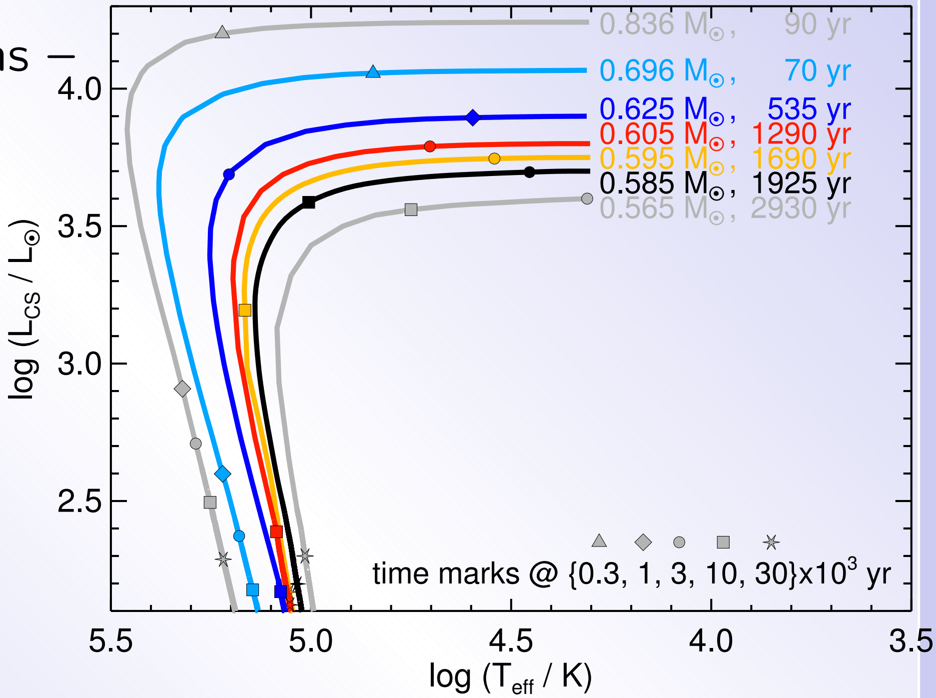
1D-hydrodynamics of circumstellar envelope with **time-dependent physics**

- ionisation, recombination, heating, cooling for 9 elem., 12 ion. stages
- inner boundary condition ($r_\mathrm{i} = 5 \times 10^{14}$ cm):
  - Star radiates as a black body with $T_\mathrm{eff}(t)$
  - $V_\infty(t),\ \rho_\mathrm{i}(t) \sim \dot{M}(t)/r_\mathrm{i}^2/V_\infty(t)$ 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 $\simeq 0.6\ M_\odot$ remnant within 30 000 years: $\simeq 125\ L_\odot$

RHD simulations for

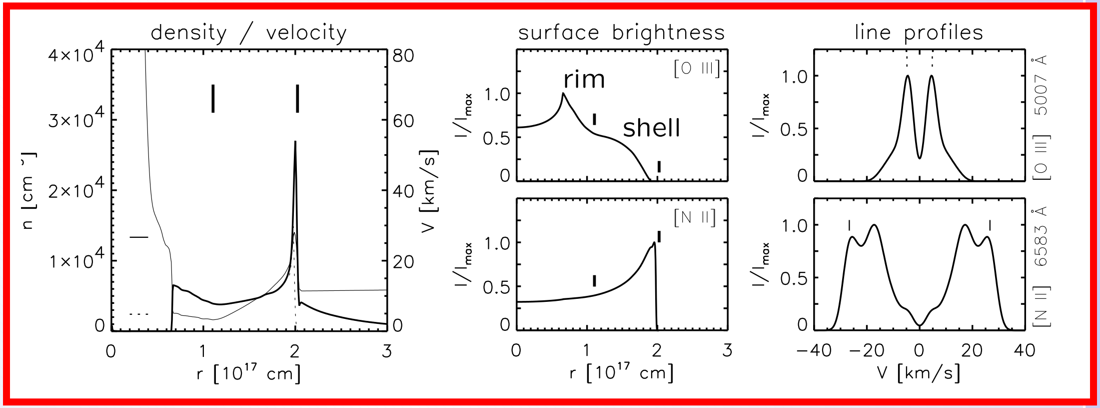
- various post-AGB remnamts: $0.565 \ldots 0.696\ M_\odot$
- various initial envelope config., e.g. $\rho \propto r^{-\alpha}$, $\alpha = 2, \ldots 3.5$,

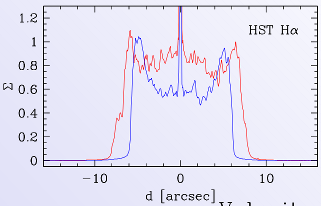
& by hydrodynamics of dusty AGB winds

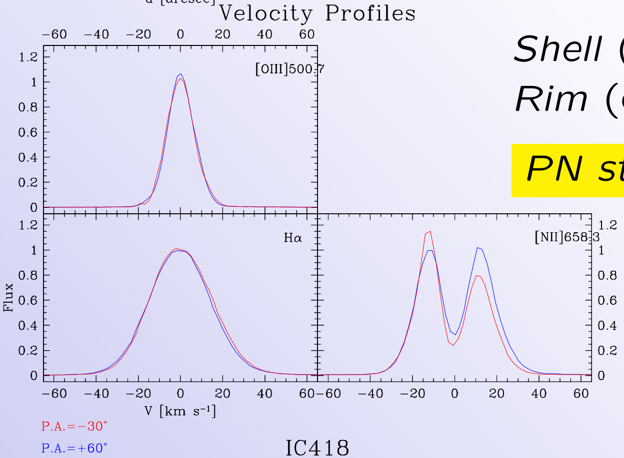
Simulations (2a)

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

Young model:
$0.595\ M_\odot$,
age $= 3364$ yr,
$T_{\rm eff} = 39\,300$ 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 !

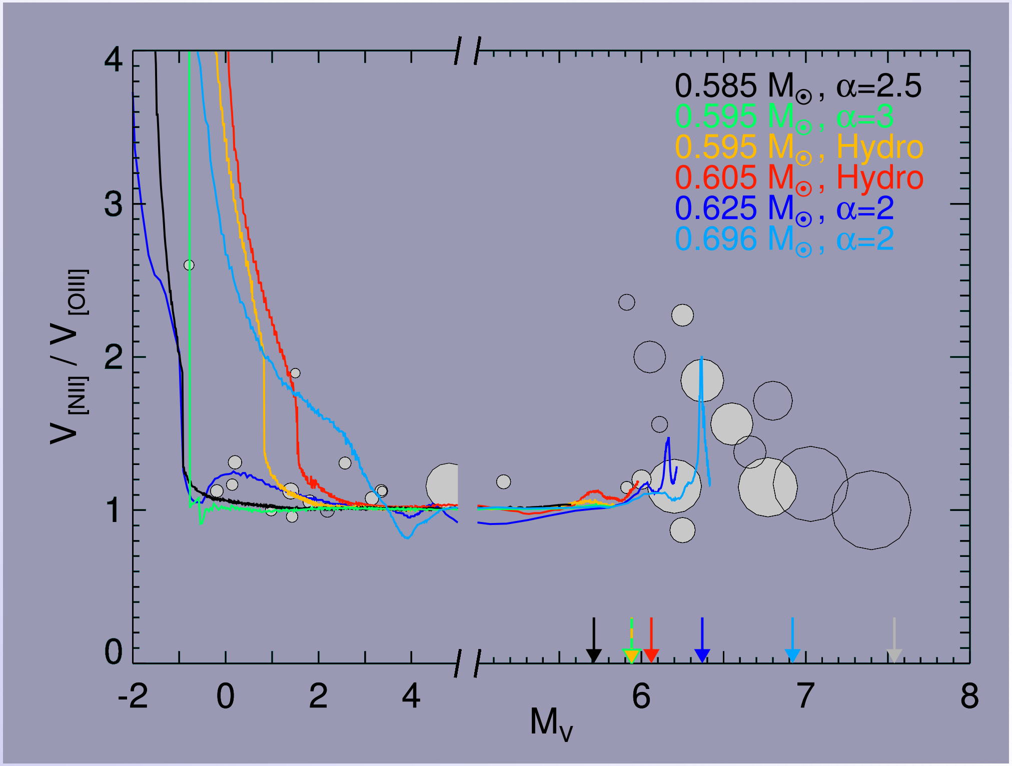
Winds interaction still not dominant !

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

for young, optically thick PNe !

Simulations (2b)

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

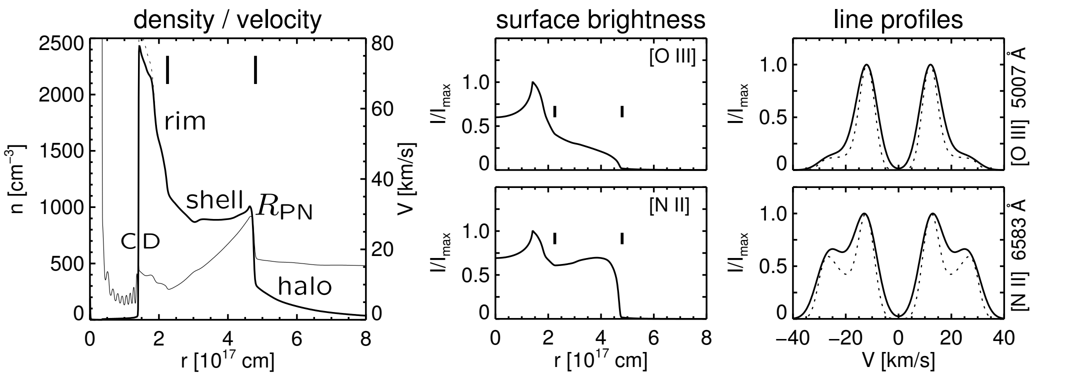
Cool luminous stars
Opt. thick PNe

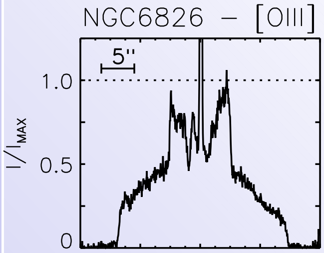
hot, faint stars
opt. thick PNe

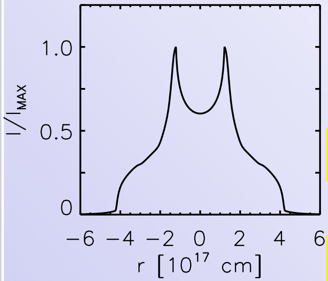
Simulations (3)

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

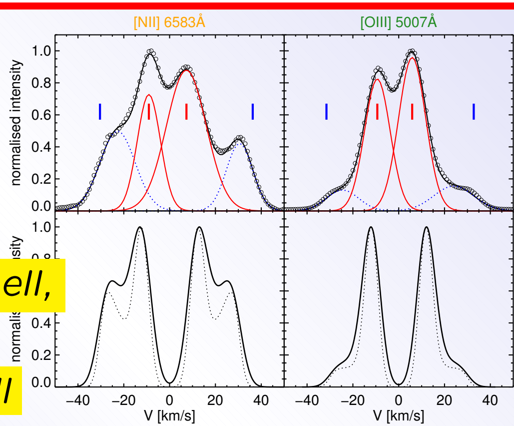
Middle-aged model:
0.595 $M_\odot$,
age $= 6100$ yr,
$T_{\rm eff} = 80\,200$ K







$M_{\rm rim} = 0.07$ $M_\odot$, ISW !
$M_{\rm shell} = 0.40$ $M_\odot$, ionisation !



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

Distinct velocities for rim & shell

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, $R_{\rm PN}$

$\Rightarrow$ This shock's propagation speed, $\dot{R}_{\rm PN}$, 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 ($= V_{\rm rim}$)
2. Half width of emission lines of spatially unresolved objects
3. Post-shock velocity $V_{\rm post} = \dot{R}_{\rm PN}/F$, with $F > 1$, *Corradi et al. 2007*

Velocities to 1. & 2. may depend (!) on ion used, correspondence to $R_{\rm PN}$?

A typical mean value used in statistical studies is 20–25 $\rm km\,s^{-1}$

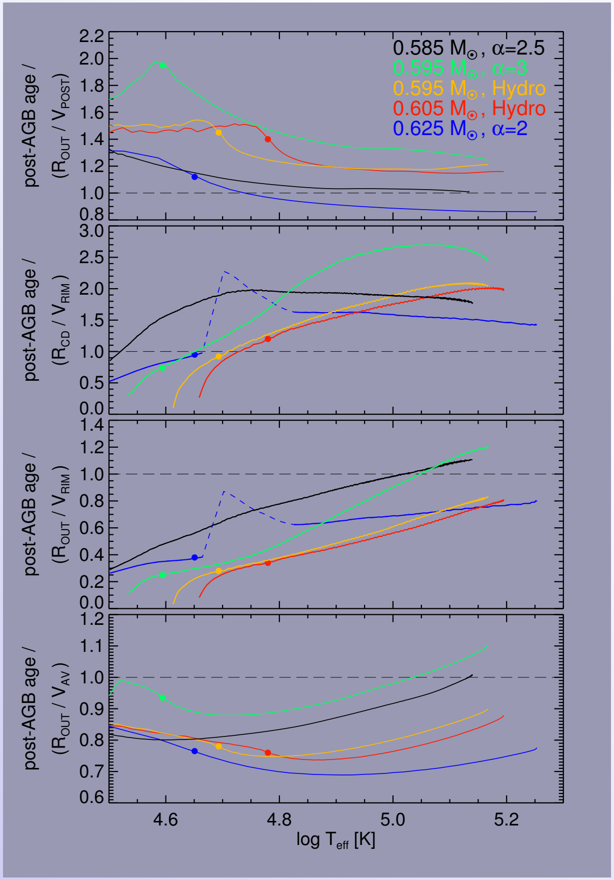
Only velocity to 3. is physically sound, independent (!) of the ion used,

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 $\neq$ post-AGB age, $\quad \text{age}_{\text{PN}} \simeq t_{\text{post-AGB}} - t_{\text{trans}}$



Predictions by our model PNe:

Shell radius/post-shock velocity:

Reasonable, except youngest PNe

Rim velocity/rim velocity:

Underestimated, except youngest PNe

Shell velocity/rim velocity:

Overestimated, except oldest PNe

Shell velocity/average velocity:

Gesicki et al. 1998

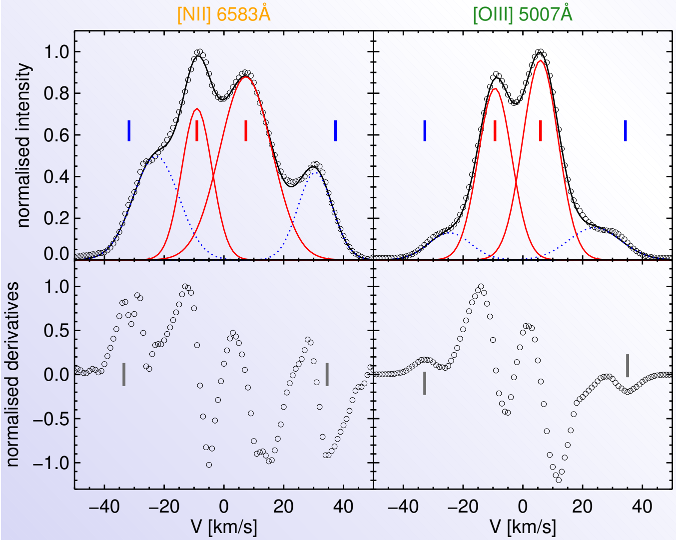
Reasonable, velocity field must be known!

Expansion velocities (2)

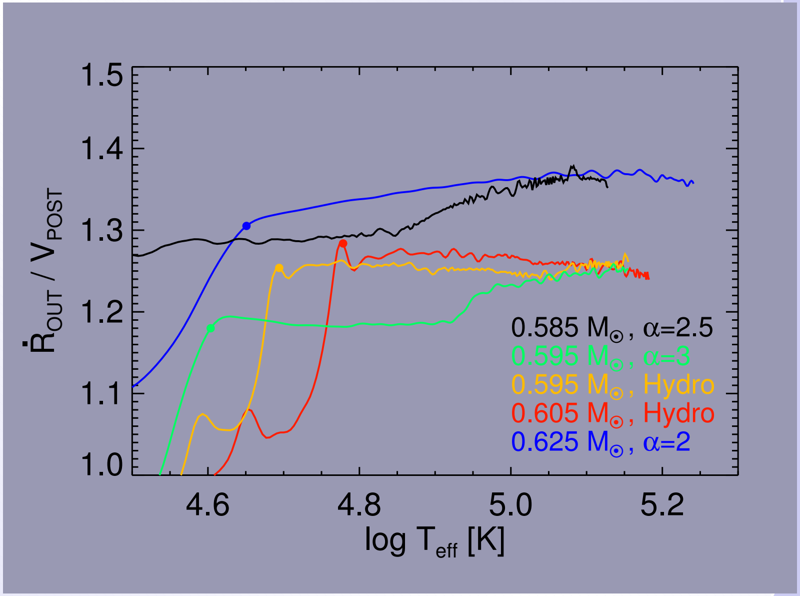
Post-shock velocity of the shell – *after Corradi et al. 2007*

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

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



Model predictions:



Robust value of $F = \dot{R}_{\rm out}/V_{\rm post}$:

(optically thin models):

1.25±0.05

Expansion velocities (3)

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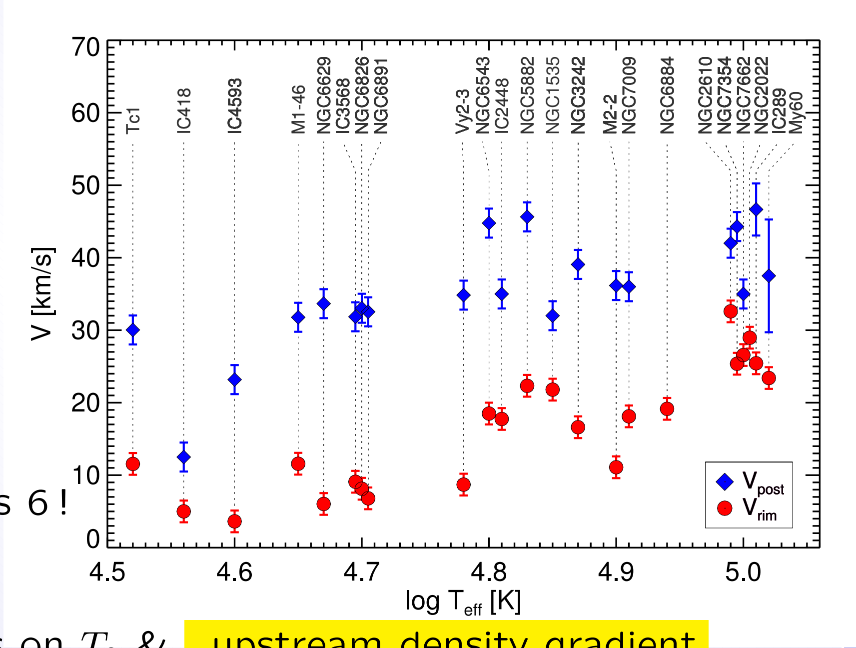
Results for 22 PNe – Tautenburg/NTT/NOT/CAT

Schönberner et al. 2014

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



Theoretical expectations:

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

e.g. Chevalier 1997

RIM: $V_{\rm rim}$ is constraint by upstream pressure of ionised/heated shell) & hot bubble pressure (winds interaction) – *e.g. Kwok et al. 1978*

first deceleration/stalling due to high shell pressure, then acceleration due to increasing wind power

Expansion velocities (4)

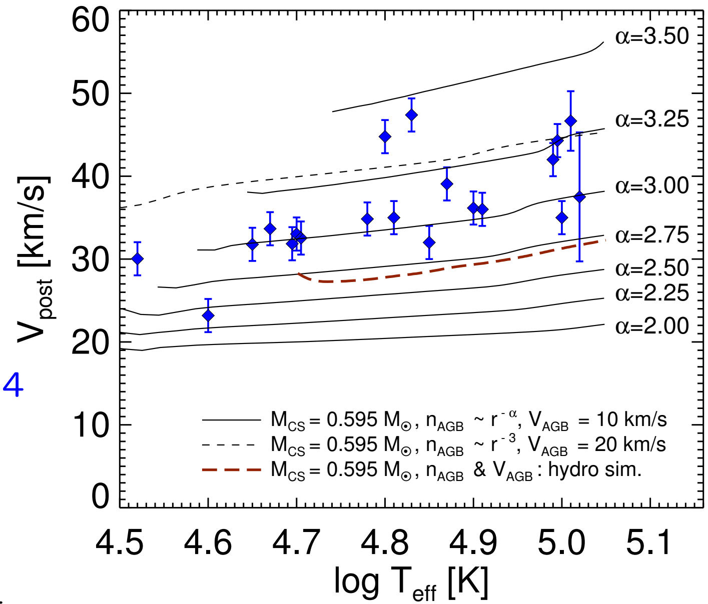
Kinematics of shells –

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

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

Observed halo intensity distribution,
SB $\propto r^{-\gamma}$?

6 objects in common: $\langle\alpha\rangle = 3.1 \pm 0.1$
$\langle\gamma\rangle = 5.2 \pm 0.2$



Schönberner et al. 2014

Since $\gamma \simeq 2\alpha - 1 \quad \Rightarrow \langle\alpha(\gamma)\rangle \simeq 3.1$

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

$\alpha > 2$, $\Rightarrow$ *final mass loss on AGB "accelerated"!*

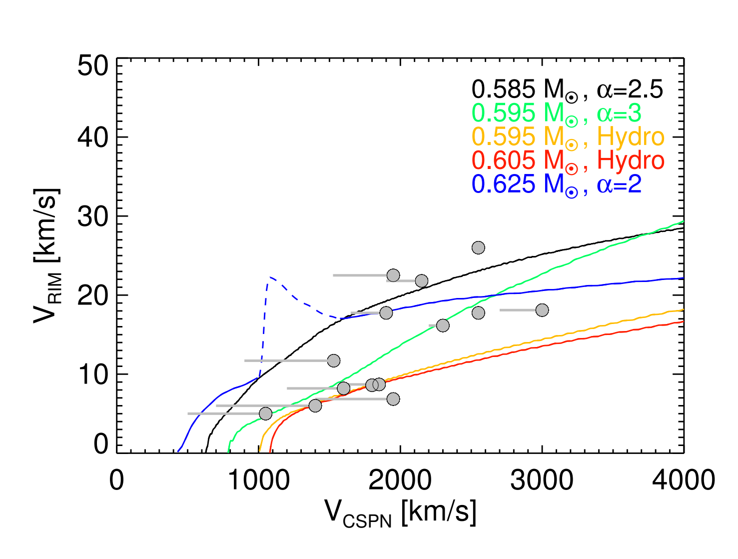
$\langle\dot{R}_{\rm PN}\rangle \simeq 45\ {\rm km\,s^{-1}}$

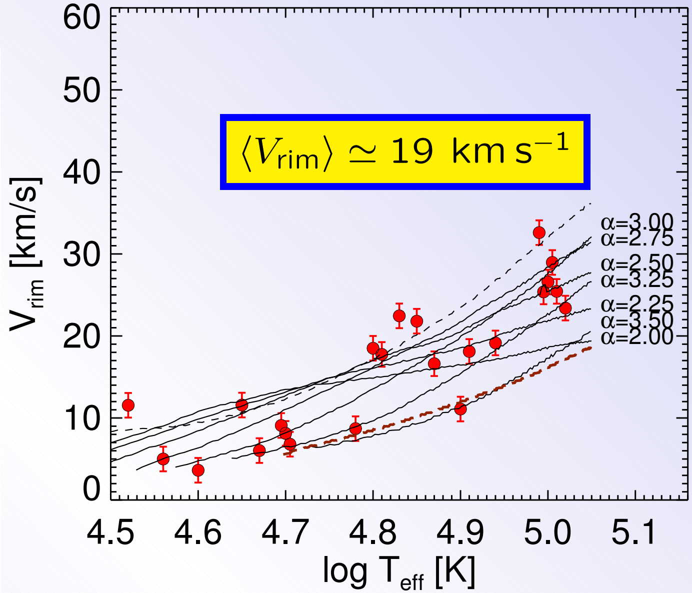
(cf. *Kwok, Volk & Hrivnak 2002* on density profiles of dusty envelopes around PPNe, $\alpha \gtrsim 2.5$)

Expansion velocties (5)

Kinematics of rims –

Sample objects with known $V_{\rm cspn}$:





$V_{\rm cspn} \propto R_{\rm cspn}^{-0.5}$, and for $L_{\rm cspn} = {\rm const} \Rightarrow T_{\rm eff} \propto R_{\rm cspn}^{-0.5} \Rightarrow$ $V_{\rm cspn} \propto T_{\rm eff}$

Increasing stellar wind power, $\dot{M}_{\rm cs} \times V_{\rm cs}^2/2$*,*

$\Rightarrow$ *increase of bubble pressure*

$\Rightarrow$ *acceleration of rim, sweep-up of upstream (shell) matter*

Theory of radiatively-driven stellar winds predicts correct rim velocities

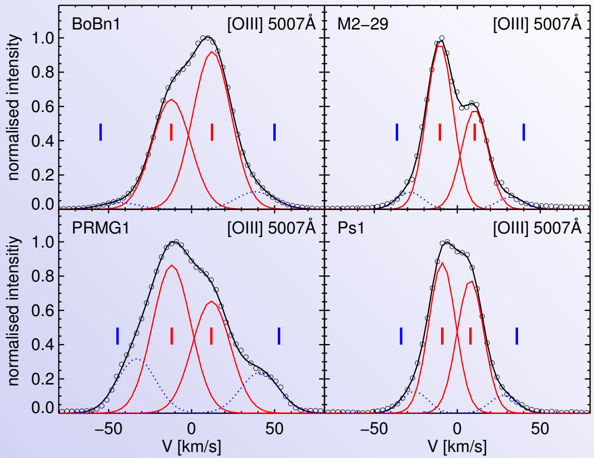
Expansion velocities (6)

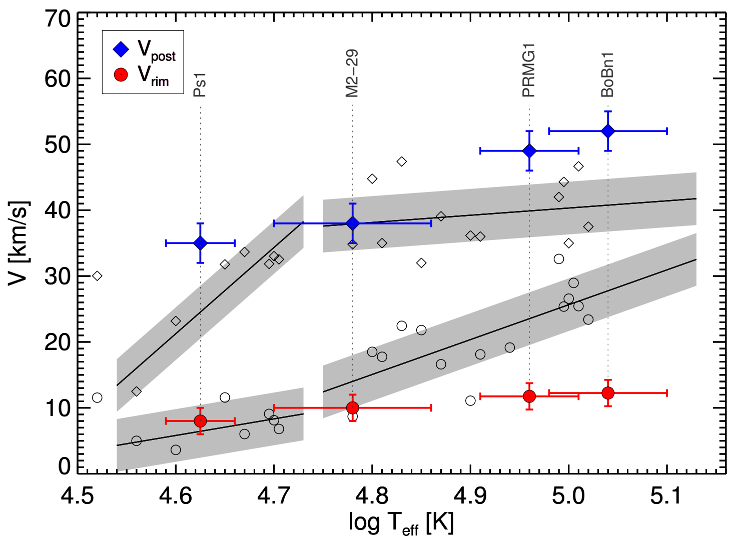
Metal-poor PNe – Final test against the "universality" of the ISW theory!

We expect: *Schönberner et al. 2014*

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

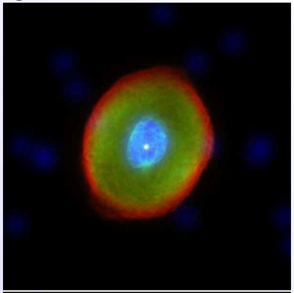


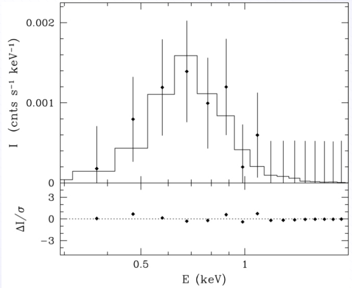


Soft X-ray emission from PNe (1)

"Hot bubble" of shocked stellar wind – filling the central cavity

©*Ruiz et al. 2013* 0.3–2.0 keV

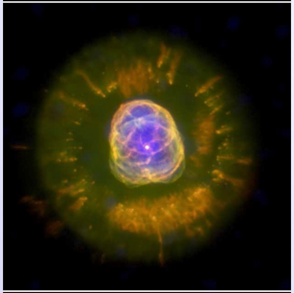


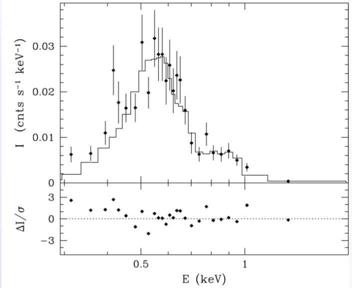


IC 418:

$T_X \simeq 3$ MK

$L_X \simeq 9\times10^{29}$ erg/s

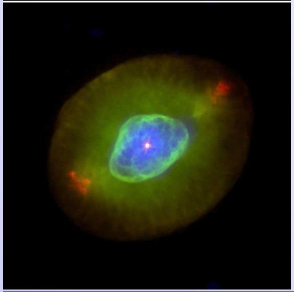


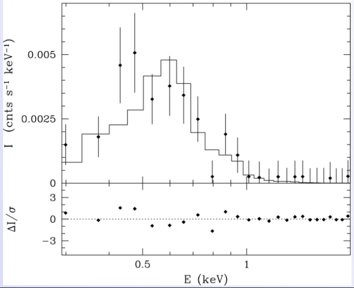


NGC 2392:

$T_X = 2.1$ MK

$L_X = 1.8\times10^{31}$ erg/s





NGC 6826:

$T_X = 2.3$ MK

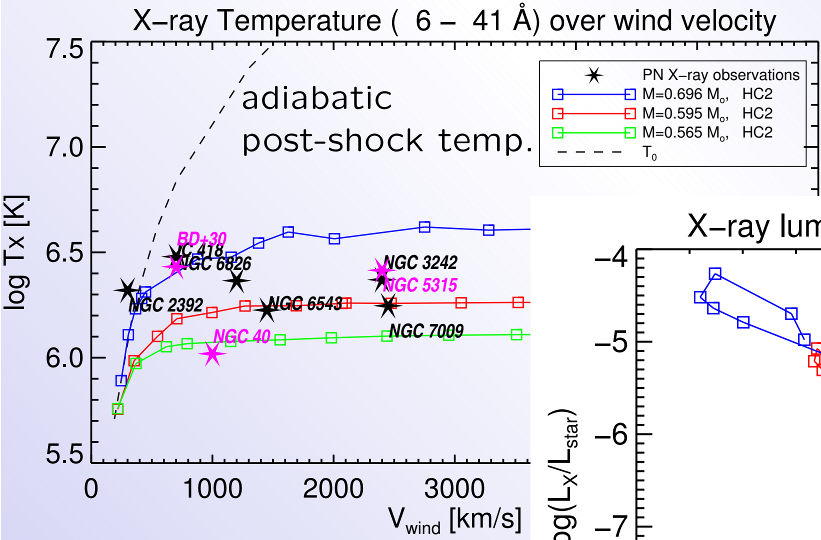
$L_X = 2.0\times10^{30}$ erg/s

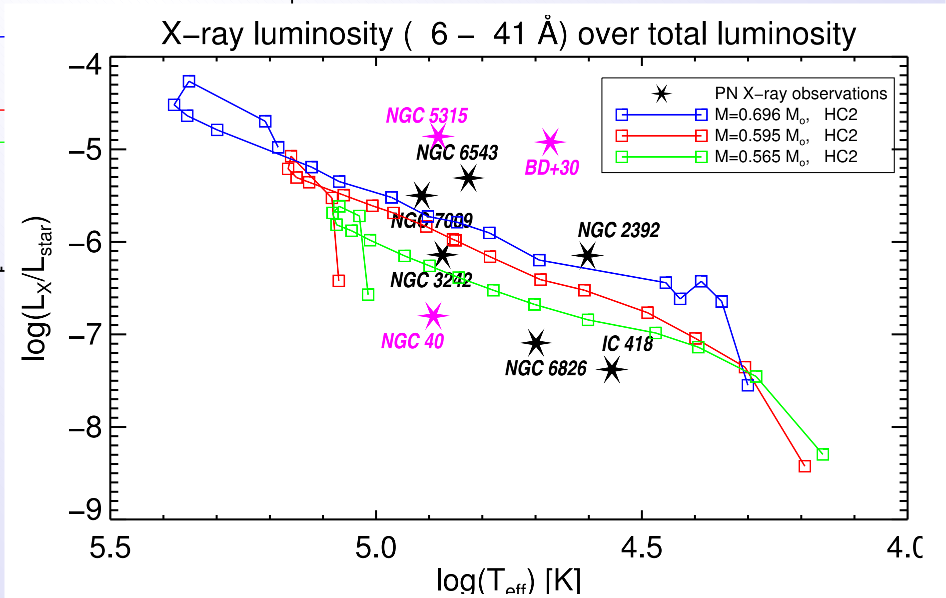
Soft X-ray emission from PNe (2)

Heat conduction –

Soker 1994, Steffen et al. 2008

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





SUMMARY

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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 $\simeq 45\ \mathrm{km\,s^{-1}}$
- Expansion of the rim driven by central-star wind (ISW !), with mean value $\simeq 20\ \mathrm{km\,s^{-1}}$
- Mass-loss rate *increases* along final AGB evolution $\alpha \simeq 3.1$
- Metal-poor PNe expand *faster* ($T_\mathrm{e}\uparrow$), their bright rim *slower* ($L_\mathrm{wind}\downarrow$) as compared to the metal-rich counterparts
- Winds interaction important in PNe with WR central stars
- Heat conduction responsible for soft X-ray emission