

Planetary Nebulae: Near and Far

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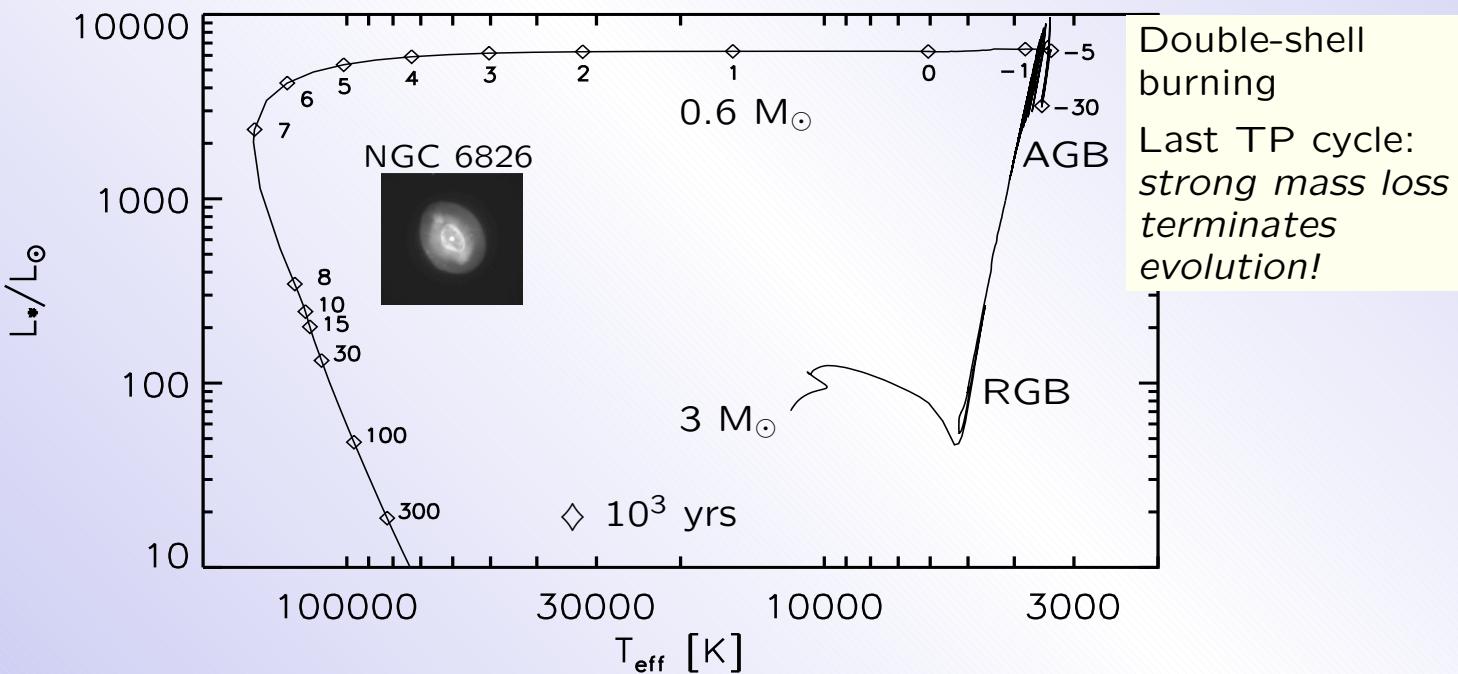
- Physics, Modelling, and Structures of PNe
- Diffuse X-ray emission of PNe
- Influence of metallicity on PNe Properties
- PNe in distant stellar systems
- Summary

The physical system (1)

Planetary Nebula:

Relic of AGB wind, reshaped by the

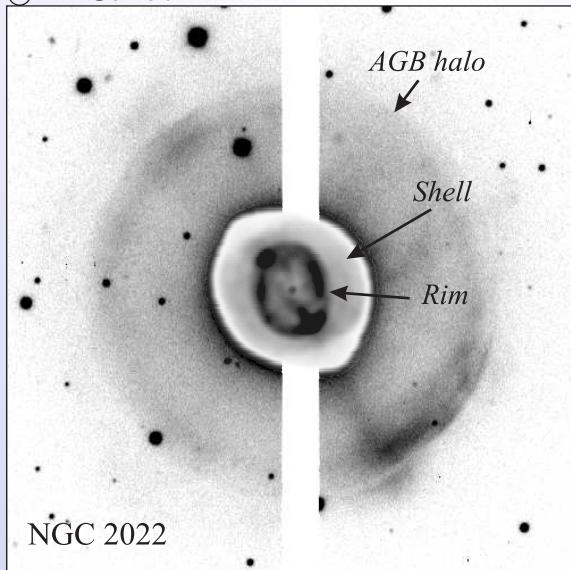
radiation field & the wind of the post-AGB (= central) star while evolving across the HR diagram



The physical system (2)

A typical round/elliptical PN –

© R. Corradi



Central star:

$$T_{\text{eff}} \simeq 100\,000 \text{ K}$$

Size of PN:

$$R_{\text{pn}} \simeq 0.2 \text{ pc}$$

\Rightarrow kin. PN age:

$$\simeq 8\,000 \text{ yr}$$

Size of halo:

$$R_{\text{halo}} \simeq 0.6 \text{ pc}$$

\Rightarrow kin. halo age:

$$\simeq 40\,000 \text{ yr}$$

Halo –

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

Planetary Nebula –

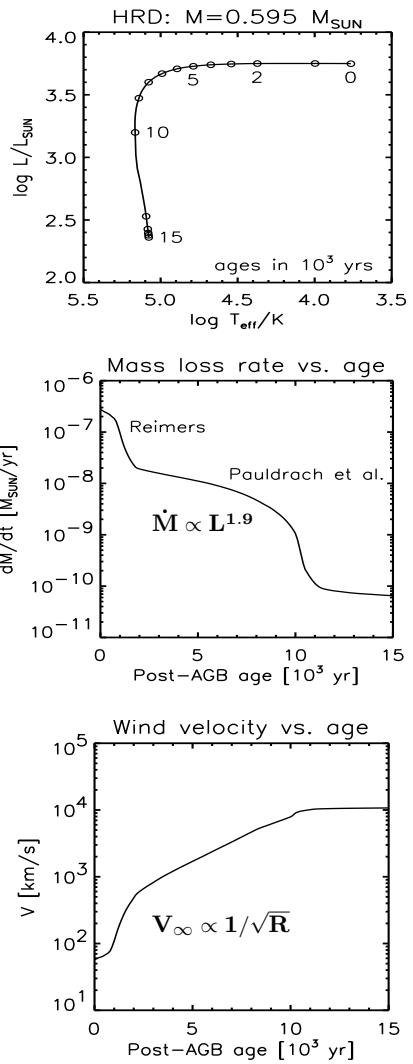
System of expanding shock waves, set up by

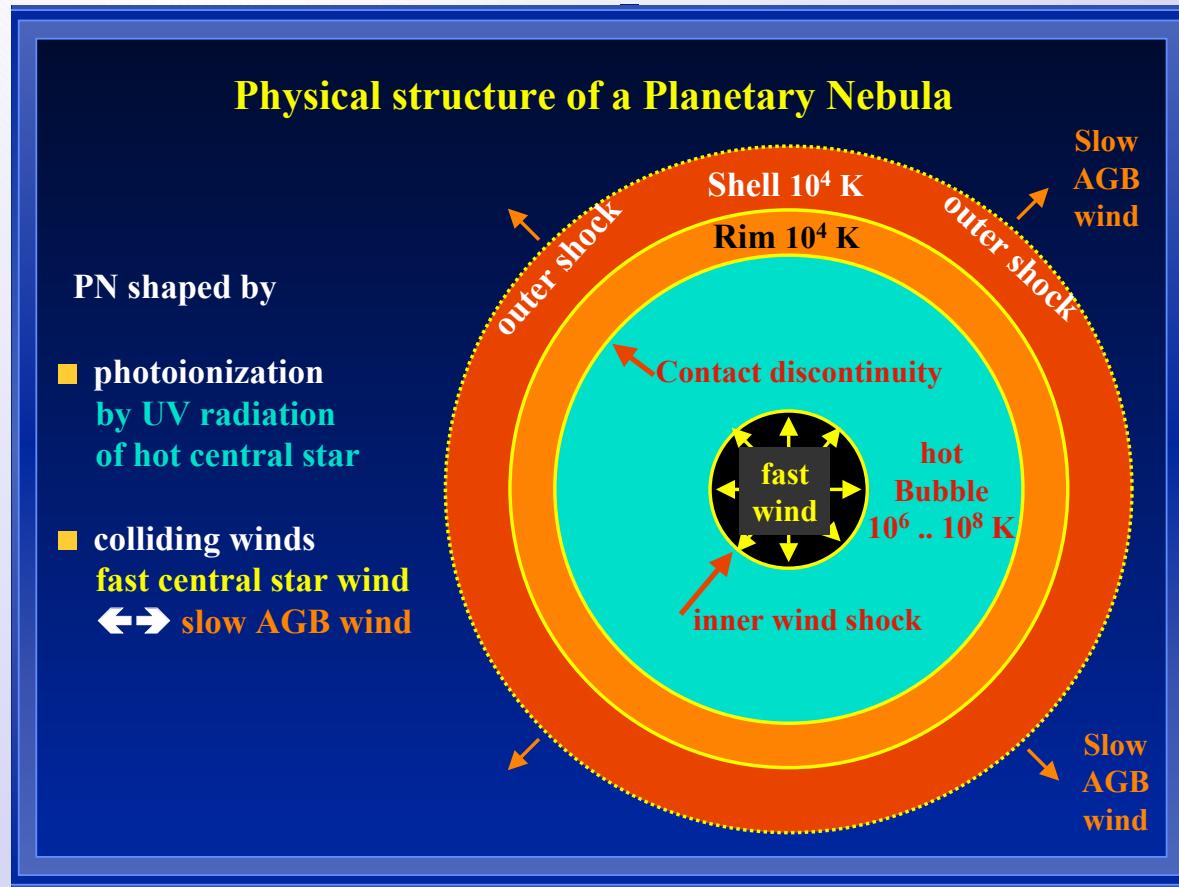
ionisation heating (shell) & wind interaction (rim)

Modelling (1)

Comb. evolution of **Star & wind envelope**

1. Post-AGB stellar models of suited masses
2. Initial wind-envelope configurations either based on two-component hydrodynamics along the tip of the AGB, or on assumed power-law density distributions
3. Post-AGB mass-loss rate, \dot{M} , and wind velocity, V_∞ , theoretically/semiempirically prescribed from actual stellar parameters
4. 1D-hydrodynamics with **time-dependent**
 - ion., rec., heat., cool. for 9 el., 12 ion. stag.
 - 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
5. Computation of observables (surface brightness, line profiles, . . .)





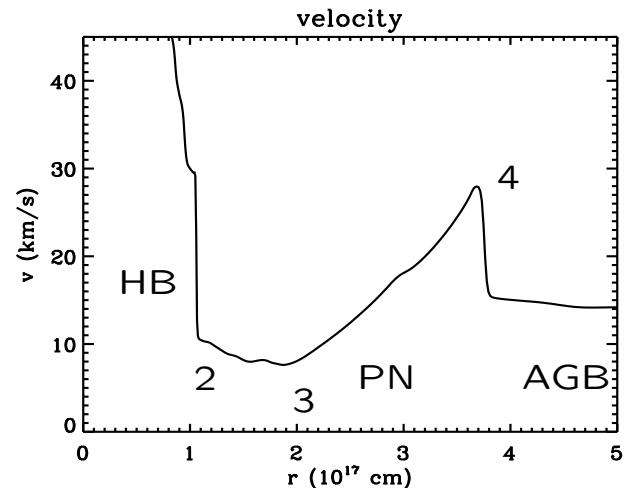
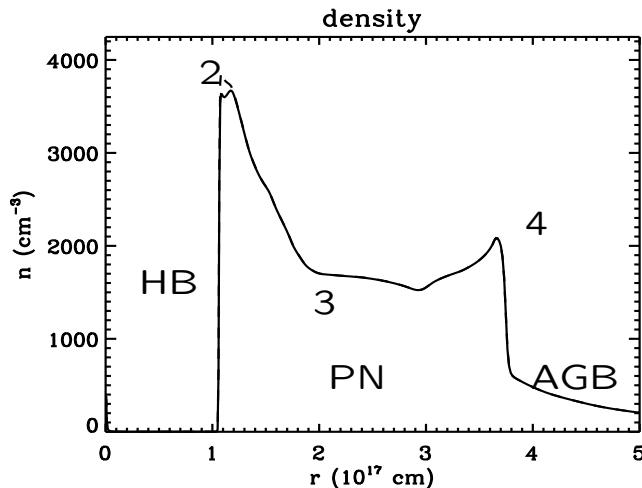
Simulations (1)

Ionization & wind interaction *reshape AGB wind*

at some dist.
from the star

1. Heating by photo-ionization drives a shock wave into the ambient slow AGB wind (halo), \Rightarrow **shell** (3 – 4)
2. Thermal pressure of *hot bubble (HB)* compresses & accelerates inner parts of the shell, \Rightarrow **rim** (2 – 3)

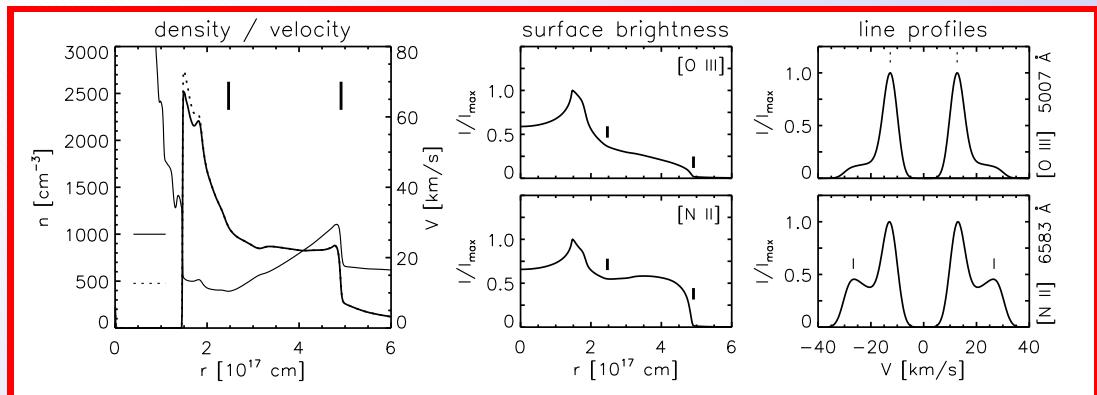
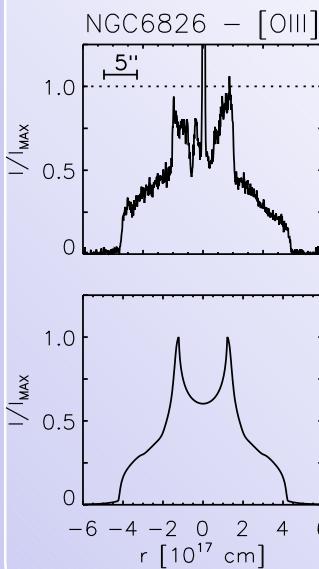
PN bounded by outer shock (4) and contact surface (2)



Simulations (2)

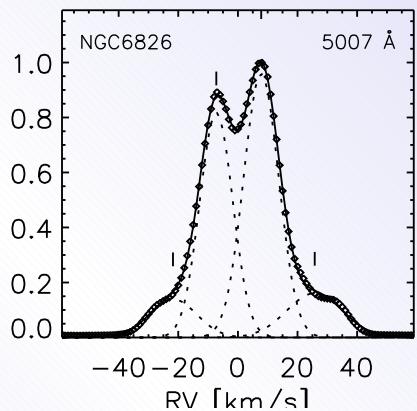
Match between models & real objects –

Middle-aged
model/objects:



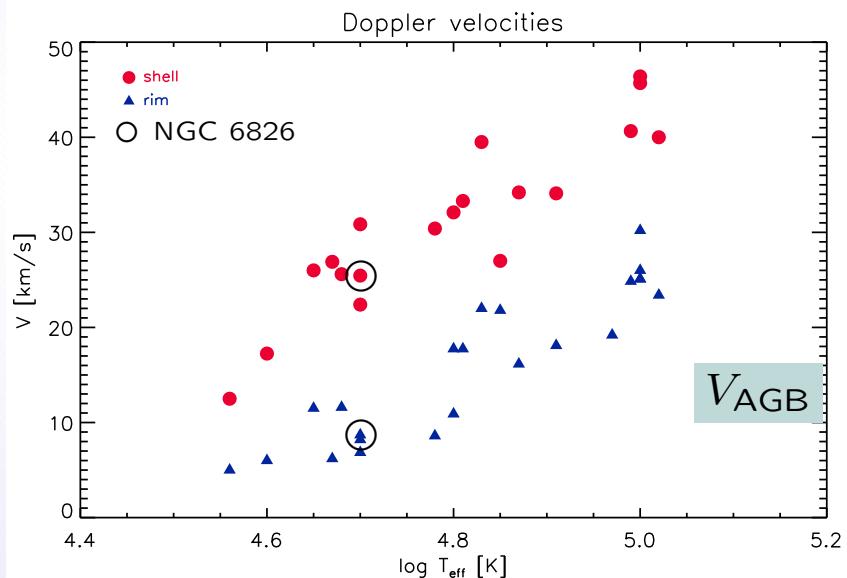
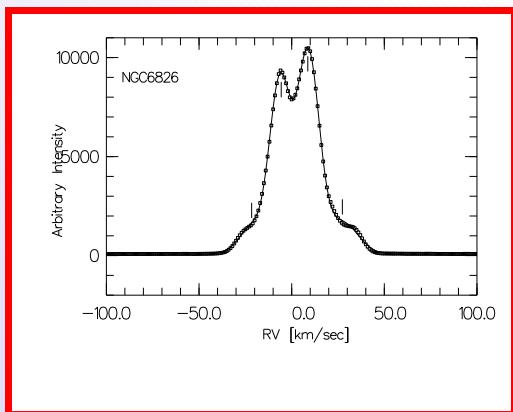
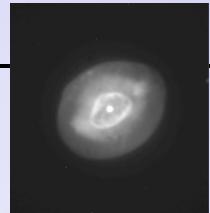
Double-shell SB structure

Distinct velocities for rim & shell



Structures (1)

Expansion properties – *Schönberner et al. 2005*
 Observations, e.g. NGC 6826



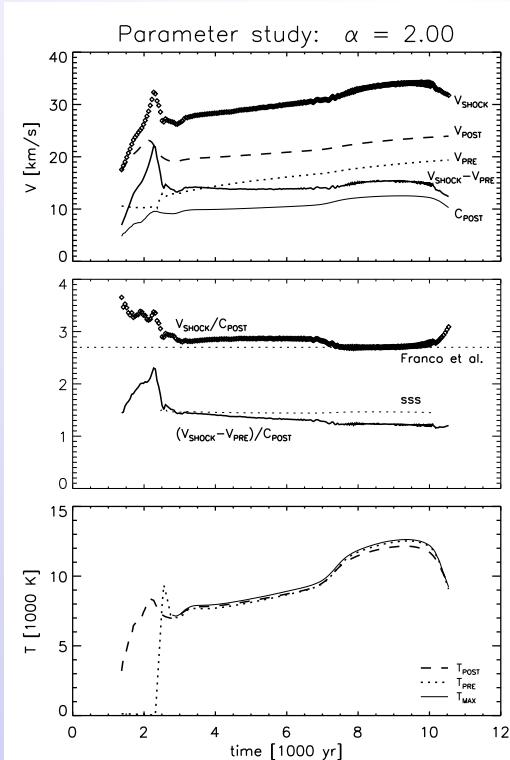
Stellar temperature as proxy
 of evolutionary progress:

Rim & shell expand independently

Rim: Kin. energy input increases bubble pressure \Rightarrow rim gas accelerated
Shell: which physics rules the expansion of the shell ?

Structures (2)

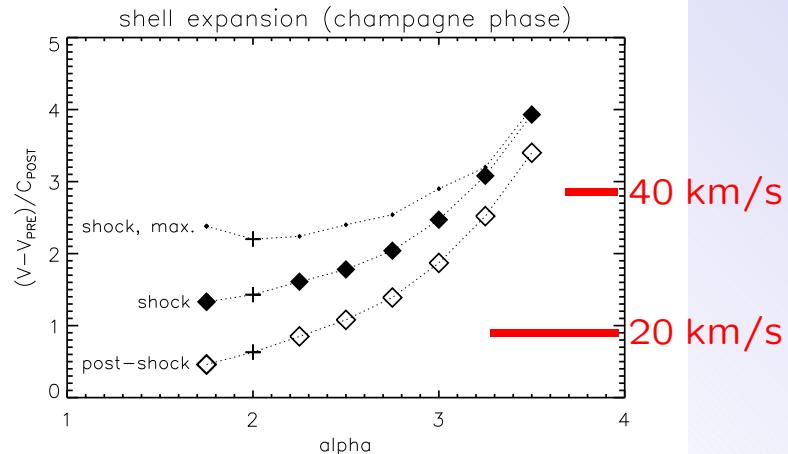
Expansion properties –
Theory: (Density $\propto r^{-\alpha}$)



Schönberner et al. 2005

$$V_{\text{shock}} - V_{\text{pre}} \simeq \text{const}(\alpha) \times C_{\text{post}} \propto T_e^{0.5}$$

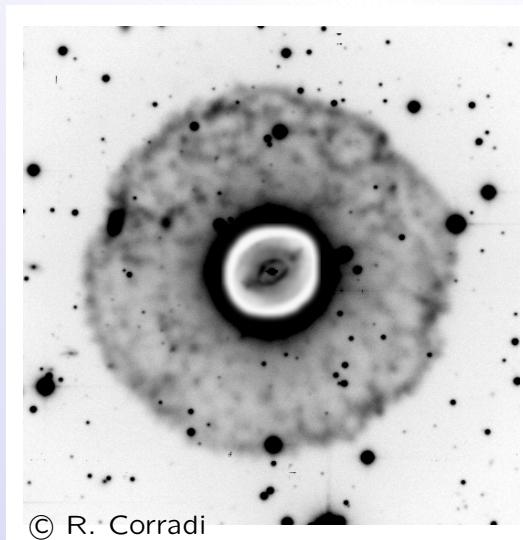
*Relative shock speed independent of density and CS parameters,
BUT dependent on density gradient:*



Observed speeds imply $\alpha \Rightarrow \gtrsim 3$ at some distance from the star!

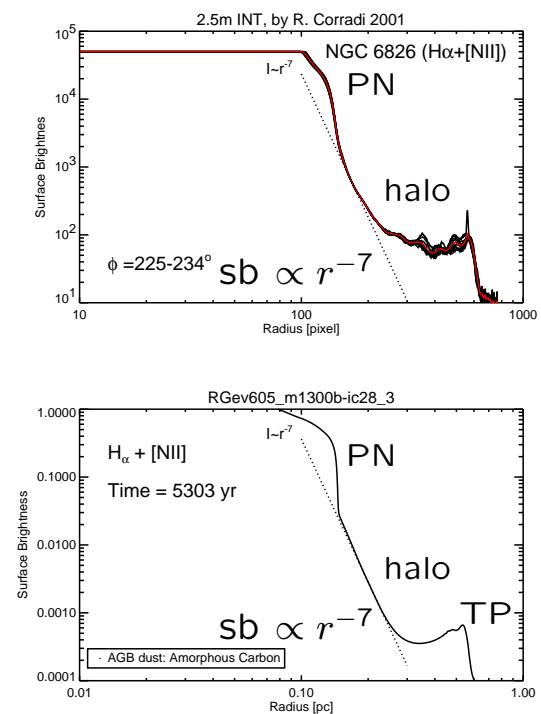
Structures (3)

Halo structure –



- Central star: $T_{\text{eff}} \simeq 55\,000 \text{ K}$
- Size of PN: $R_{\text{pn}} \simeq 0.13 \text{ pc}$
- \Rightarrow kin. PN age: $\simeq 5\,000 \text{ yr}$
- Size of halo: $R_{\text{halo}} \simeq 0.55 \text{ pc}$
- \Rightarrow kin. halo age: $\simeq 37\,000 \text{ yr}$

H α surface brightness of NGC 6826

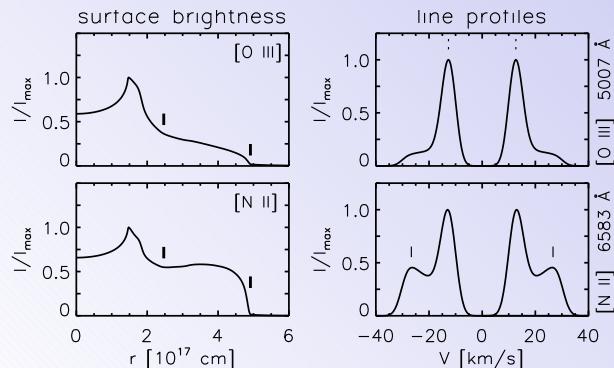
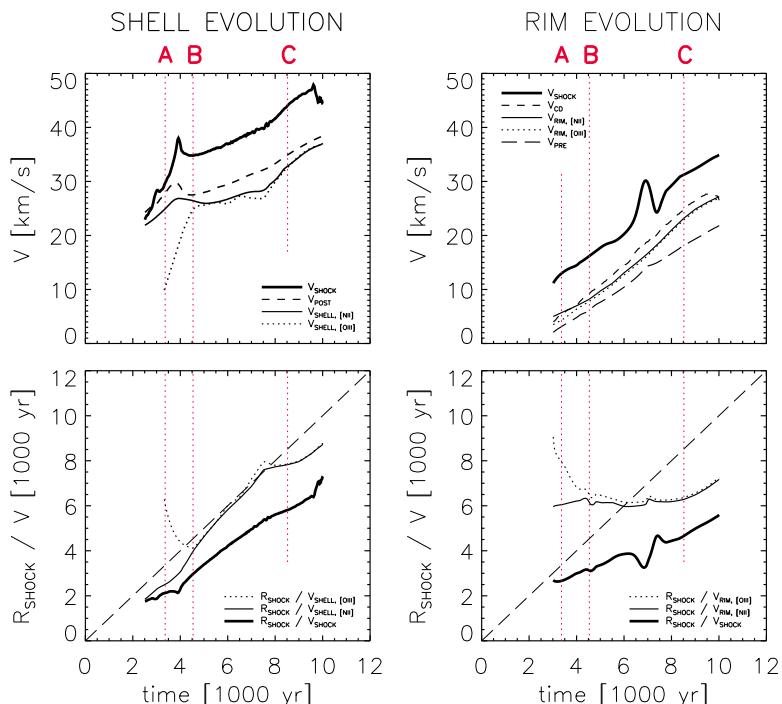


Well matched by our hydro simulations:

- Brightness/size ratios of PN & halo
- Halo brightness distribution $\propto r^{-7}$

Structures (4)

Kinematical ages – $R_{\text{shock}}/V(??)$



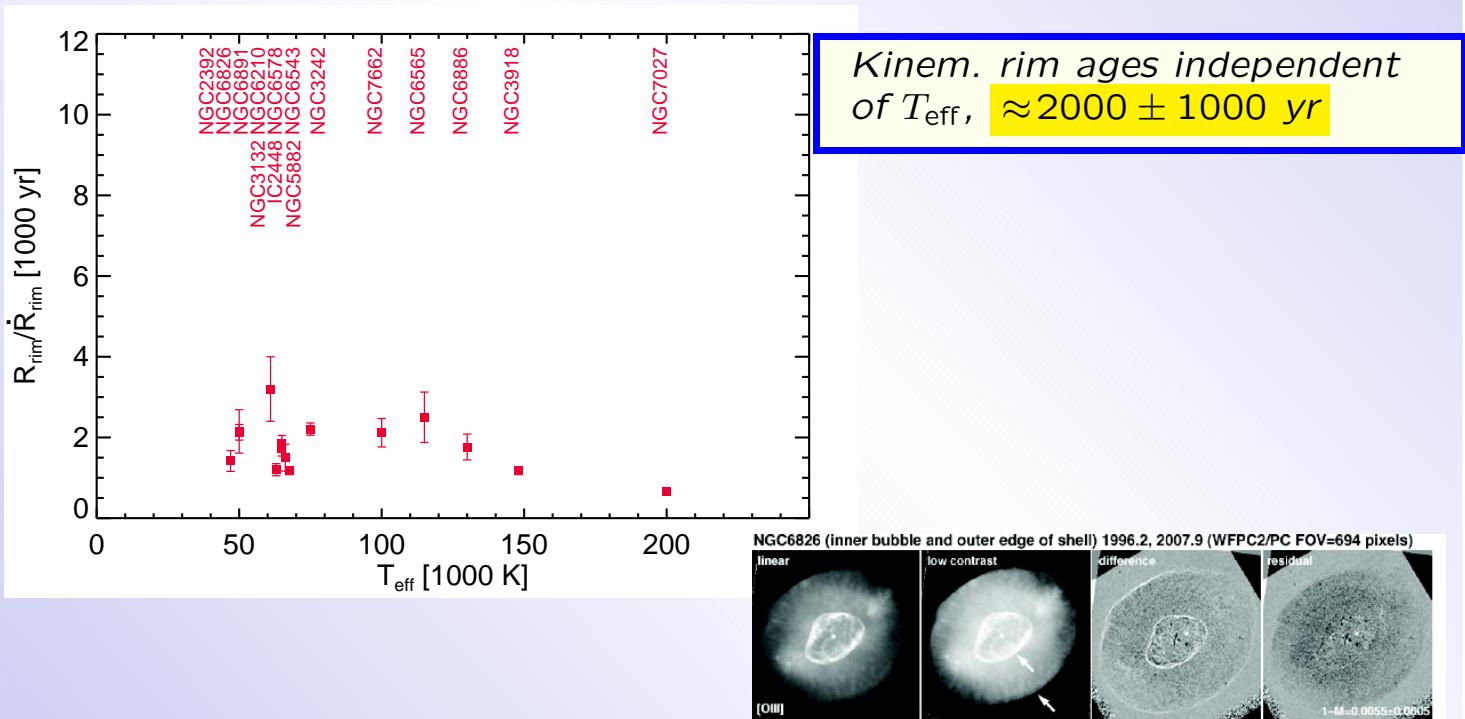
$V_{\text{shock}} (= \dot{R}_{\text{shock}})$ **not measurable**
spectrosc. ("pattern velocity")

Doppler velocities $V_{[\text{NII}]}$ or $V_{[\text{OIII}]}$
may work well for the shell only!

!! Pattern velocities are compared with Doppler velocities !!
 ⇒ In general, kinematical ages different for shell & rim !!

Structures (5)

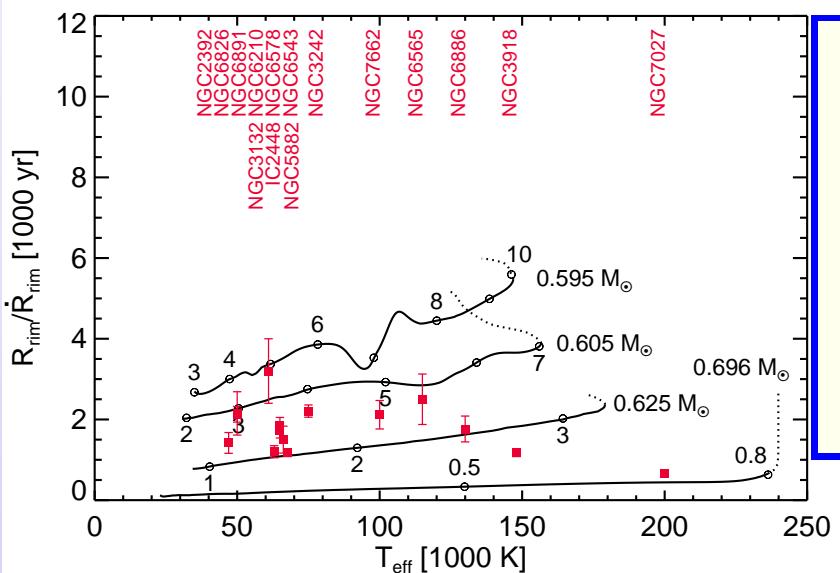
Kinematical ages – $R_{\text{rim}}/\dot{R}_{\text{rim}}$,
 proper motion, $\dot{\theta}$, of rims (HST imaging)
Balick et al., in prep.



©Balick

Structures (5)

Kinematical ages – $R_{\text{rim}}/\dot{R}_{\text{rim}}$,
 proper motion, $\dot{\theta}$, of rims (HST imaging)
Balick et al., in prep.

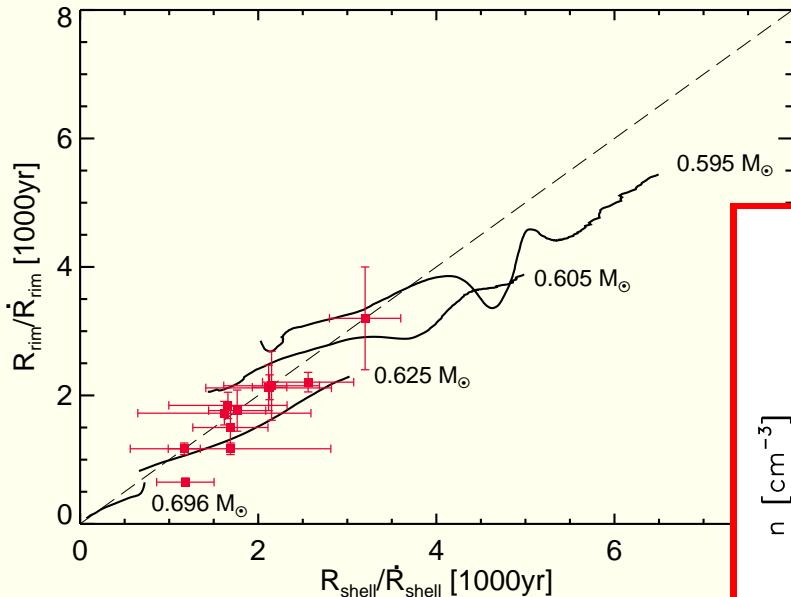


Kinem. rim ages independent of T_{eff} , $\approx 2000 \pm 1000 \text{ yr}$
Good match with observations for $M_{\text{cs}} \simeq 0.6 \dots 0.63 M_{\odot}$,
NGC 7027: $\simeq 0.69 M_{\odot}$.
Observed typical kinematical rim ages, $\approx 2000 \text{ yrs}$,
about half of the real ages,
marked along the tracks !

Structures (6)

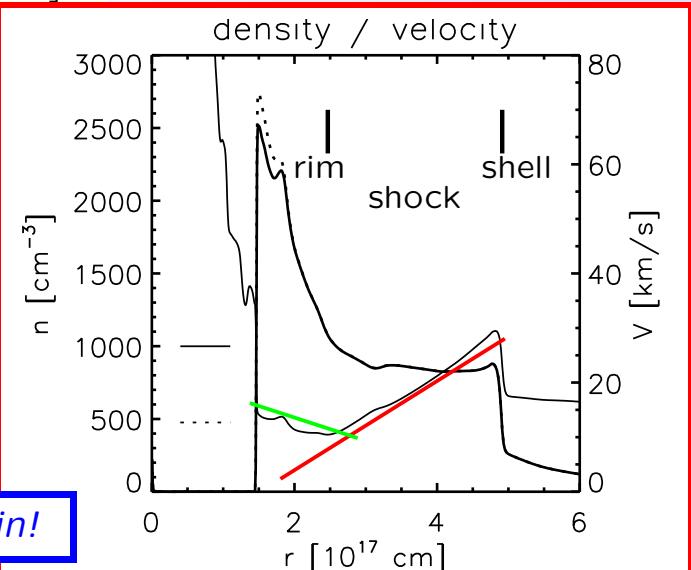
Kinematical ages from shells and rims are about equal –

Does this mean PNe expand according to $v(r) \sim r$?



NO:

$v(r)$ does not intersect with the origin!



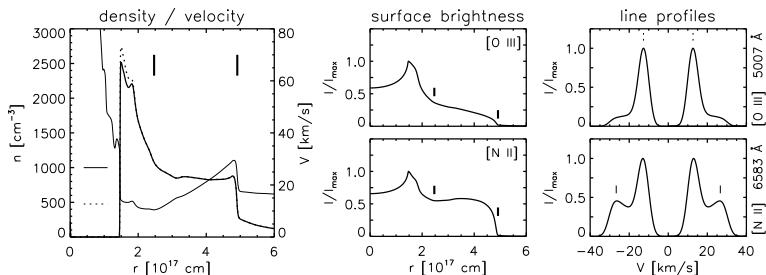
Structures (7)

Expansion parallaxes –

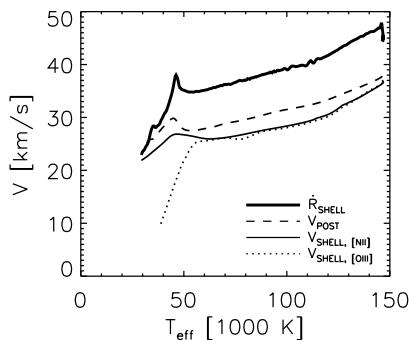
Comparing proper motions of rim & shell, $\dot{\theta}$, in plane of sky
with gas (Doppler) l.o.s velocities, V , of rim & shell

Schönberner et al. 2005

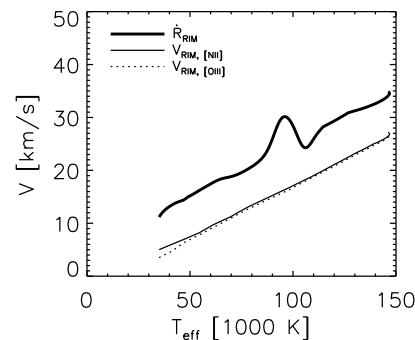
$$\text{Distance} \rightarrow D = V/\dot{\theta} \times F_{\text{corr}}$$



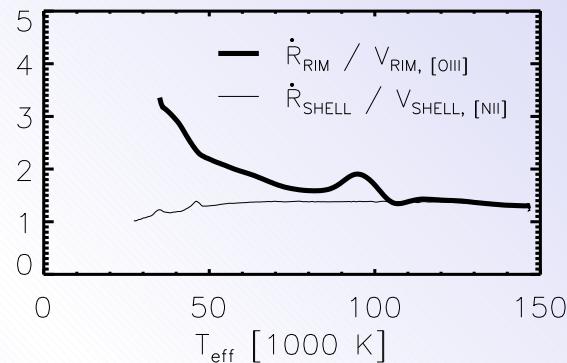
SHELL EVOLUTION



RIM EVOLUTION



Corrections from our 1D models:



AGAIN: spectroscopic velocities underestimate the real expansion!

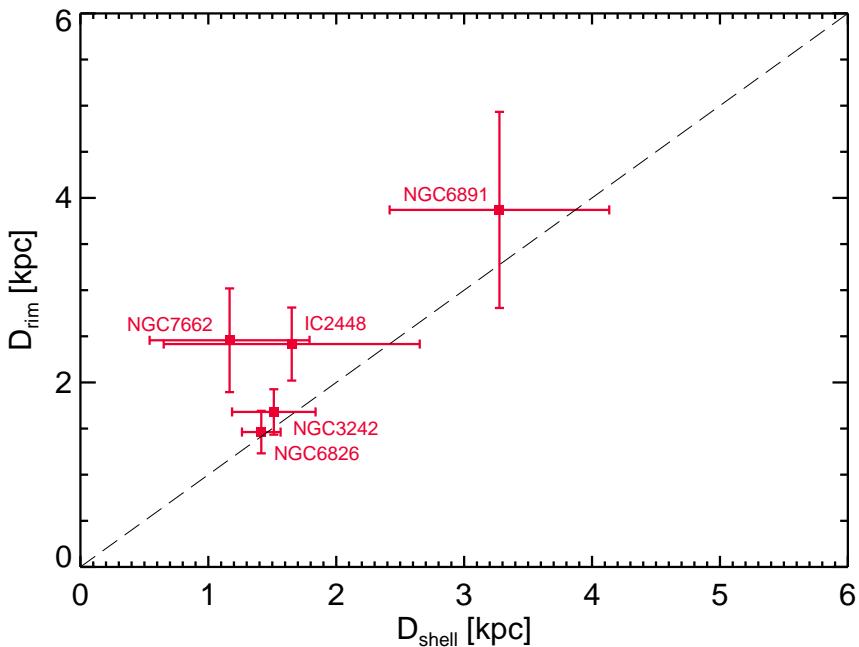
Expansion distances MUST be corrected by factors of 1.3–3

Structures (8)

Expansion parallaxes –

Application of the Balick et al. HST proper motion measurements.

comparisons between rim & shell, *including corrections from models:*



Reasonable agreement
between rim & shell!

Accurate distances for
NGC 6826 & NGC 3242:

$$D(3242) = 1.6 \pm 0.2 \text{ kpc}$$

$$\Rightarrow L = 7200 \pm 1800 \text{ } L_{\odot}$$

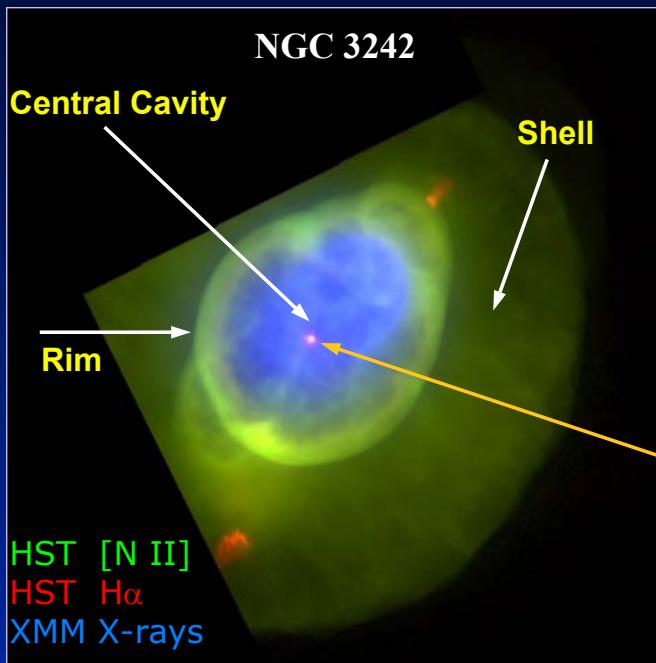
$$D(6862) = 1.4 \pm 0.1 \text{ kpc}$$

$$\Rightarrow L = 6100 \pm 900 \text{ } L_{\odot}$$

$$M_{\text{cs}} \simeq 0.60 \dots 0.62 \text{ } M_{\odot}$$

Diffuse X-ray emission (1)

X-ray detection of hot gas in PNe



**“Limb-brightened” ?
diffuse X-ray emission
within sharp cavity**

from hot, shocked wind gas:

$$N_e \simeq 15 \text{ cm}^{-3}$$

$$T_X \simeq 2.2 \times 10^6 \text{ K}$$

$$L_X \simeq 10^{31} \text{ erg s}^{-1}$$

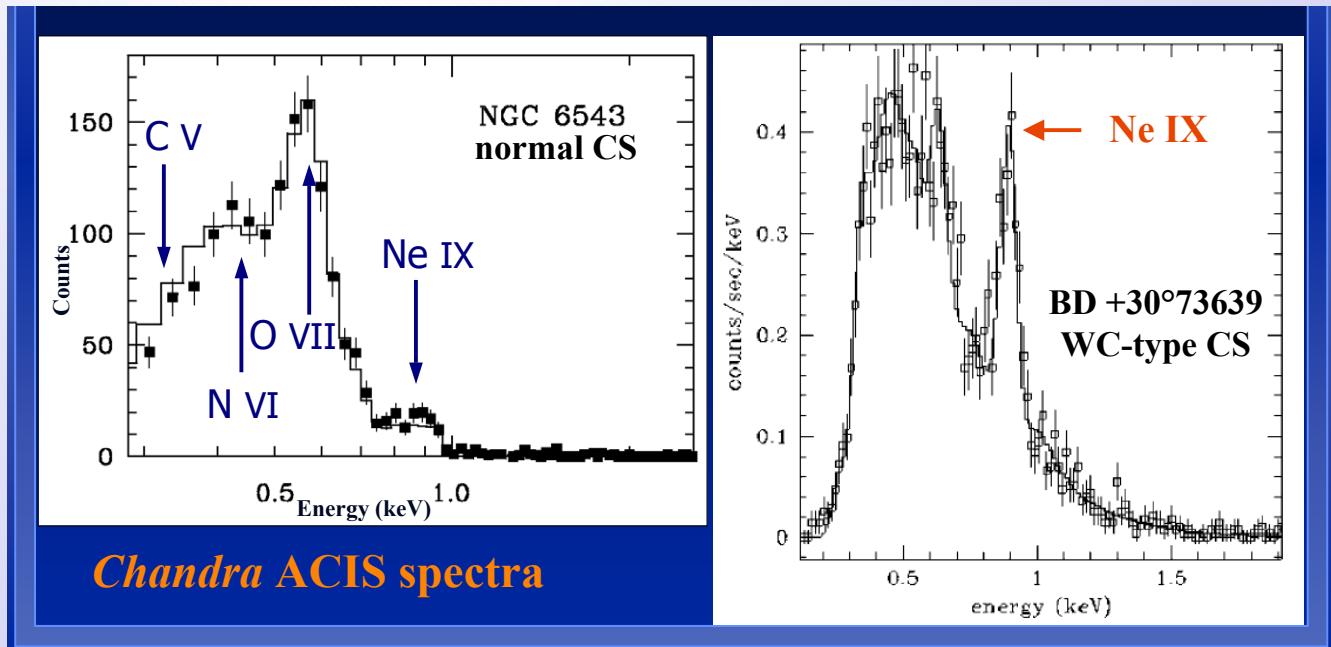
central star
no X-ray source

© M. Guerrero 2005

Diffuse X-ray emission (2)

Examples of X-ray spectra –

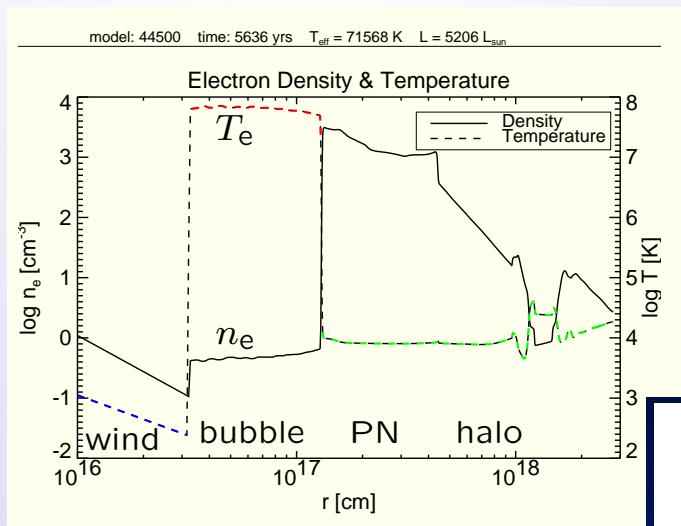
Two different stellar spectral types:



$$\begin{aligned}N_e &\simeq 40 \text{ cm}^{-3} \\T_X &\simeq 1.7 \times 10^6 \text{ K} \\L_X &\simeq 10^{31} \text{ erg s}^{-1}\end{aligned}$$

$$\begin{aligned}N_e &\simeq 200 \text{ cm}^{-3} \\T_X &\simeq 3 \times 10^6 \text{ K} \\L_X &\simeq 1.6 \times 10^{32} \text{ erg s}^{-1}\end{aligned}$$

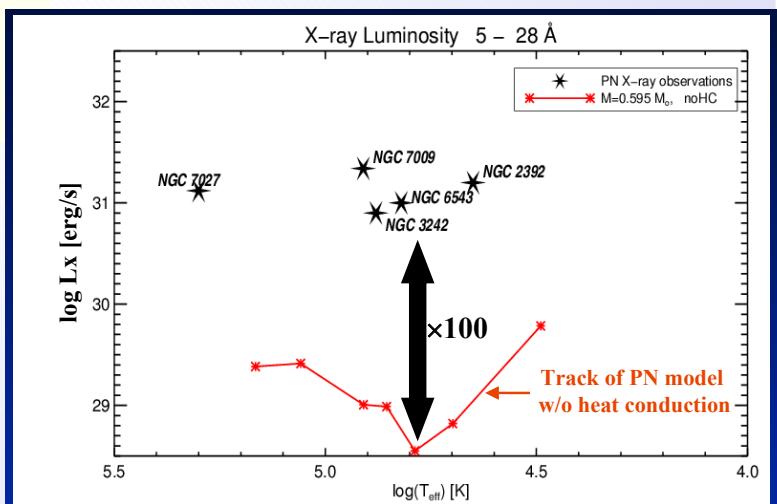
Diffuse X-ray emission (3)



Bubble density too low, –
bubble temperature too high!

$\approx 10^7 \dots > 10^8 \text{ K}$

X-ray luminosity too low –
by factor ≈ 100 !



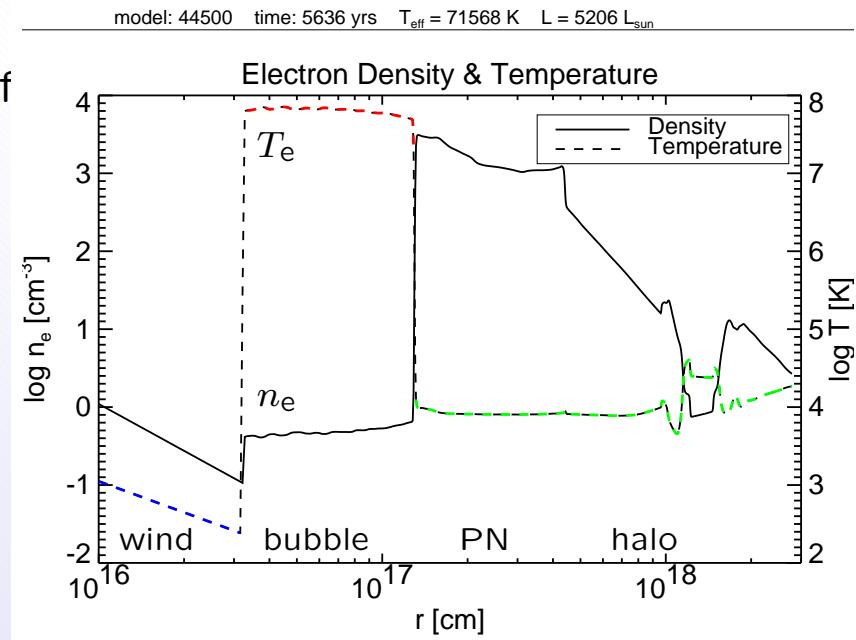
Diffuse X-ray emission (4)

Heat conduction across bubble/PN interface –

Weaver et al. 1977

$$\vec{q} = -D \nabla T_e, \quad D = 1.5 \times 10^{-5} T_e^{3/2} / \ln \Lambda$$

Nebular gas evaporates
into the bubble because of
heat transfer by electrons



Diffuse X-ray emission (4)

Heat conduction across bubble/PN interface –

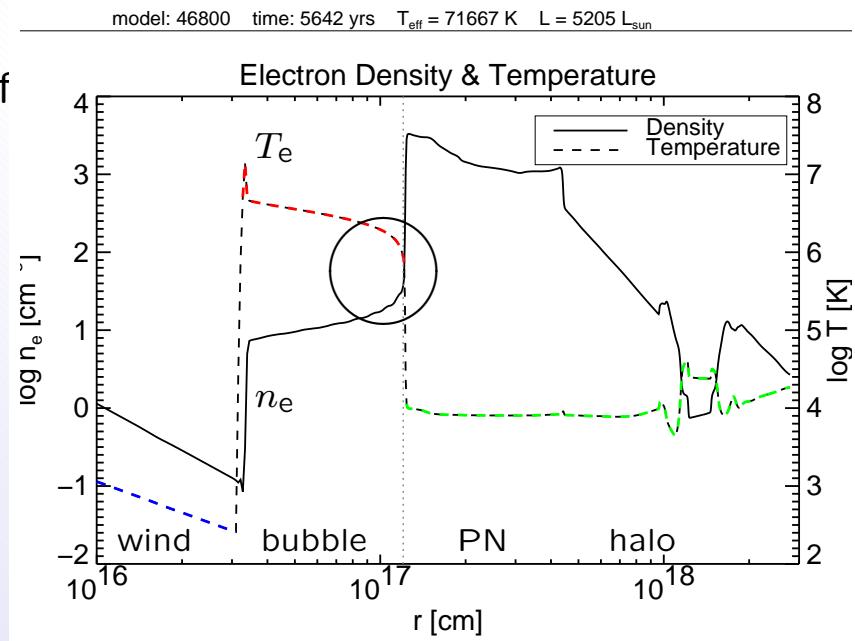
Weaver et al. 1977

$$\vec{q} = -D \nabla T_e, \quad D = 1.5 \times 10^{-5} T_e^{3/2} / \ln \Lambda$$

Nebular gas evaporates
into the bubble because of
heat transfer by electrons
 \Rightarrow

$$T_e \longrightarrow \approx (1 \dots 2) \times 10^6 \text{ K}$$

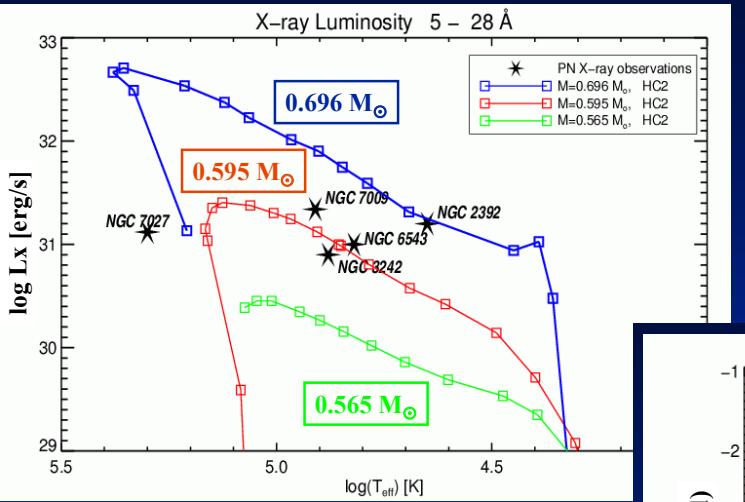
$$n_e \longrightarrow \approx 10 \dots 100 \text{ cm}^{-3}$$



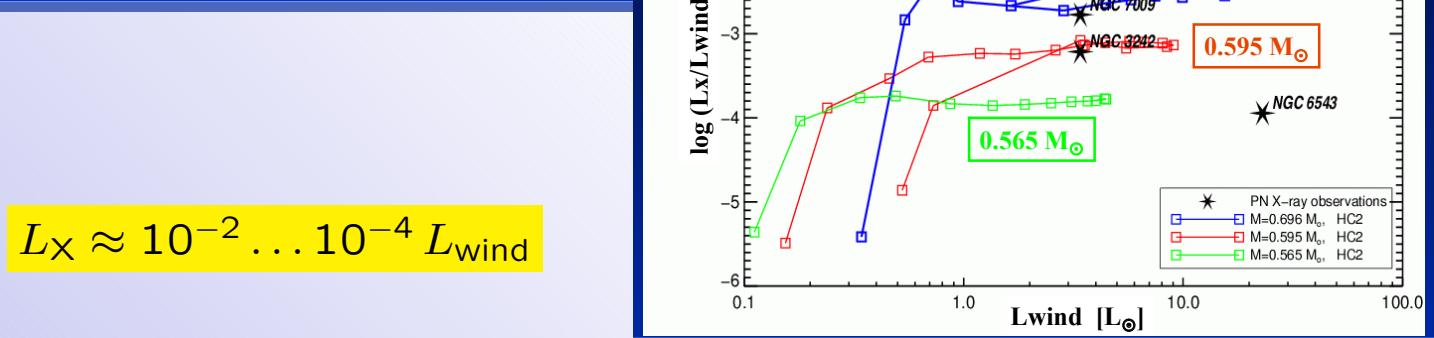
Diffuse X-ray emission (5)

Hydrodynamic simulations with heat conduction –

Steffen et al. 2008



$$L_X \approx 10^{-6} L_{\text{star}}$$

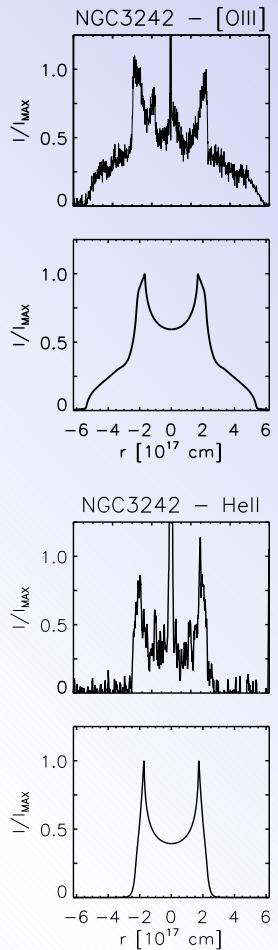


$$L_X \approx 10^{-2} \dots 10^{-4} L_{\text{wind}}$$

Diffuse X-ray emission (6)

Hydrodynamics with heat conduction –
Steffen et al. 2008
 A test case, NGC 3242 – *Distance = 1.6 ± 0.2 kpc*
 comparison with 2 models of our $0.595 M_{\odot}$ sequence

	Mod. 1	Mod. 2	NGC 3242
Age (yr)	5600	6100	$\gtrsim 4100$
Size (pc)	0.137	0.157	0.147
T_{eff} (K)	71 700	80 500	75 000
L_{cs}/L_{\odot}	5200	5050	$\simeq 7200$
\dot{M}_{wind} (M_{\odot}/yr)	9.7×10^{-9}	8.6×10^{-9}	$\simeq 7 \times 10^{-9}$
v_{wind} (km/s)	2100	2500	2400
$L_{\text{X}}/L_{\text{cs}}$	5.0×10^{-7}	6.8×10^{-7}	6.6×10^{-7}
$L_{\text{X}}/L_{\text{wind}}$	7.2×10^{-4}	7.7×10^{-4}	$\approx 1.3 \times 10^{-3}$
T_{X} (K)	2.1×10^6	2.1×10^6	2.2×10^6
$n_{\text{e,X}}$ (cm^{-3})	15	14	14
$n_{\text{e,rim}}$ (cm^{-3})	2600	2200	2400
$n_{\text{e,shell}}$ (cm^{-3})	1400	950	1000



Influence of metallicity (1)

- The wind power of the star decreases with metallicity
- The line cooling efficiency of the gas decreases with metallicity



With respect to the Galactic Disk, PNe in stellar populations with lower metallicity are expected

- *to have different structures, i.e. rim-shell structure may disappear,*
- *to expand more rapidly since the gas becomes hotter,*
- *to be not necessarily in thermal equilibrium since their line cooling efficiency is lower and their cooling by expansion more efficient !*

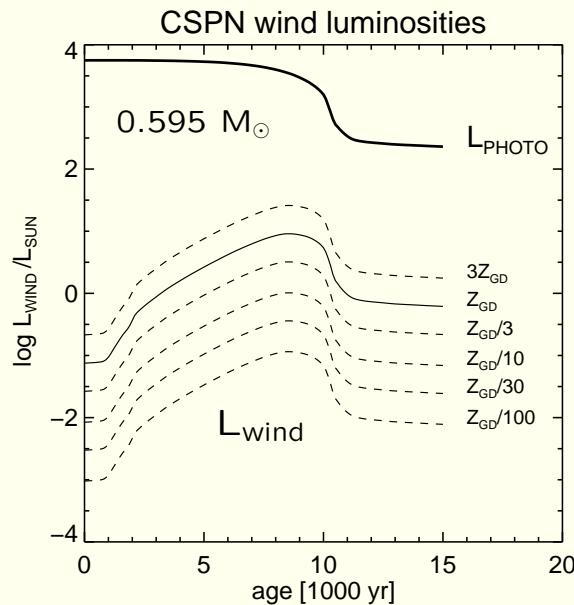
Influence of metallicity (2)

Dependence of central-star wind strength on metallicity is approximated as

- $\dot{M} \sim Z^{0.69}$
- $v_\infty \sim Z^{0.13}$

Vink et al. 2001

Leitherer et al. 1992



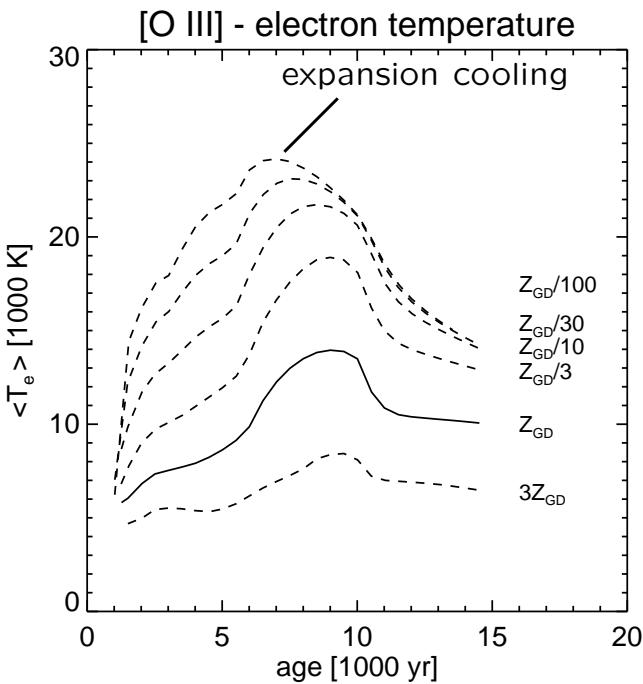
$$L_{\text{wind}} = \dot{M} v_\infty^2 / 2 \sim Z^{0.95}$$

Mean composition of
Galactic disk PNe, Z_{GD} ,
as reference:

El.	Abund.
H	12.00
He	11.04
C	8.89
N	8.39
O	8.65
Ne	8.01
S	7.04
Cl	5.32
Ar	6.46

Influence of metallicity (3)

Param. study, power-law initial wind envelopes with $\alpha = 3$ –
Mean [O III] electron temperatures of our models:



$$\langle T_e \rangle = \frac{\int T_e N_e N_i dV}{\int N_e N_i dV}$$

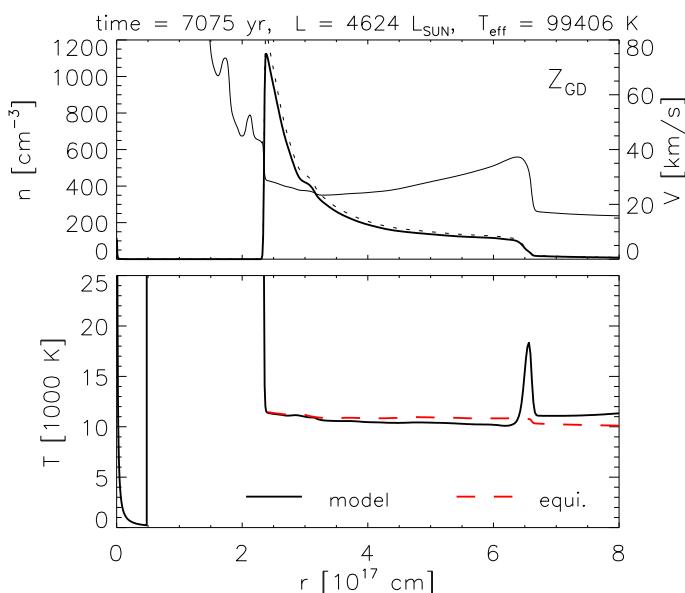
- General temperature increase with stellar temperature
⇒ Increase of shock speed
Stellar photons more energetic
- Electron temperature increases with decreasing metallicity;
Line cooling from heavier ions reduced
- *For low metallicities, 'expansion cooling' becomes significant at low densities and limits the electron temperature at about 24 000 K, instead of $\approx 31 000$ K!*

Influence of metallicity (4)

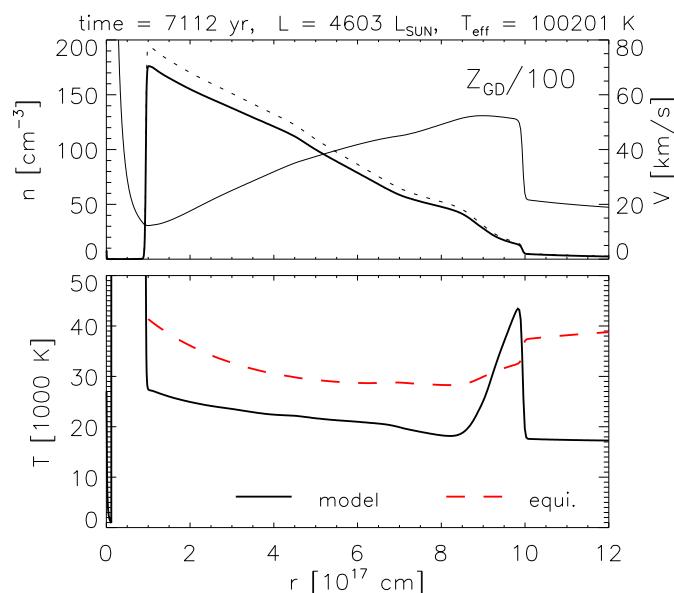
Thermal equilibrium? Dynamical source/sink term $p(\nabla \cdot \vec{v})$?

Two models at same position in the HRD, but with different metallicities,

$$Z = Z_{\text{GD}} \text{ vs. } Z = Z_{\text{GD}}/100$$



No significant expansion cooling!

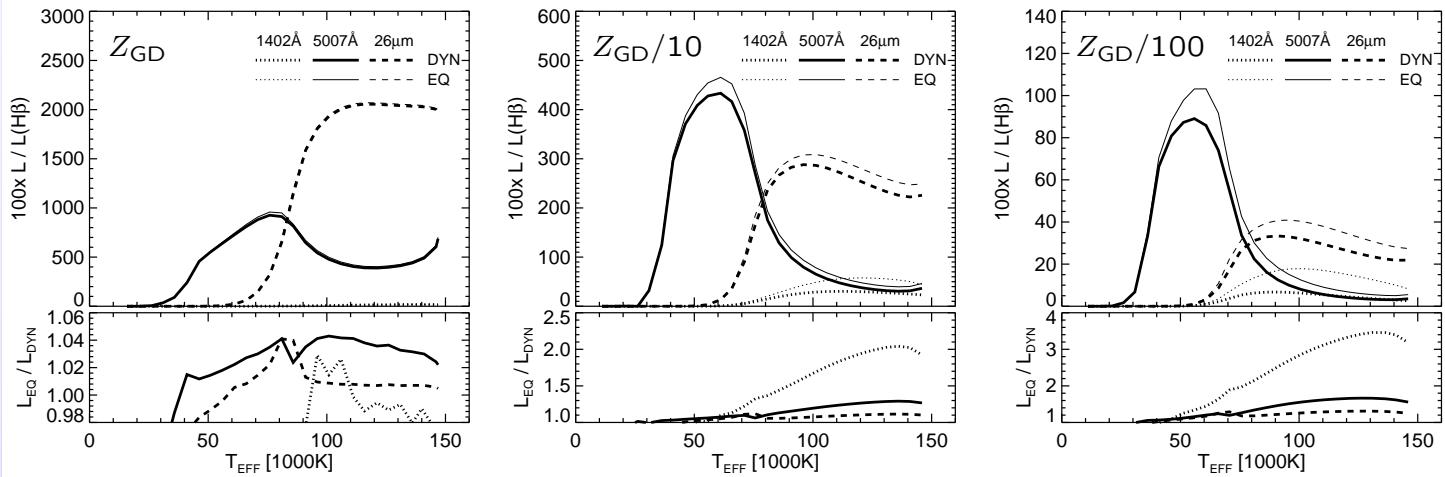


Expansion cooling significant

$$\Delta T_{\text{max}} \simeq 10\,000 \text{ K}$$

Influence of metallicity (5)

Thermal equilibrium? Dynamical source/sink term $p(\nabla \cdot \vec{v})$?
 Examples of collisionally excited oxygen lines (UV, optical, IR):



- Dynamical models always with **weaker** line strengths
 - Differences significant for $Z \gtrsim Z_{\text{GD}}/10$ & $T_{\text{eff}} \gtrsim 70\,000\text{ K}$
- ⇒ Consequences for photo-ionisation modelling!

PNe in distant stellar systems (1)

Usage of PNe important tool of investigating properties of unresolved stellar populations –

- Kinematic studies for probing gravitational potentials of galaxies
- Luminosity functions for distance estimates of galaxies
- Chemical abundance determinations for unravelling the chemical history of galaxies
- ...

Problems:

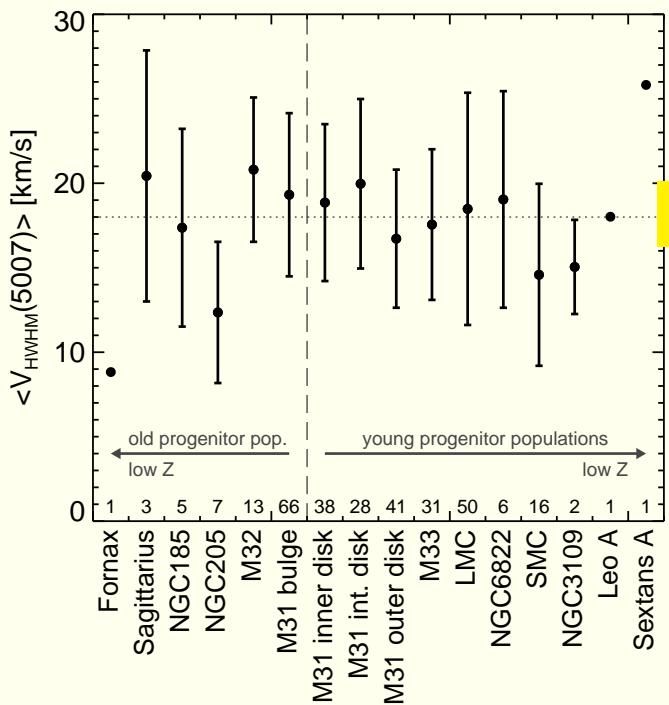
- Rather large variation of the metallicity, $\approx 3Z_{\text{GD}} \dots \approx Z_{\text{GD}}/10$
- Morphology unknown
- Generally only spatially unresolved line profiles available
- Often too few lines available for constraining a photoionisation model,
⇒ plasma diagnostics with corrections for unseen ions
- ...

PNe in distant stellar systems (2)

Do observed ‘expansion velocities’ of bright PNe reflect the metallicity variation of their parent population? –

Mean V_{HWHM} -‘velocities’ from integrated [O III] 5007 Å line profiles of bright PNe in different extragalactic systems:

Richer 2006

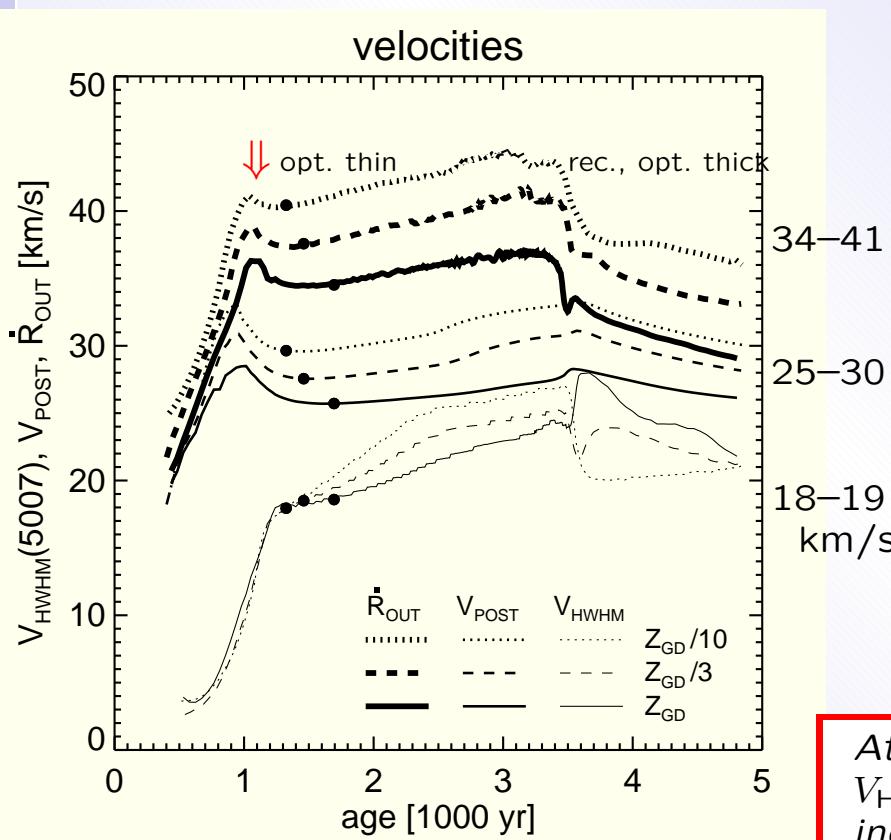


18 km/s

No apparent differences of V_{HWHM} for galaxies of quite different ages & metallicities

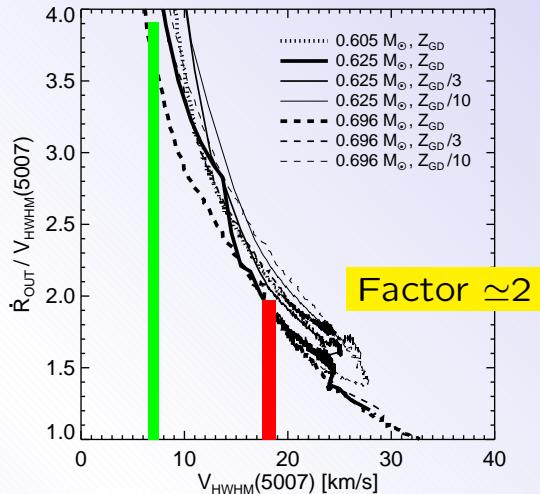
PNe in distant stellar systems (3)

Expansion properties of bright PN with massive central star –



$$\begin{aligned} M_{CS} &= 0.625 \text{ M}_\odot \\ \dot{M}_{AGB} &= 10^{-4} \text{ M}_\odot/\text{yr} \\ V_{AGB} &= 15 \text{ km/s} \end{aligned}$$

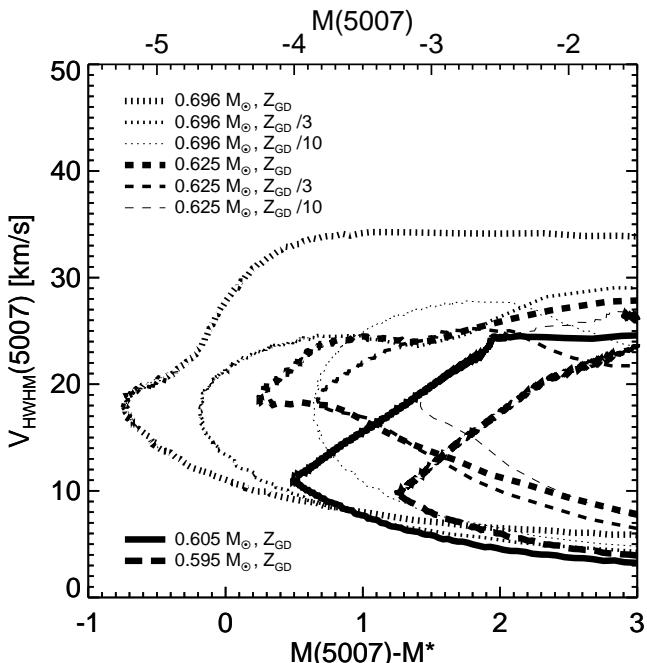
Korrektur for real expansion, \dot{R}_{out} :



At max. $[O III]$ brightness (●):
 $V_{HWHM}(5007) \approx 18 \text{ km/s}$, quite
independent of metal content!

PNe in distant stellar systems (4)

Evolution of V_{HWHM} with [O III] brightness $M(5007)$ –
dependence on M_{cs} and Z
Hydrodynamical models
Schönberner et al. 2010, subm.



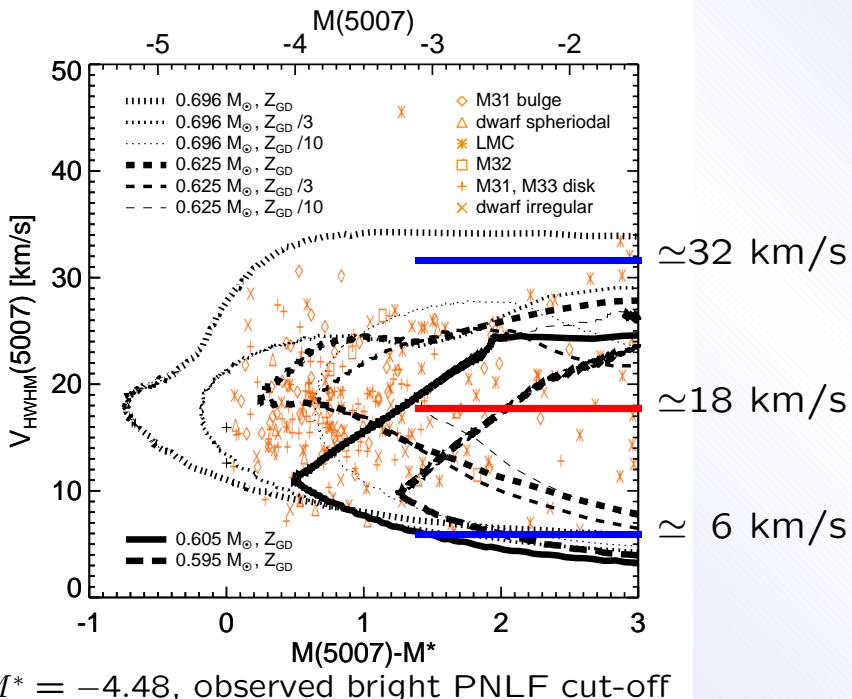
$M^* = -4.48$, observed bright PNLF cut-off

PNe in distant stellar systems (4)

Evolution of V_{HWHM} with [O III] brightness $M(5007)$ –
dependence on M_{cs} and Z

Hydrodynamical models & Observations Local Group

Richer 2006



Observed V_{HWHM} range fully covered by the models

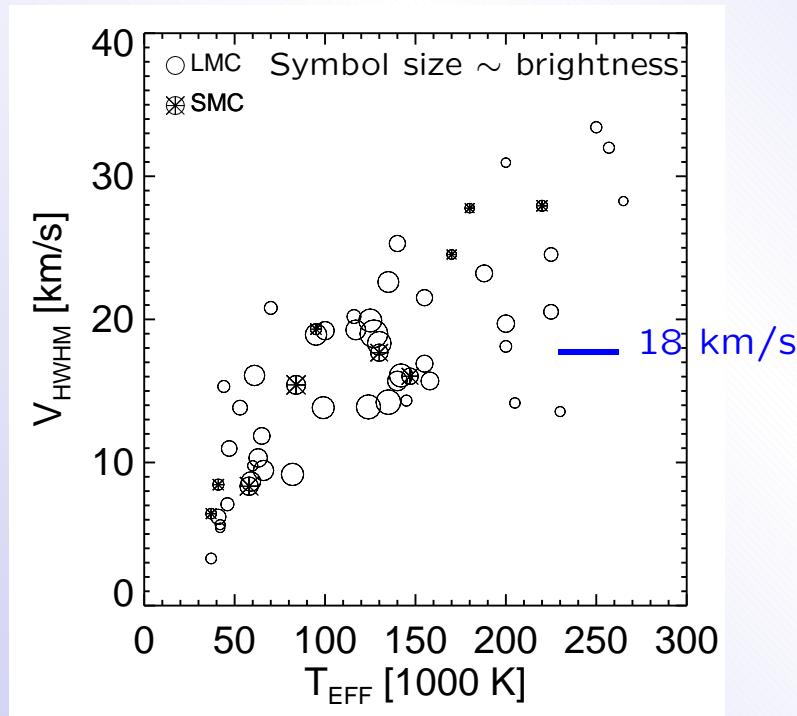
Mean V_{HWHM} at maximum brightness $\simeq 18 \text{ km/s}$, independent of population properties

Maximum central star mass $\simeq 0.63 M_{\odot}$

PNe in distant stellar systems (5)

Evolution of $V_{\text{HWHM}}(5007)$ with stellar effective temp. –
Magellanic Clouds

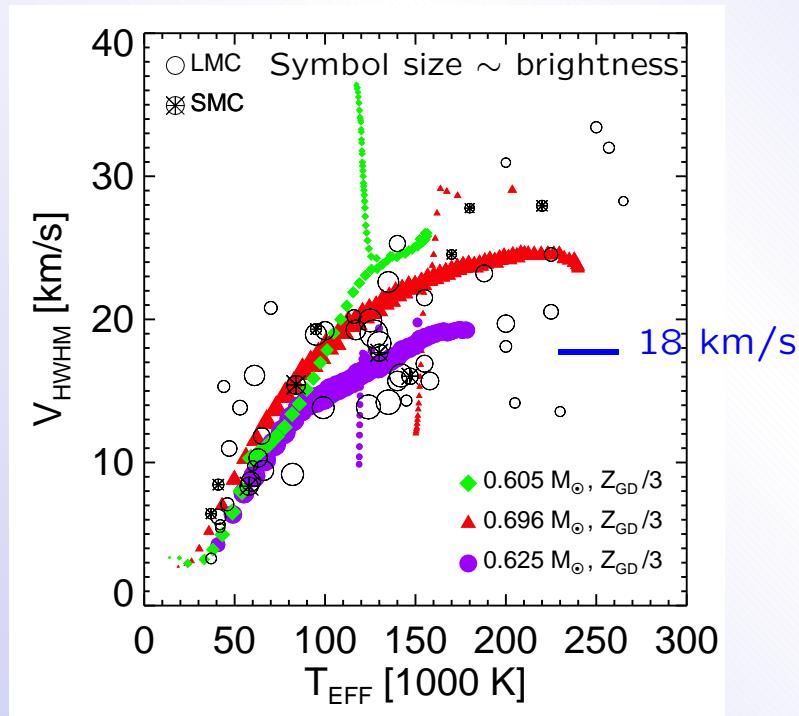
Dopita & Meatheringham 1991a,b



PNe in distant stellar systems (5)

Evolution of $V_{\text{HWHM}}(5007)$ with stellar effective temp. –
Magellanic Clouds

Schönberner et al. 2010, subm.



SUMMARY

Hydrodynamics simulations in spherical geometry extremely successful in understanding basic properties of PNe

formation & evolution:

- *Morphology & expansion is driven by the central star, controlled by metallicity via the electron temperature*
- *PNe in metal-poor populations may not be in thermal equilibrium with respect to photo-heating & line cooling*
- *Heat conduction by electrons is essential for explaining the diffuse X-ray emission from shocked stellar wind gas*

Still not understood: *why is sphericity exception, not the rule?*

(binary interaction, jets, disks, magnetic fields, . . .)

CHEERS,

Tony!

