The Expansion of Planetary Nebulae

Theory vs. observation

D. Schönberner

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AIP

– Personal Memories

– The Physical System & its Modelling

– Expansion velocities

– Summary

Personal Memories (1)

- *First personal contact with Romek, September 1981:*
  "Int. Astron. Tagung Innsbruck 1981" of the German AG, with "Karl-Schwarzschild-Lecture" held by B. Paczyński

A44 Evolution of Planetary Nebulae Nuclei

R. TYLENDA (Astron. Inst., Toruń)

My first paper on the evolution of PNe was just in press *(A&A 103, 119)*

A45 Entwicklung der Zentralsterne Planetarischer Nebel

D. Schönberner (Inst.f.Theor.Physik u.Sternwarte, Univ.Kiel)

Es wird über Rechnungen berichtet, welche die Entstehung der Zentralsterne Planetarischer Nebel durch hohe Massenverlust-raten auf dem Asymptotischen Riesenast simulieren.

- *Realisation of a visit in Warszawa/Torun at NCAC, March 1988:*
  (Still times of the "cold war": official invitation of the PAN, visa, transit GDR, . . .)

  Employing your code with time-dependent ionisation for simple model PNe evolving along my post-AGB tracks

- *Finish of the work at Kiel University during "Kieler Woche", June 1989:*

  Basically, the paper was addressing the question on deriving stellar parameters as "seen" through the nebula:
  "On the observed HR diagram of PNNi", *(A&A 234, 439)*

Personal Memories (2)

The referee report was unique:

Astronomy and Astrophysics (January, 1990)

Referee's report on the paper by Schonberner and Tylenda
"On the observed HR diagram for PNNi".

Based on an evolutionnary model for PNe, the authors argue that, due to the frequent "matter-bounded" nature of the nebula, usual estimates of PN nuclei parameters derived from nebula properties can be strongly biased in large portions of the HR diagram. They are seemingly able to re-interpret published diagrams and to show that theoretical evolutionary tracks are consistent with observation, assuming a black body spectrum for the PNNi in their models.

The impression is that observations are too serious things to be left to observers to interpret. It is very unfortunate that collaborations between different specialists are not the rule in this kind of touchy subjects. Models of stars and nebulae are quite elaborate for years and it is surprising to see such a destructive contribution to appear so lately.

One may easily argue about most of the assumptions of the authors, but the general idea could hardly be wrong. The problem is that PNe are probably more complex than the present idealized version so that it would be difficult to use the present results to infer anything secure about PNNi from published observations beyond what is already stated by the authors. Thus the paper is terribly negative in that it does not try to propose any solution. The strategy of observations may need be revised and accurate modelling of accurately observed objects may well be much more necessary than currently believed by most researchers, including modellers. The approach by grids is probably not fruitful at the present stage because too many umproven assumptions must be made to arbitrarily reduce the number of free parameters. The situation is evidently even worse when the simplistic empirical methods correctly criticized by the authors are used.

This paper poses a problem of ethic in the field because, in fact, everybody is more or less aware of this "Damocles spade". Let us try to understand the tree before the forest, instead of continuing "doing our best", however bad it is. I am afraid these comments are for the edithors rather than for the authors, but a debate is urgently needed to decide what should be the standard of a publishable paper to day.

I recommand publication without revision.

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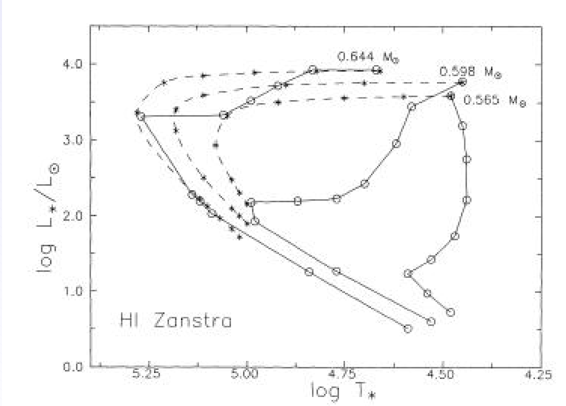
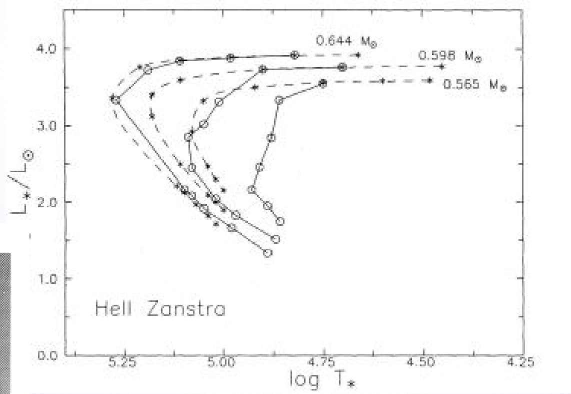
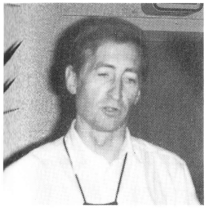


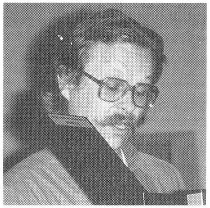
"Zanstra wall", $T_{\rm star} \lesssim 10^5$ K



IAU-Sympos. No. 155, Innsbruck 1992:



D. SCHÖNBERNER

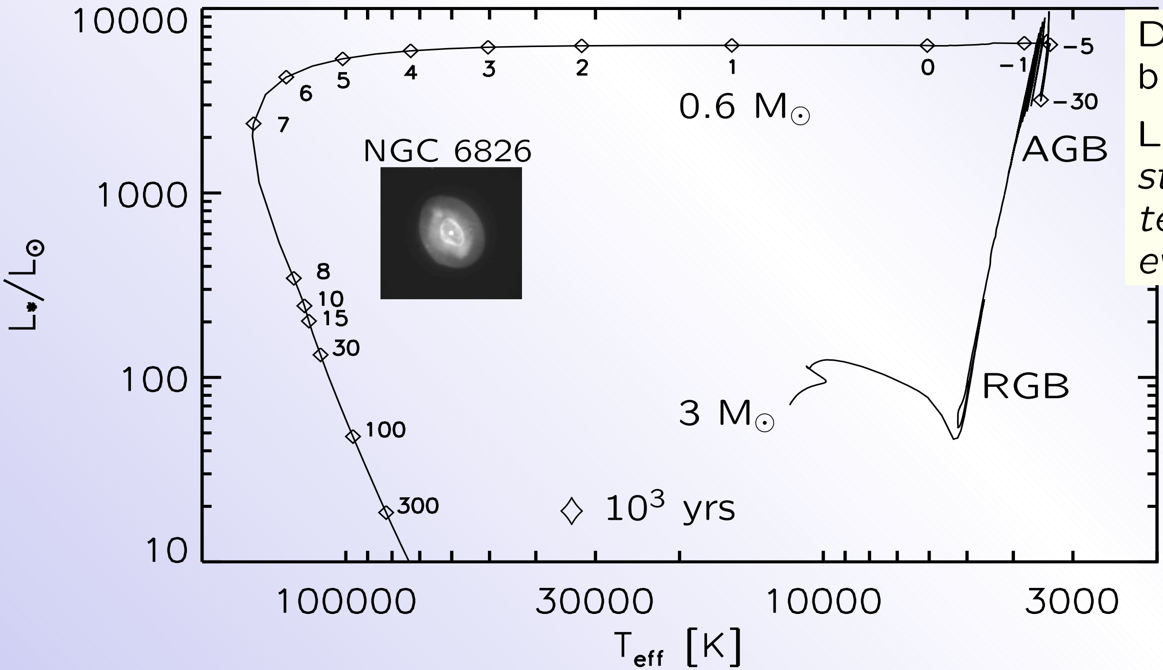


R. TYLENDA

The physical system (1)

Planetary Nebula:

Relic of AGB wind, reshaped by the steadily changing *radiation field & wind* of the post-AGB (= *central*) star while evolving across the HR diagram toards the WD stage



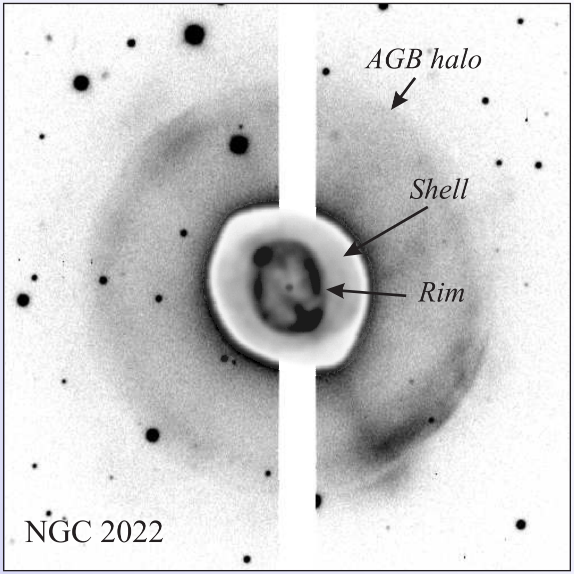
Double-shell burning

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

The physical system (2)

A typical round/elliptical PN –

© R. Corradi



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

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

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

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

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

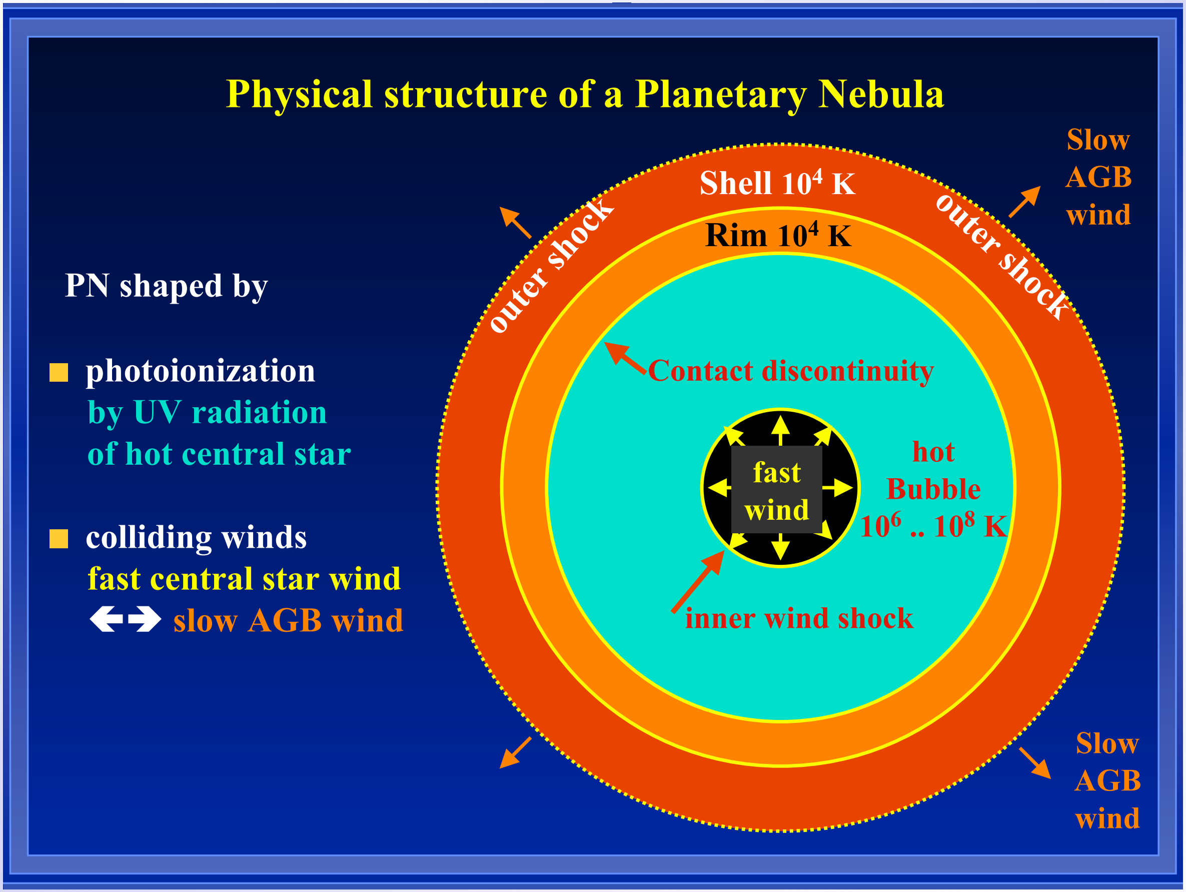
Halo –

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

Planetary Nebula –

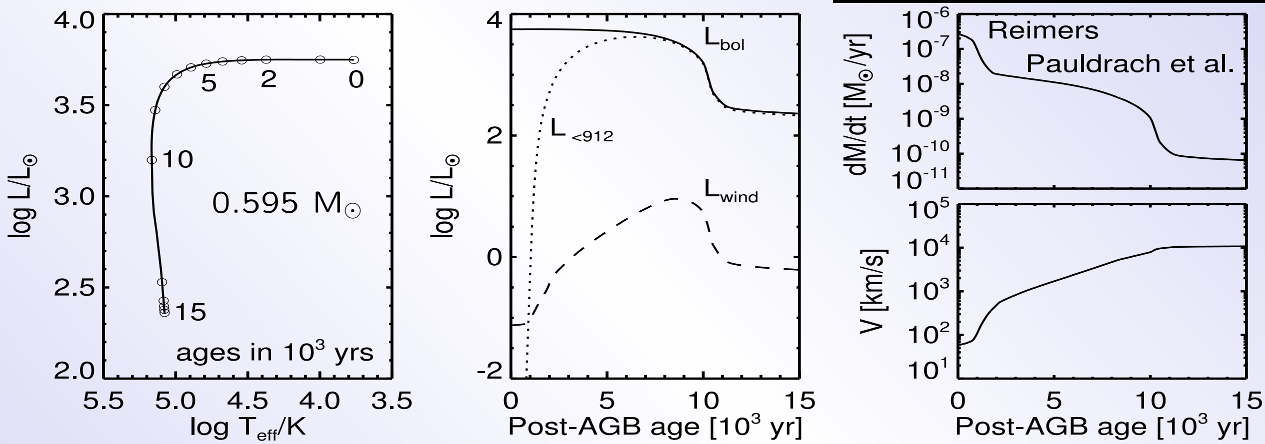
System of shock waves, expanding into the AGB wind, set up by ionisation heating (shell) & wind-wind interaction (rim)

The physical system (3)



Simulations (1)

Consistent modelling the evolution of **Star & wind envelope**



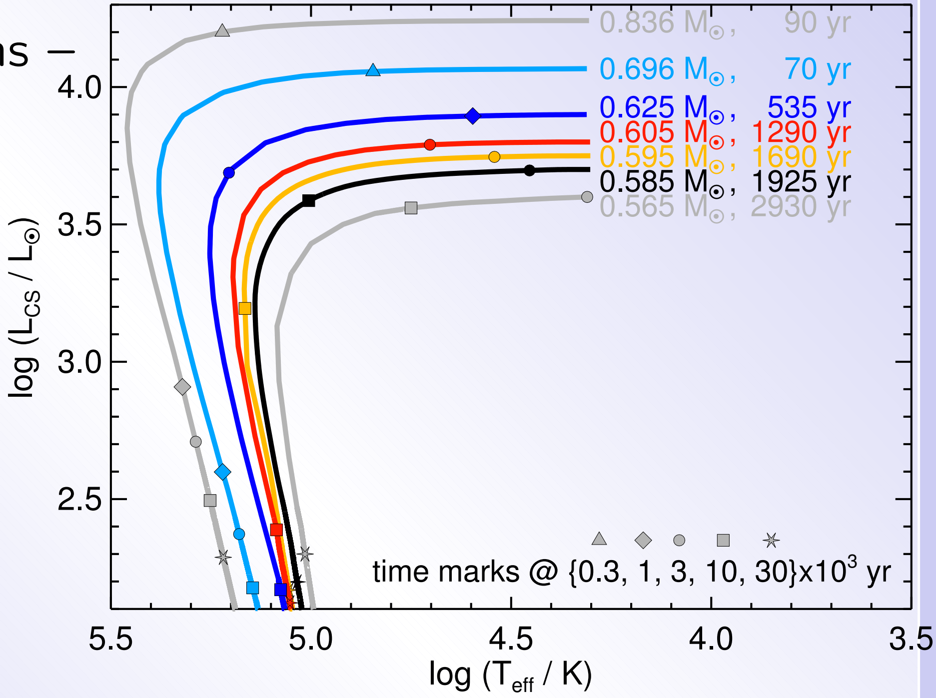
1D-hydrodynamics of circumstellar envelope with **time-dependent**

- ionisation, recombination, heating, cooling for 9 elem., 12 ion. stages
- inner boundary condition ($r_\mathrm{i} = 5\times10^{14}$ 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)

Simulations (1a)

The post-AGB tracks used for the simulations –



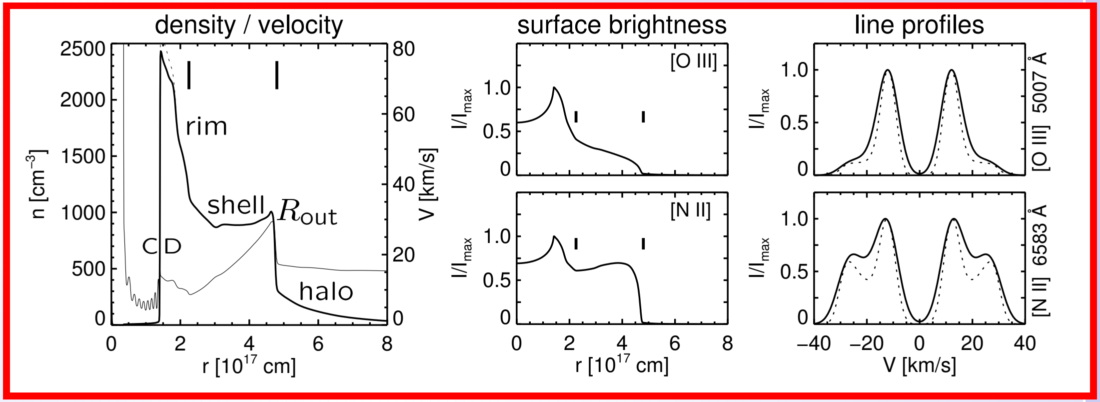
Post-AGB evolution extremely sensitive to remnant masses in terms of luminosity & time scale

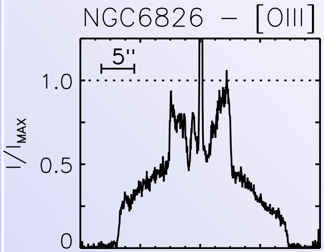
Limiting luminosity for a $\simeq 0.6\ M_\odot$ remnant within 20 000 years: $\simeq 150\ L_\odot$

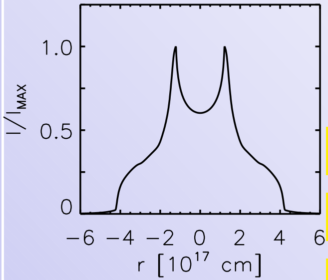
Simulations (2)

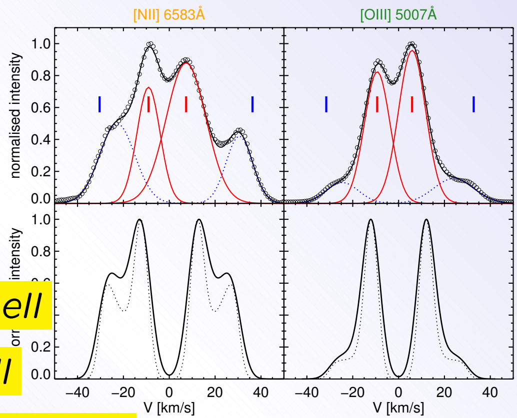
Match between models & real objects –

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









Double-shell structure: rim & shell

Distinct velocities for rim & shell

Shell with positive(!) velocity gradient

Expansion properties (1)

What is the *true* expansion velocity of a planetary nebula?

The radial position of the outer shock, $R_{\rm out}$, defines the nebular radius,
the shock's propagation speed, $\dot{R}_{\rm out}$, is the true PN expansion velocity

However,
this shock velocity cannot be measured spectroscopically!

Other "expansion" velocities are:

1. A representative velocity derived from the peak separation of Doppler split emission lines
2. A representative velocity from the half width of emission lines of spatially unresolved objects
3. The post-shock velocity $V_{\rm post}$ $(= \dot{R}_{\rm out}/F,\ F \simeq {\rm const})$ *Corradi et al. 2007*

Velocities to 1. & 2. depend (!) on ion used,
a typical mean value used in statistical studies is 20–25 $\rm km\,s^{-1}$

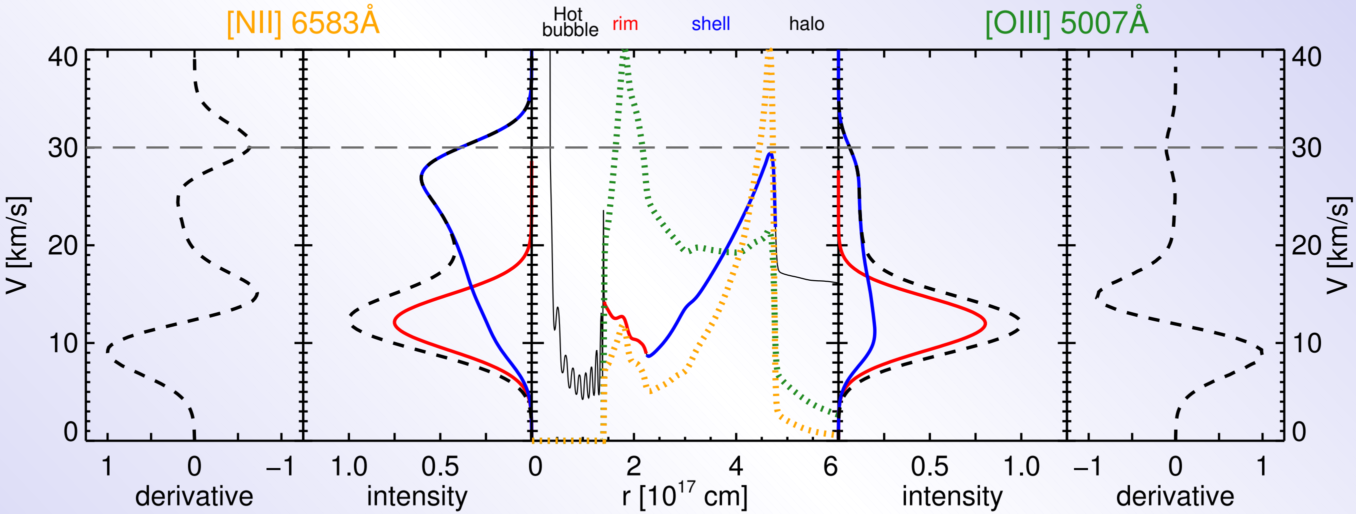
Only velocity to 3. is physically sound, independent (!) of the ion used,
correction F depends on shock strength, $= 1.25 \pm 0.5$ *Jacob et al., in press*

Spectroscopically measured velocities below the true velocity!

Expansion properties (2)

How to get the post-shock velocity ? *Corradi et al. 2007*

Decomposed line components of rim and shell:



Model: $M_{CS} = 0.595\ M_\odot$, age = 6106 yr, $T_{eff} = 80177$ K, $L_{CS} = 5057\ L_\odot$, $M_{ion}^{rim} = 0.07\ M_\odot$, $M_{ion}^{shell} = 0.40\ M_\odot$

"– –": extremes of the line profile derivative = post-shock velocity V_{post}

True expansion $\dot{R}_{out} = V_{post} \times 1.25 = 37.5\ \mathrm{km\,s^{-1}}$

Corradi et al. 2007, A&A 474, 529

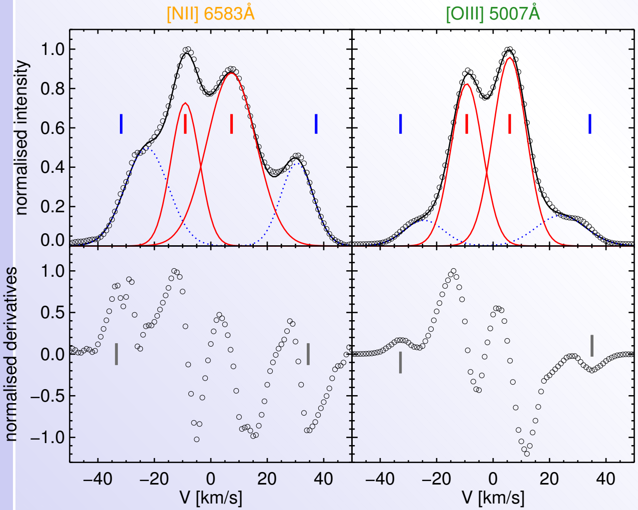
Expansion properties (3)

AIP

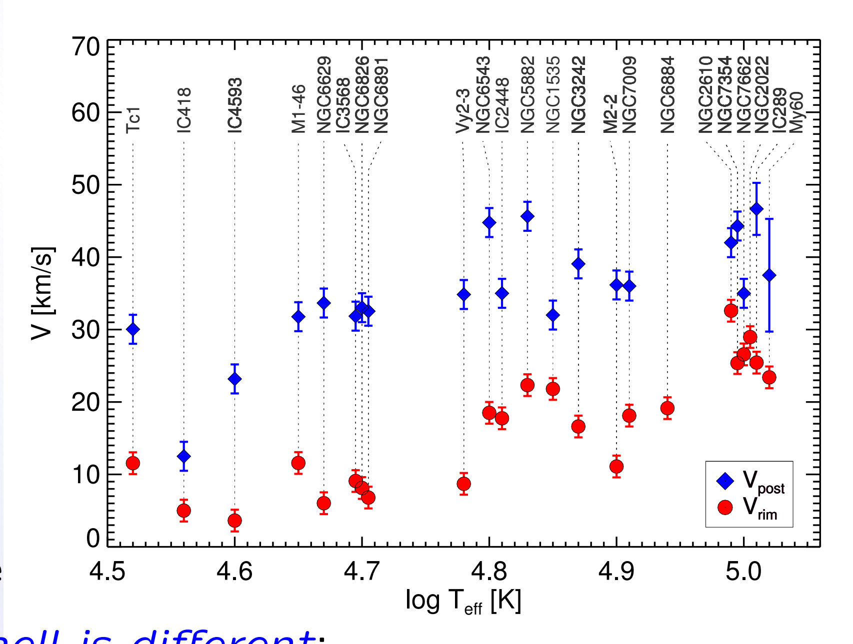
Example & Results for 22 PNe – Tautenburg/NTT/CAT/NOT

NGC 6826:

Schönberner et al., in prep.



22 double-shell PNe: *(no WR objects!)*



$V_{\rm rim}$ from Gauss decomposition

$V_{\rm post}$ from line profile derivative

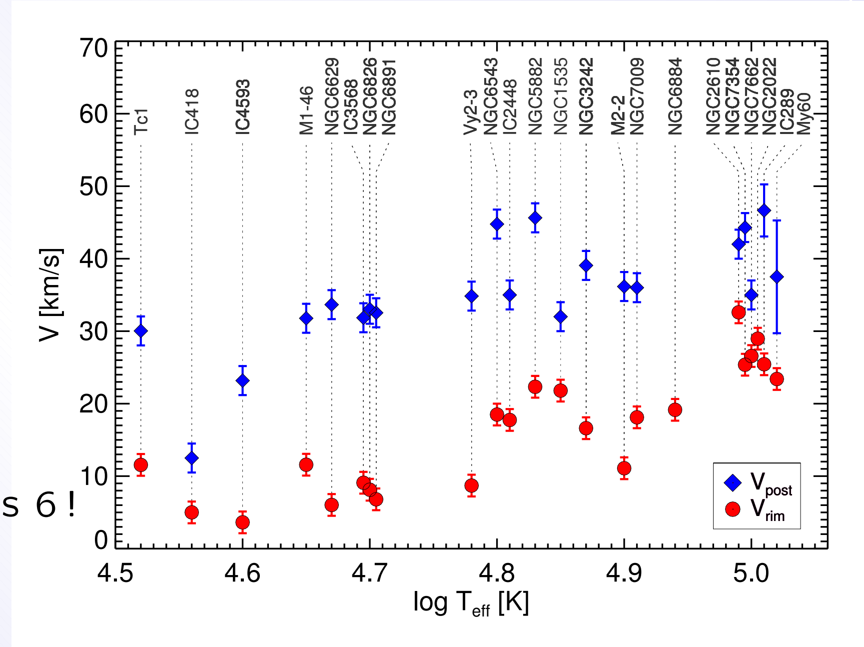
⇒ *Kinematics of rim & shell is different*:

$\langle V_{\rm post} - V_{\rm rim} \rangle \simeq 20\,{\rm km\,s^{-1}} \rightarrow \simeq 10\,{\rm km\,s^{-1}}$

Expansion properties (4)

Results:

- $V_{\mathrm{post}} > V_{\mathrm{agb}}$!
  rapid increase of V_{post}
  from ≈ 20 to $\simeq 40$ km s^{-1}
- For $\log T_{\mathrm{eff}} \lesssim 4.7$:
  $V_{\mathrm{rim}} < V_{\mathrm{agb}}$!
  Then increase of V_{rim} from
  $\lesssim 10$ to ≈ 25–30 km s^{-1}
- $V_{\mathrm{post}}/V_{\mathrm{rim}}$ can be as large as 6 !



Photoionisation/-heating causes deceleration of inner nebular edge against pressure of shocked stellar-wind ("bubble") gas!

Later the "bubble" starts in shaping and accelerating the rim *only*!

Expansion properties (5)

Kinematics of shells –

$V_{\rm post}$ for a series of models with power-law density profiles, $\rho \propto r^{-\alpha}$:

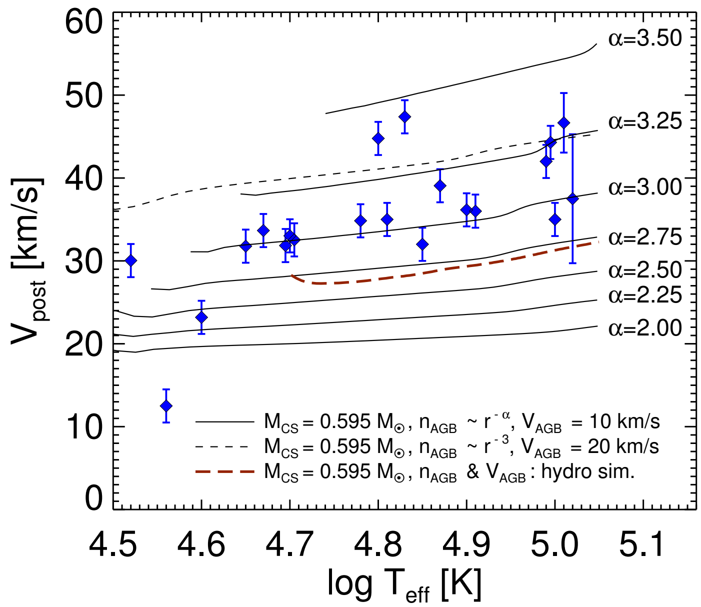
PNe expand into environments with $\alpha \approx 2.8$–3.4

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

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

Corradi, priv. comm.: $\langle\gamma\rangle = 4.6 \pm 0.3$

Since $\gamma \simeq 2\alpha - 1$ $\Rightarrow \langle\alpha(\gamma)\rangle \simeq 2.8$



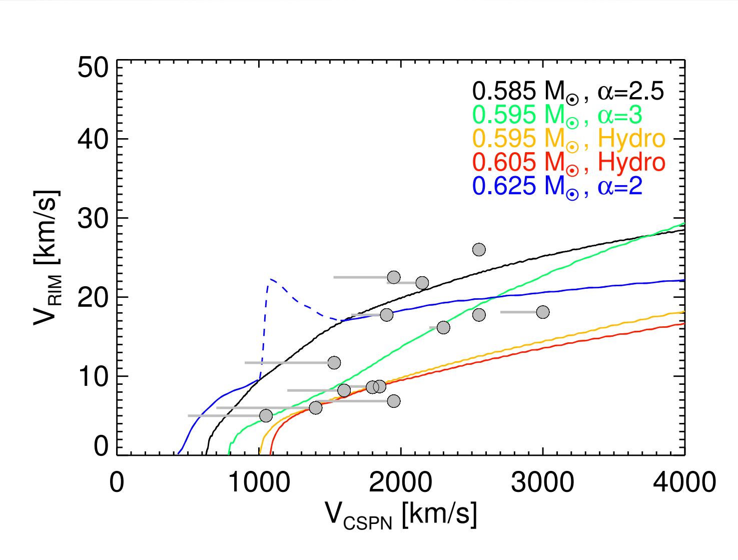
Post-shock velocities consistent with upstream density gradients

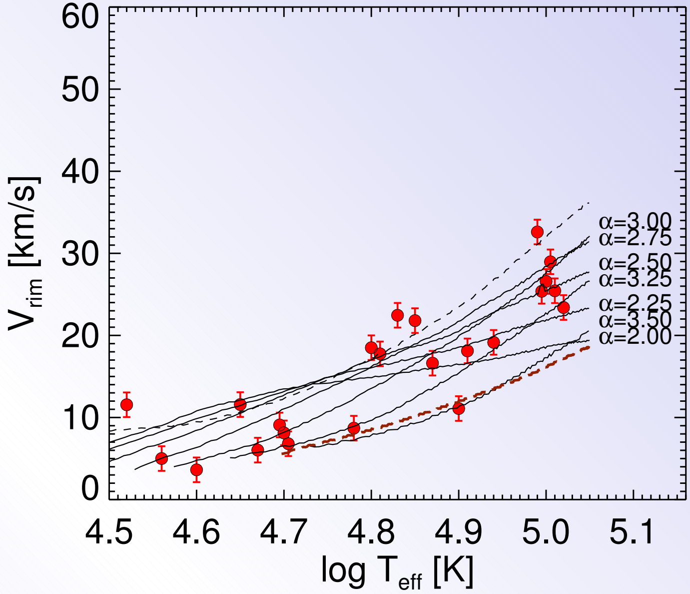
$\alpha > 2$, $\Rightarrow$ *Final mass loss on AGB "accelerated"*

N.B.: $V_{\rm post} \neq$ const. because of electron temperature increase during evolution

Expansion properties (6)

Kinematics of rims –





Increasing stellar wind power, $\dot{M}_{\rm cspn} \times V^2_{\rm cspn}/2$, accelerates rim

Expansion properties (7)

PNe during recombination/ reionisation –

High stellar temperature, 156 000 K, high stellar luminosity, 2200 $L_\odot$, post-AGB age = 7000 years

After 650 years:

High stellar temperature, 126 000 K, low stellar luminosity, 300 $L_\odot$

Recombination progresses inwards if $\tau_{\text{rec}} < |L/\dot{L}|$

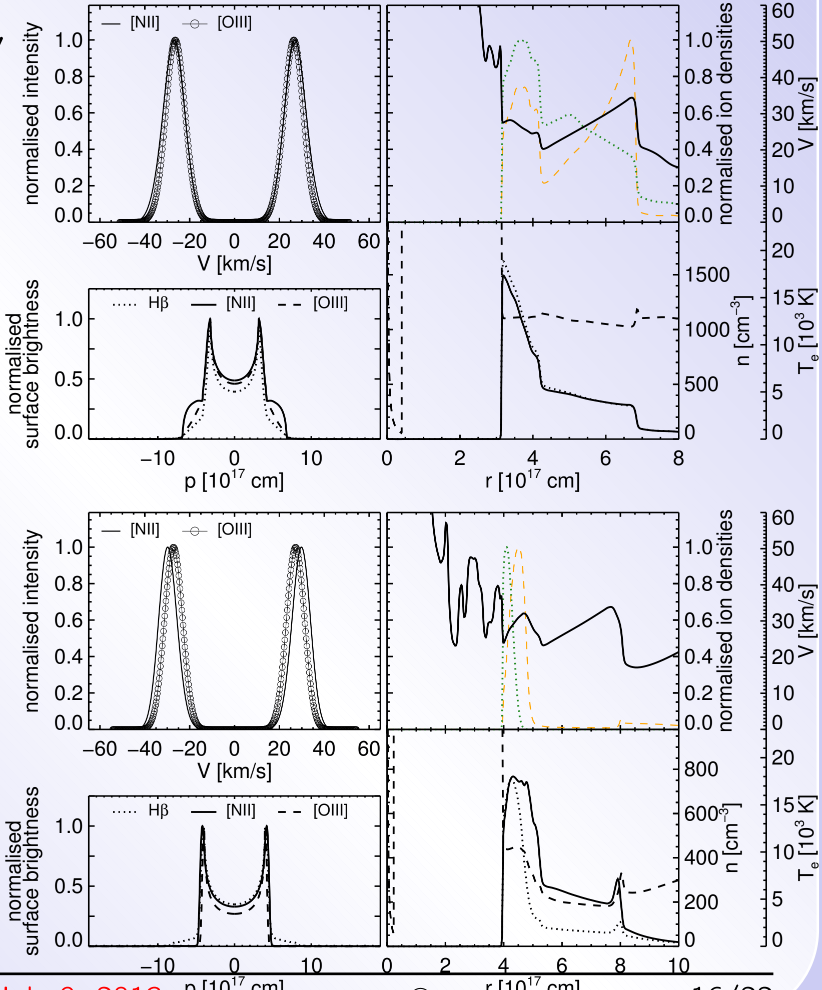
$\Rightarrow$ *"Recombination halo"*

Tylenda 1986

$(L/\dot{L})_{\text{min}} \simeq 500$ yr ($\simeq 0.6\ M_\odot$)

Hydrogen: $\tau_{\text{rec}} = (1.2\,10^5\,\text{yr})/N_{\text{e}}$

$\Rightarrow N_{\text{e}} > 240\ \text{cm}^{-3}$



Expansion properties (8)

PNe during recombination/ reionisation –

After 1800 years:

Set-up of new ionised shell with new leading shock of high speed, $\sim 40\ \mathrm{km\,s^{-1}}$

Strong ionisiation stratification

Old shell nearly fully recombined, low electron temperature

Old leading shock decelerating

After 5000 years:

Reionisation still not complete

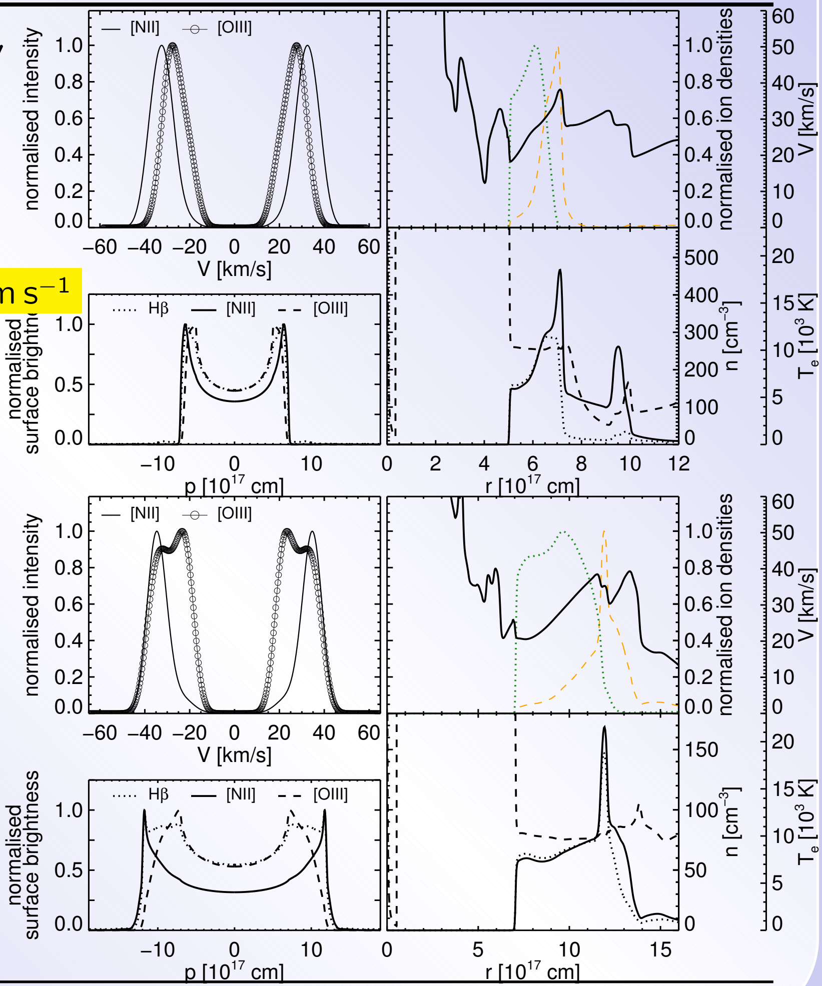
Long-lasting ionisiation stratification

[O III] line split, [NII] single compon. !

Velocities from line-peak separations:

$V_{[\mathrm{OIII}]} < V_{[\mathrm{NII}]}$

e.g. $20\ \mathrm{km\,s^{-1}}$ vs. $35\ \mathrm{km\,s^{-1}}$!

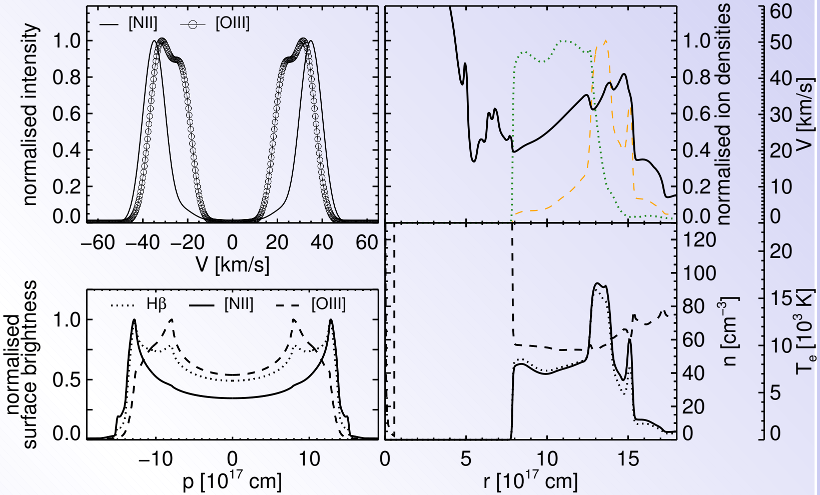


Expansion properties (9)

PNe during reionisation –

After 6500 years:

[O III] still split,
Bright "ring" or rim with small attached shell =
"fossil" reionised shell at 10–20 % level



Recombination & reionisation preferably for PN with more massive, faster evolving central stars ($> 0.6\ M_\odot$):

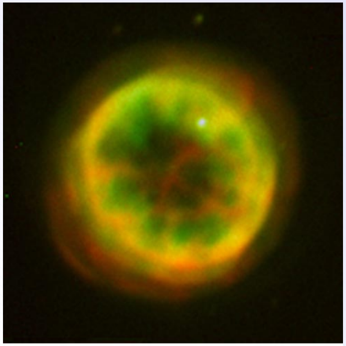
Faster evolution $\rightarrow$ denser nebula at "turn-around" point
$\rightarrow$ shorter recombination time

Expansion properties (10)

PNe during reionisation –

Two objects from Tylenda's list,
NGC 6894 & NGC 2438:

$L \simeq 300\ \mathrm{L}_\odot$, $T_{\rm eff} \gtrsim 100\,000$ K

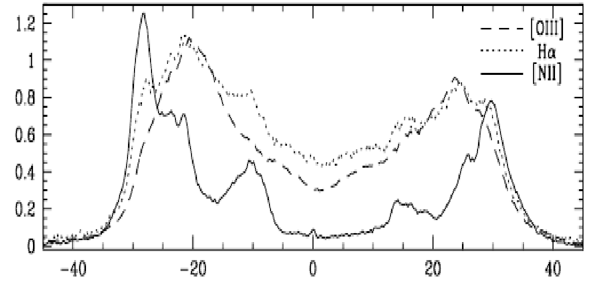


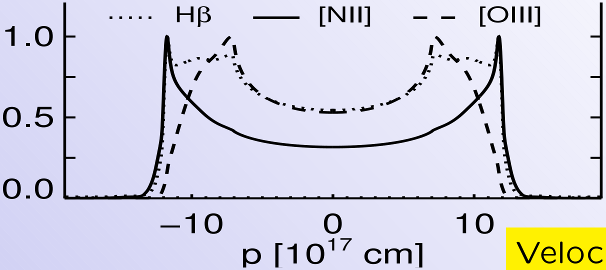
NGC 6894 G069.4-02.6 20 16 23.96 +30 33 53.2
R = log[NII], G = log[OIII], B = HeII4686
Balick 1987 AJ 94, 671

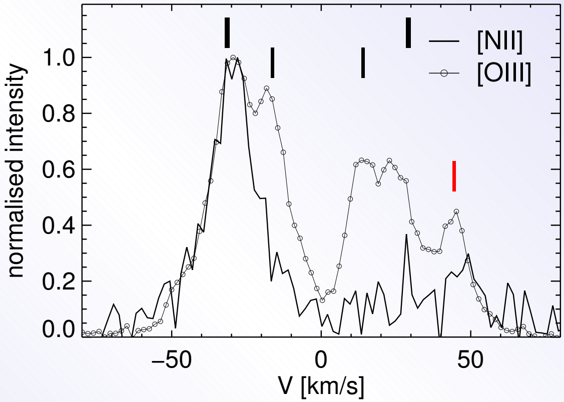
NGC 2438 G231.8+04.1 07 41 51.43 -14 43 54.9 R:G:B=log(Ha+[NII]),both,log[OIII]
ref: Schwarz, H.E., Corradi, R.L.M., Melnick, J 1992 A&A Suppl, 96, 23
image files courtesy R Corradi. N is NOT up. See ref for orientation.

©PNIC, B. Balick

NGC 2438: *Corradi et al. 2000*







Velocity range of re-ionised shell: $\simeq 15 \ldots \simeq 30$ km s^{-1}

Reionised "fossil" shell at $\simeq 45$ km s^{-1} ?

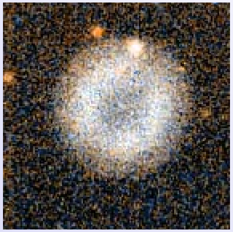
Expansion properties (11)

PNe during reionisation –

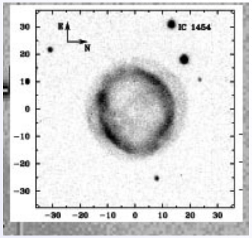
Sample of PNe which are recombining/ reionising

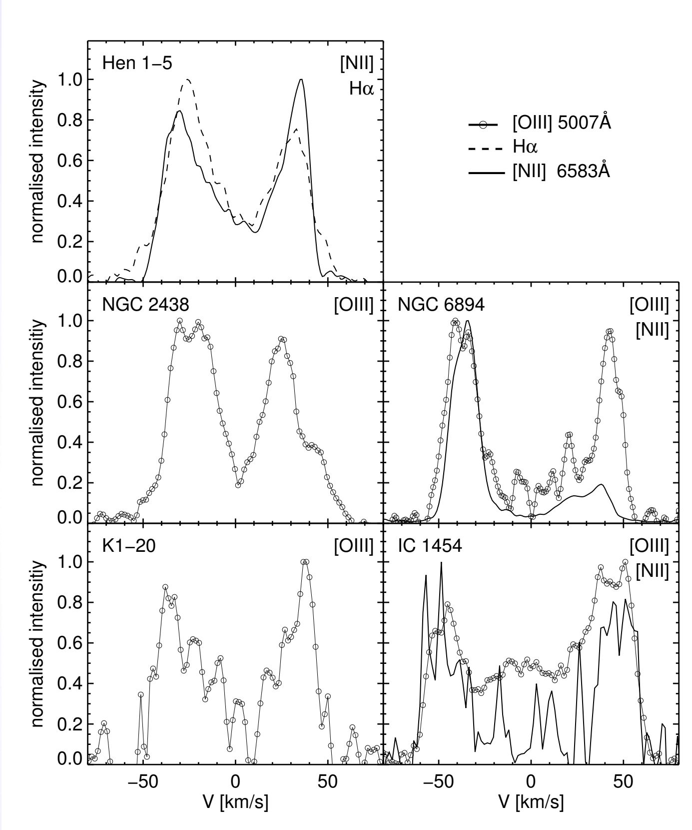
All central stars (except for Hen 1-5) have only $\lesssim 200\ \mathrm{L}_\odot$ but $T_{\mathrm{eff}} > 100\,000$ K

K 1-20:



IC 1454 (A 81):





- Well-developed central cavity
- Expansion fast, ($\simeq 40 \ldots 55\ \mathrm{km\,s^{-1}}$)
- Tendency for $V_{\mathrm{NII}} > V_{\mathrm{OIII}}$
- Long-lasting reionisation stage

Recombination does not necessarily lead to nebular deceleration, reionisation creates a new, fast expanding shock wave !

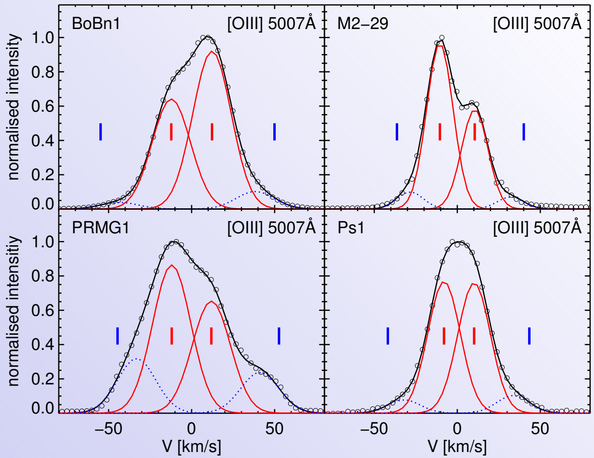
Expansion properties (12)

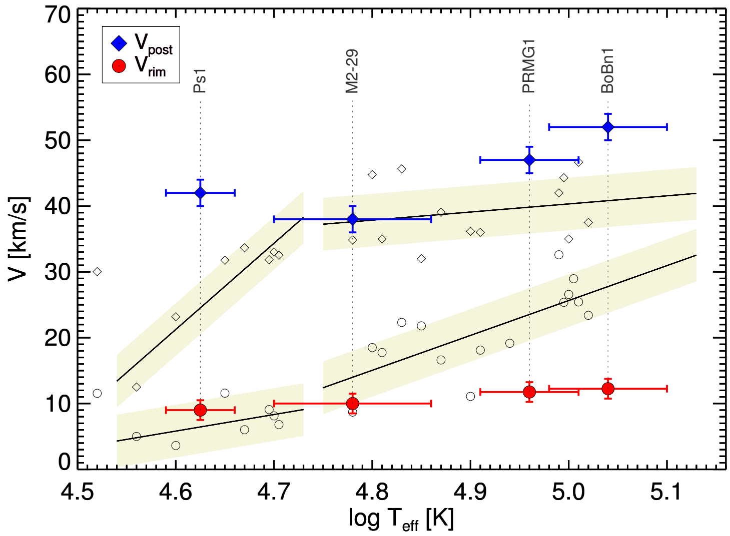
Metal-poor PNe – Test of the "Interacting Stellar Winds" theory

According to theory as outlined here,

- Shock and post-shock speed 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 halo PNe,
BoBn 1, M2-29, PRMG 1, Ps 1/K648





SUMMARY

Evolution & expansion of PNe well explained by
1D-radiation-hydrodynamics simulations (even in 1D !)

- *Overall, ionisation is driving the expansion, not the stellar wind*

- *A PN does not get extinct/decelerated/collapsed after the central star has faded*

- *On average, the true expansion velocity is* $\simeq 40\,\text{km}\,\text{s}^{-1}$

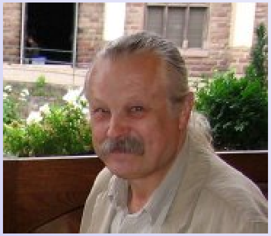
  Jacob et al. 2013, in press

- *Visibility time up to 0.9 pc is only* $\simeq 21\,000$ *yr*

  Jacob et al. 2013, in press

- *Death rate density* $(1.4 \pm 0.5) \times 10^{-12}$ *PNe/pc*^{3}*/yr*

  Jacob et al. 2013, in press



Welcome to the club, Romek !