On the Reliability of Planetary Nebulae as Extragalactic Probes

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Introduction

Planetary nebulae (PNe) are important tools to investigate the unresolved stellar component of extragalactic systems,

but

do we understand their physics sufficiently well ?

We started a new project, **XPN**, to investigate theoretically & observationally how the diagnostics of PNe is influenced by their *structure,*
element composition,
& dynamics

Final goal is to gain insight into the reliability of PNe as probes for measuring chemical abundances of their parent stellar population !

Post-doc position for project **XPN** wanted, for 2 + 1 years !

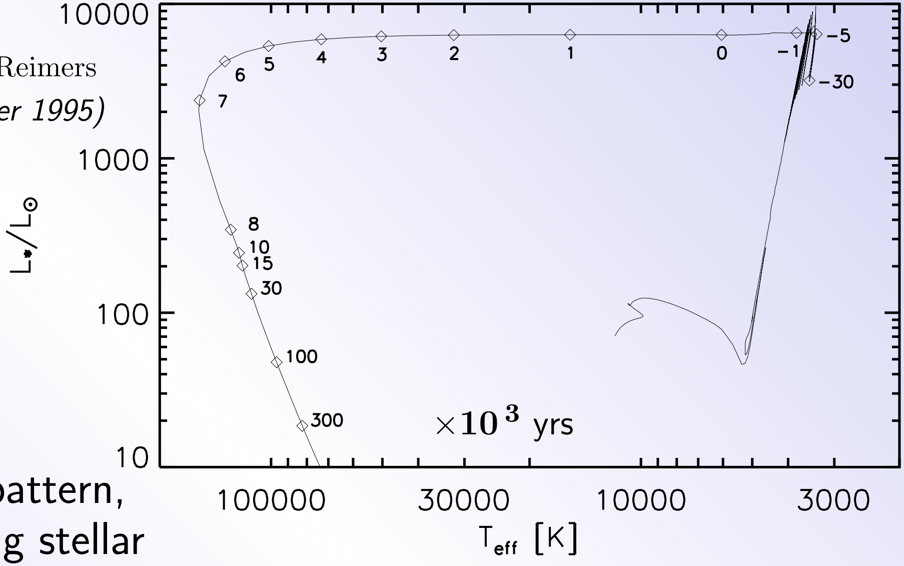
Here we report on preliminary results based on 1D radiation hydrodynamics simulations, addressing for the first time the question how the properties of PNe depend on their metallicity

The basic physical system

$\boxed{\mathbf{3}\ \mathrm{M}_\odot \longrightarrow \mathbf{0.605}\ \mathrm{M}_\odot}$

with $\dot{M}_{\rm agb}(t) \sim L^{2.7}/M^2 \times \dot{M}_{\rm Reimers}$

(Blöcker 1995)



While evolving,
the AGB remnant
(= *central star*)
forms a PN at the
inner edge of the
AGB-wind envelope
by setting up a shock-wave pattern,
driven by the rapidly changing stellar

radiation field & **wind power**
(*ionization*) (*wind interaction*)

Hydrodynamics with fully time-dependent treatment of all the physical processes involved, including the proper central-star evolution !

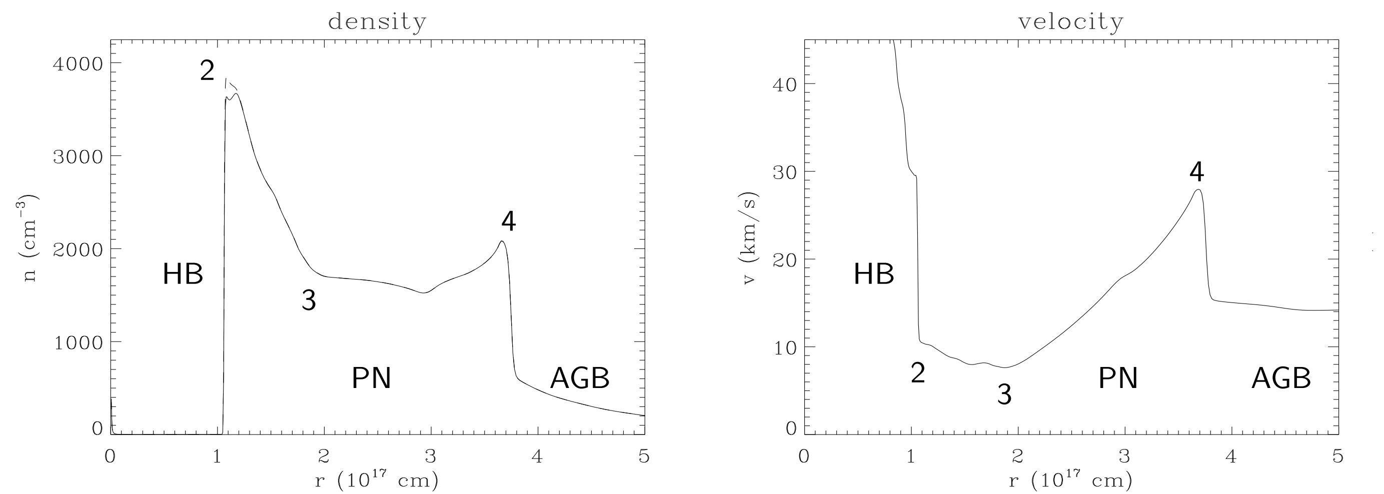
Dynamics & kinematics of PNe

Ionization & wind interaction lead to typical double-shell structures :

Marten & Schönberner 1991, Frank 1994, Mellema 1994, Perinotto et al. 2004

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

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



Thermal equilibrium ?

Radiative vs. expansion cooling ?

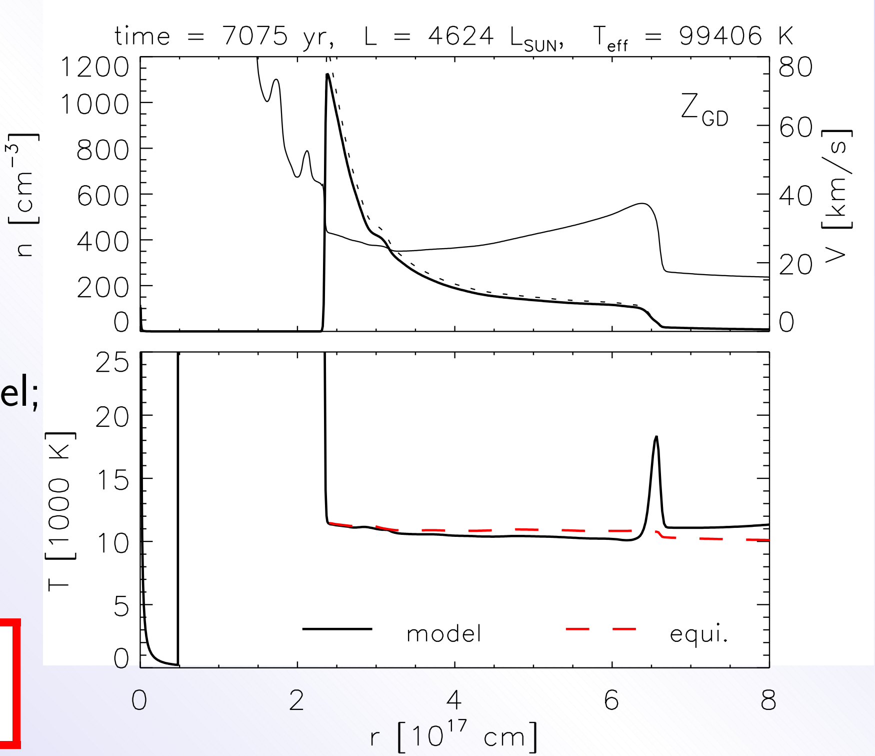
Top: Radial structure of a typical middle-aged hydrodynamical PN model with a hot, luminous central star & Galactic Disk metallicity

Bottom: Radial temperature distribution of the same model;

Dashed: Thermally relaxed (by setting $v = 0$)

Thermal equilibrium fair approximation !

Z_{DG} = metallicity of Galactic Disk $\simeq Z_{\odot}$



Dependence of PNe properties on metallicity ?

- The PN expansion speed is proportional to the sound speed, i.e. $\sim \sqrt{T_\mathrm{e}}$
- The wind power of the central star decreases with metallicity
- The cooling efficiency of the gas decreases with metallicity

$\Longrightarrow$

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

1. *to have different structures, i.e. rim-shell structure may disappear*
2. *to expand more rapidly since the gas becomes hotter,*
3. *to be not necessarily in thermal equilibrium since they are more dilute !*

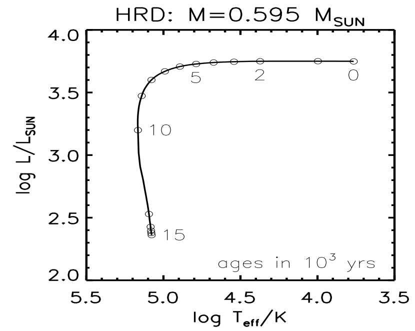
The physical model (1),

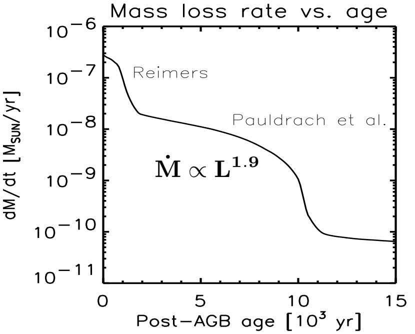
Combined evolution of ***Star & wind envelope***

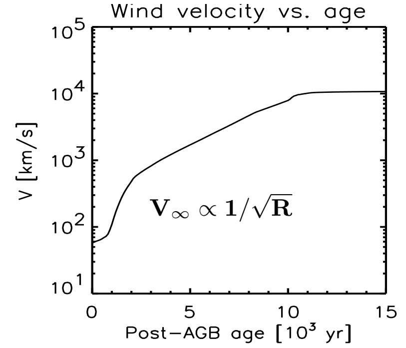
1. Post-AGB stellar models of *Blöcker (1995)*
2. Initial wind-envelope configurations either based on two-component hydrodynamics along tip of AGB

   Steffen, Szczerba & Schönberner 1998

   or from assumed power-law density distributions
3. Post-AGB mass-loss rate, $\dot{M}$, & wind velocity, V_∞, theoretically/semiempirically prescribed from stellar parameters *Reimers 1975, Pauldrach et al. 1988, Marten & Schönberner 1991*
4. 1D-Hydrodynamics of envelope with ***time dependent***
   - ionization, recombination, heating & cooling
   - inner boundary condition ($r_\mathrm{i} = 5 \cdot 10^{14}$ cm):
     - – Star radiates as a black body with $T_\mathrm{eff}(t)$,
     - – $V_\infty(t), \quad \rho_\mathrm{i}(t) \sim \dot{M}(t)/r_\mathrm{i}^2/V_\infty(t)$ from wind model



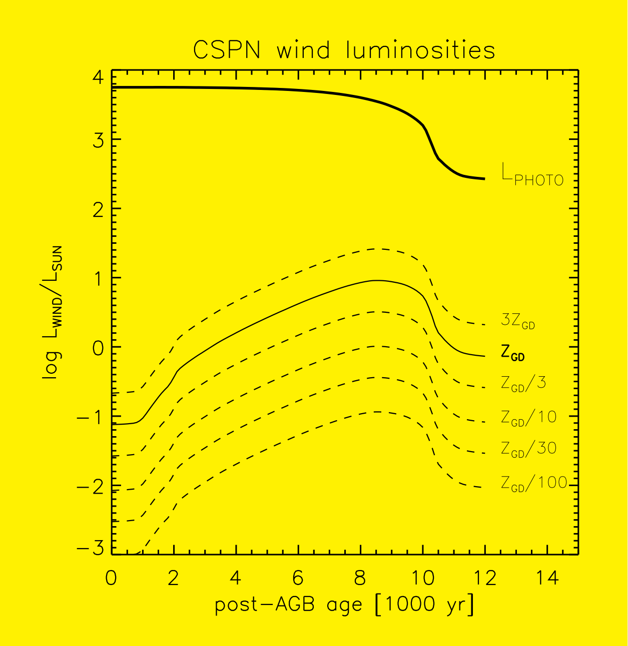


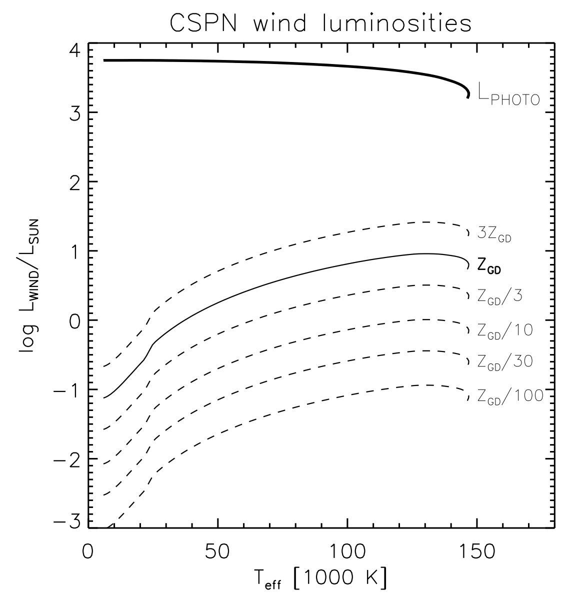


The physical model (2)

The wind dependence on metallicity is approximated as follows:

- $\dot{M} \sim Z^{0.69}$ *Vink et al. 2001*
- $v_\infty \sim Z^{0.13}$ *Leitherer et al. 1992*



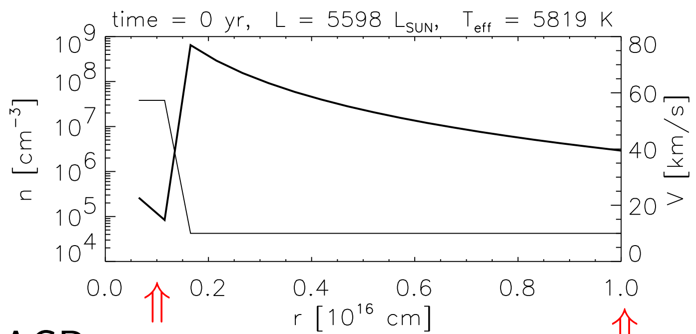


$L_{\mathrm{wind}} = 0.5\, \dot{M}\, v_\infty^2 \sim Z^{0.95}$ $Z_{\mathrm{GD}} \simeq Z_\odot$ 'GD': Galactic Disk

Initial configuration

The initial nebular model structure,

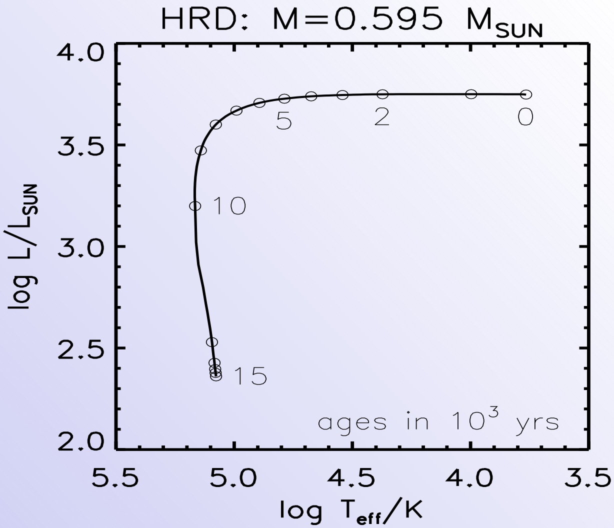
$\rho \sim r^{-3}$
$v = 10$ km/s
Z(up to Ne) $= 3\cdot Z_{\rm GD} \ldots Z_{\rm GD}/100$

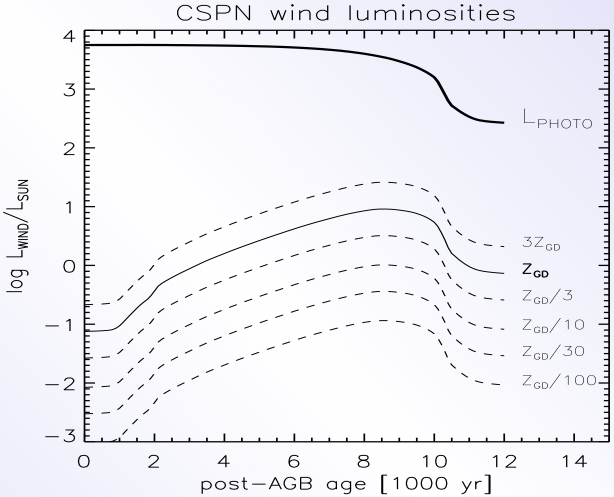


coupled to an evolving 0.595 M$_\odot$ post-AGB model with Z-dependent wind prescription

$v_{\rm post-agb}$
$\rho_{\rm post-agb}$

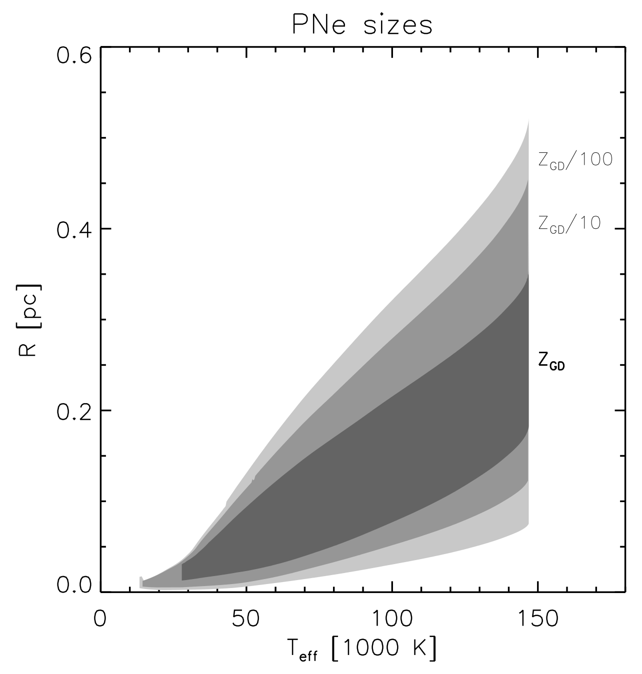
$\dot M = 1.3 \times 10^{-4}$ M$_\odot$/yr

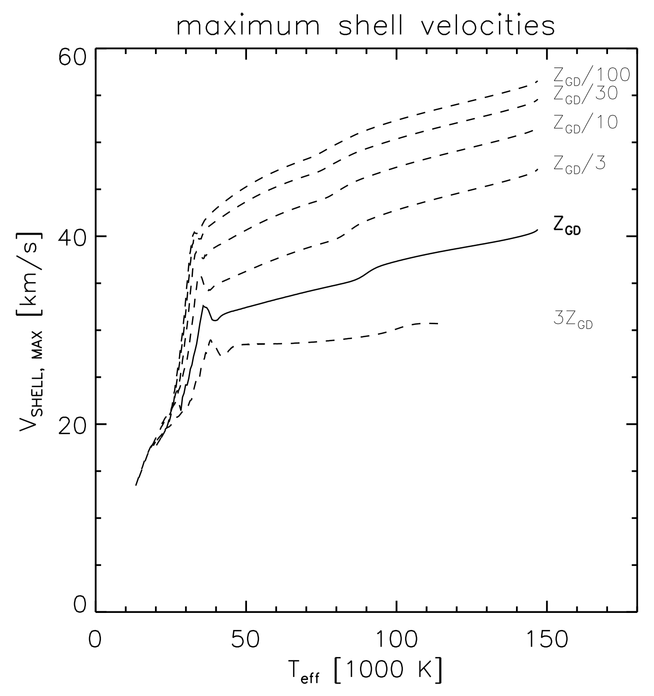




Results (1)

Maximum velocities within the PN shells

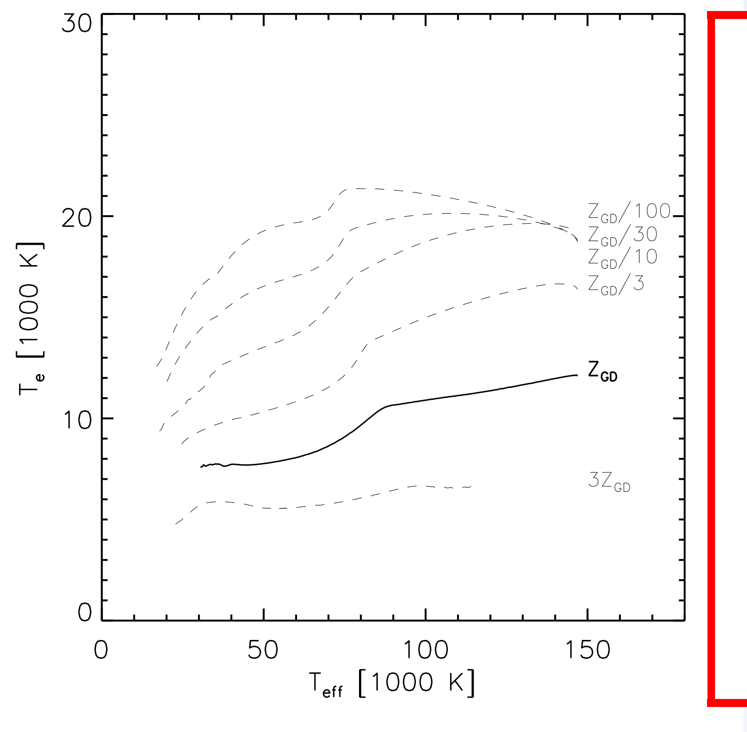




Radial extensions

Results (2)

Averaged [O III] electron temperatures of our models: $T_e = \frac{\int T(r) N_e N_i \, dV}{\int N_e N_i \, dV}$

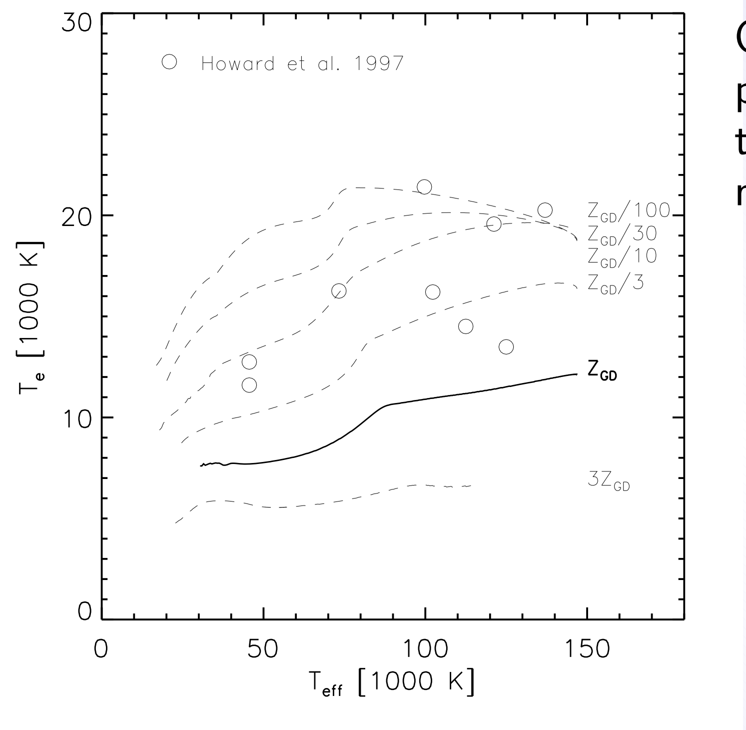


- General temperature increase with stellar effective temperature
- Electron temperature increases with decreasing metallicity
- *At low metallicity, 'expansion cooling' dominates at low densities & limits the electron temperature at about 20 000 K !*

Expansion cooling: $\sim \mathrm{div}\, v(r) = \partial v/\partial r + 2v/r$

Results (3)

Comparison of *Halo* PNe with our models :

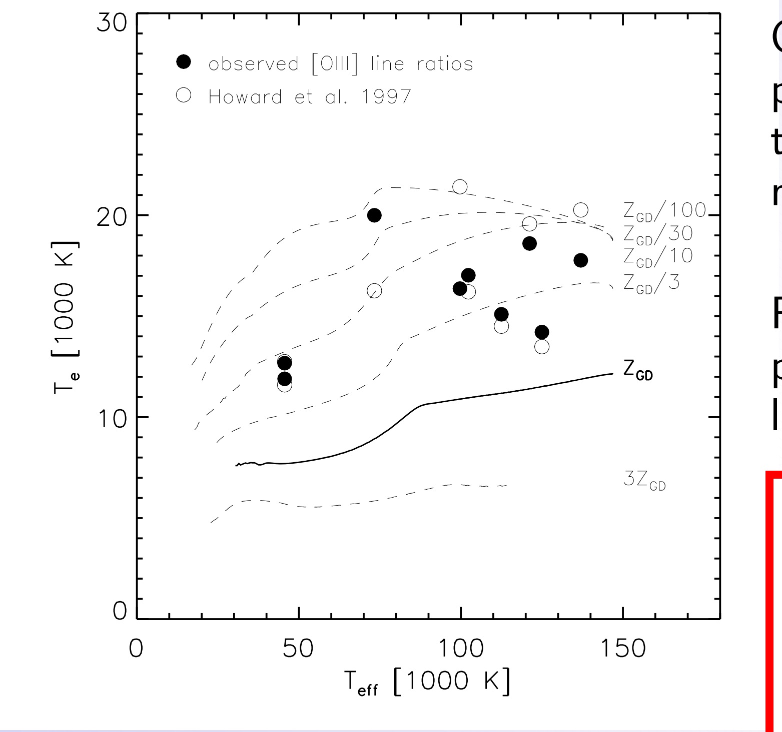


Open symbols are electron temperatures from [O III] line ratios, based on photoionization models (‘Cloudy’)

Howard et al. 1997

Results (4)

Comparison of *Halo* PNe with our models :



Open symbols are electron temperatures from [O III] line ratios, based on photoionization models (‘Cloudy’)

Howard et al. 1997

Filled symbols are electron temperatures from *observed* [O III] line ratios

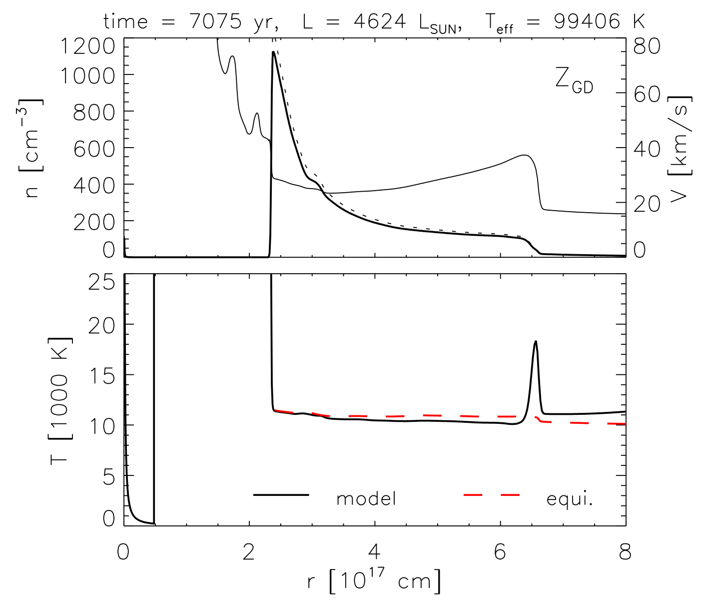
- *No Halo PN hotter than $\simeq$ 21 000 K !*
- *In some cases, photoionization models give poor fits to the observed spectra !*

Results (5)

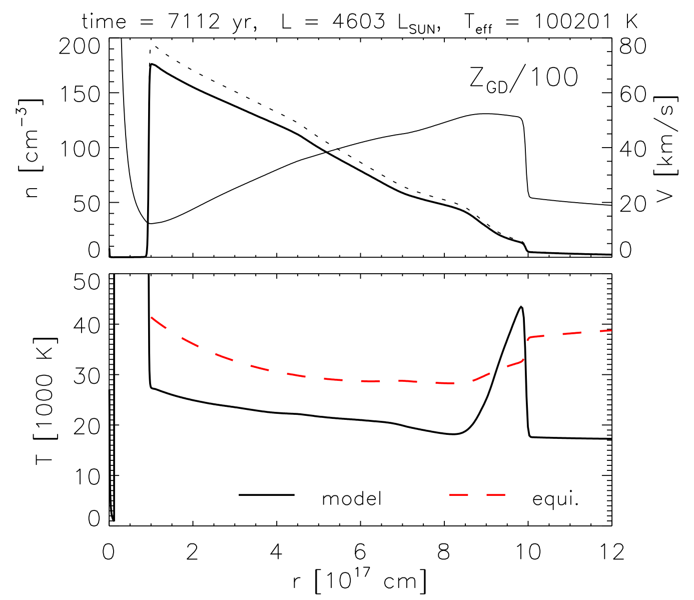
Thermal equilibrium,

at same position in the HRD, but with different metallicity, i.e. $Z = Z_{\rm GD}$ vs. $Z = Z_{\rm GD}/100$

NB: Note the different ranges of the axes !



No significant expansion cooling !

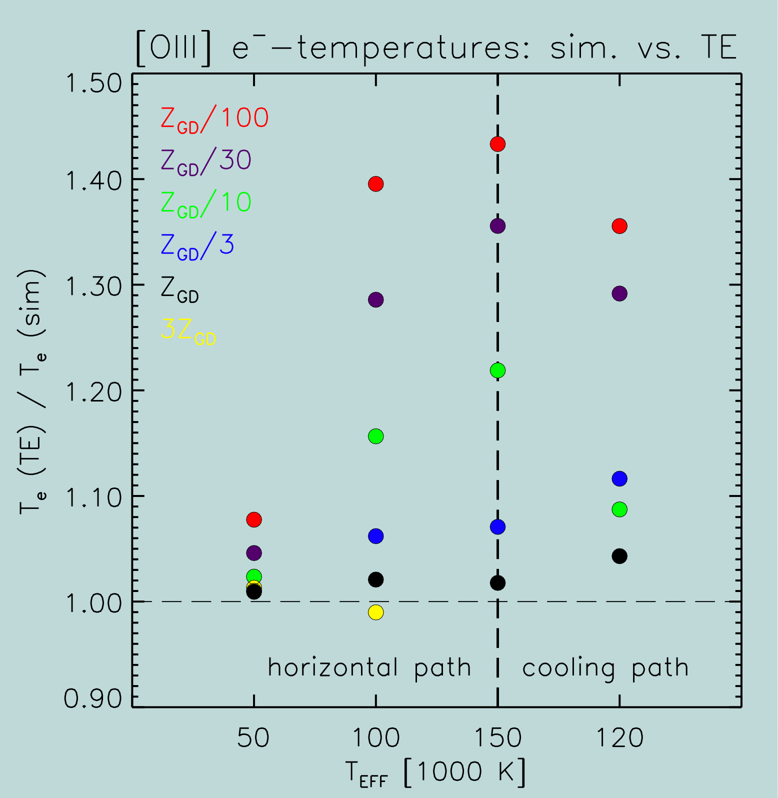


Expansion cooling exceeds radiative cooling,

$\Delta T \simeq 10\,000$ K

Results (6)

Comparison between average equilibrium & simulation electron temperatures at selected positions ($T_{\rm eff}$) along the evolutionary track:



Deviations from thermal equilibrium significant for

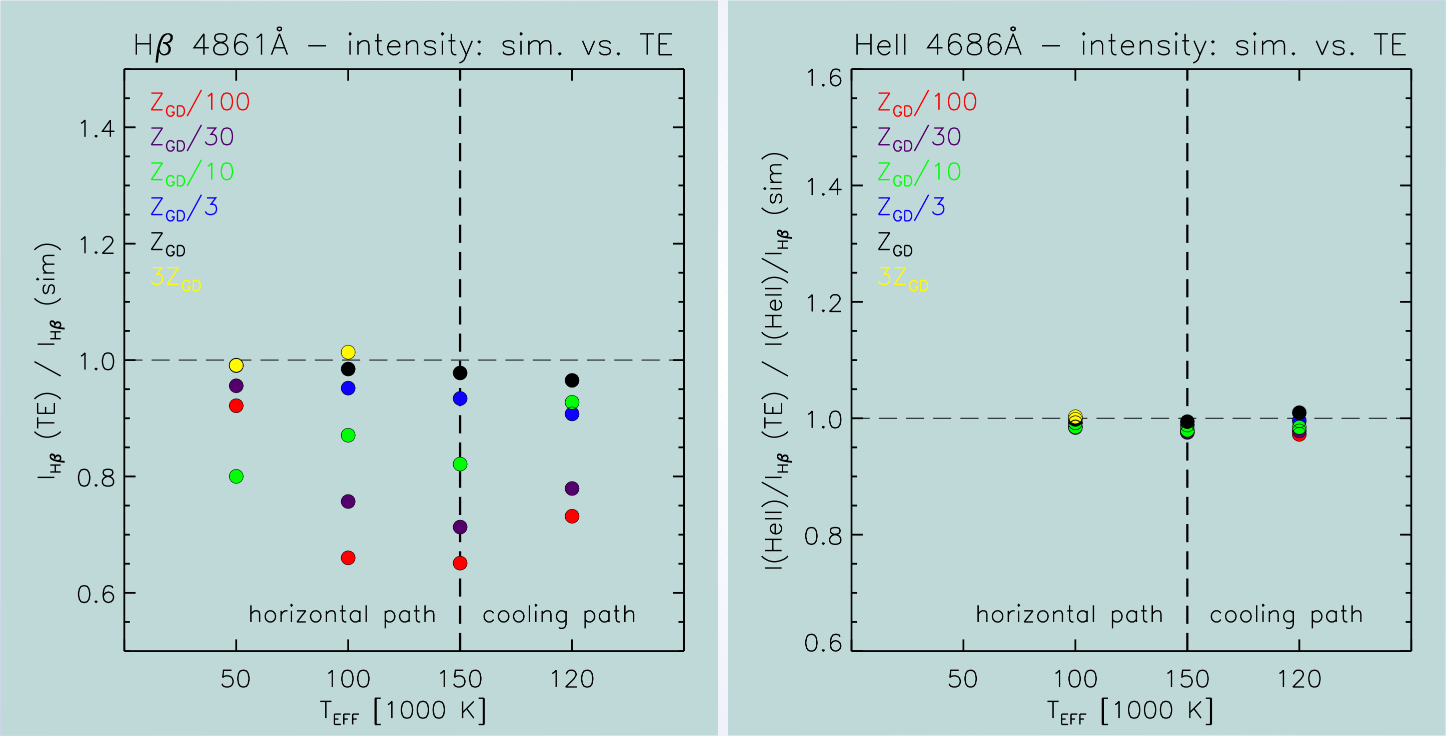
more dilute PNe with hotter central stars ($T_{\rm eff} \gtrsim 50\,000$ K)

&

$Z \lesssim 1/10\, Z_{\rm GD}$

Results (7)

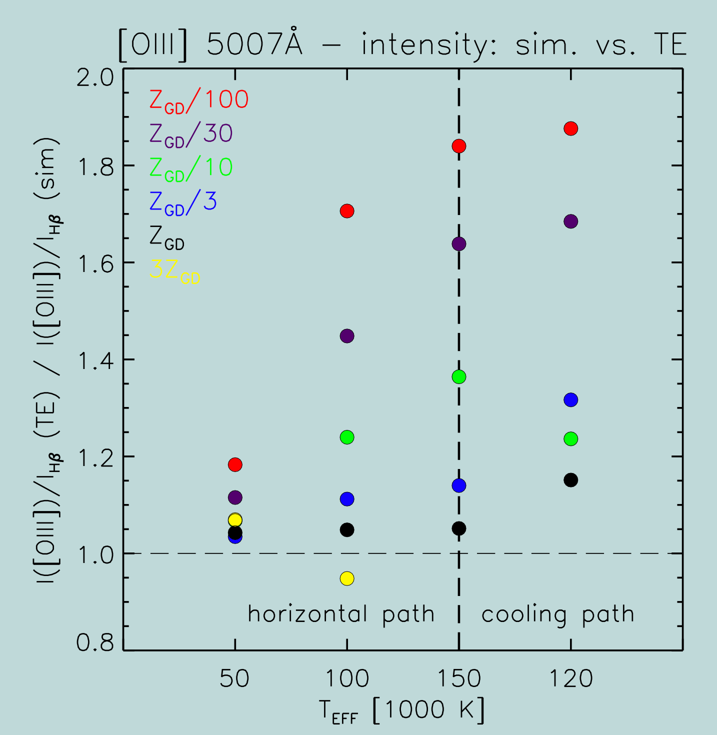
Line comparisons, *Recombination lines,* Hβ & He II :

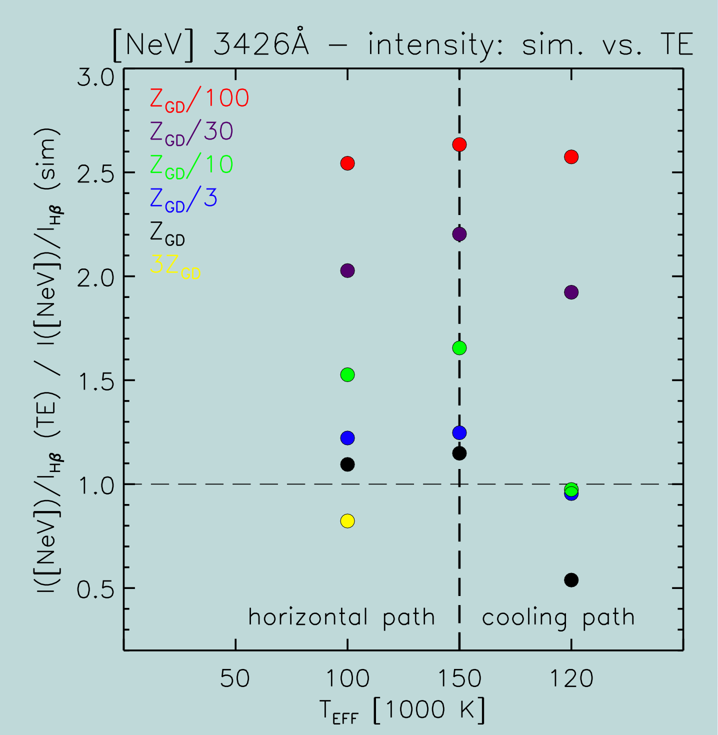


Hydrogen lines *stronger* in hydro simulation !

Results (8)

Line comparisons, *Collisionally excited lines,* [O III] & [Ne V], *rel. to* Hβ :



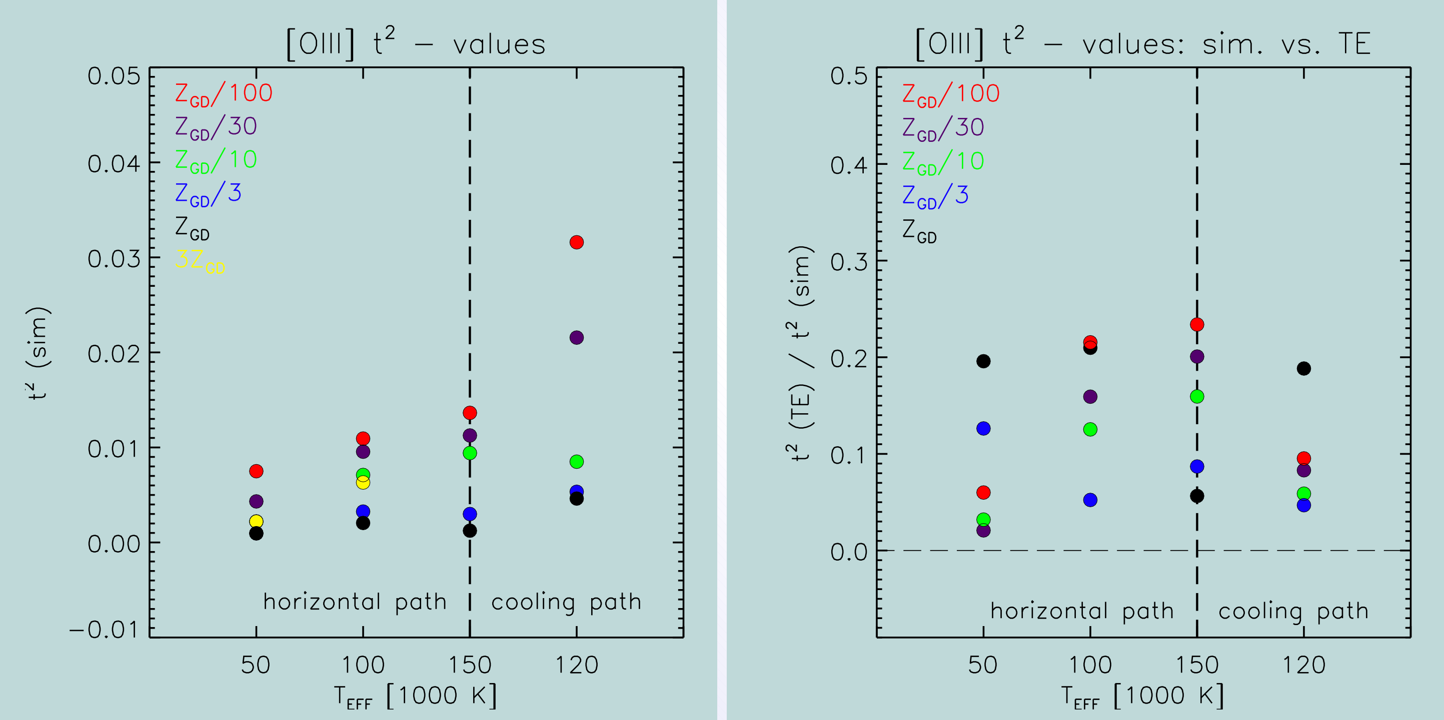


Collisionally excited lines *weaker* in hydro simulations !

Results (8)

The t^2 parameter :

$$t^2 = \frac{\int (T - T_e)^2 \, N_e N_i \, dV}{{T_e}^2 \int N_e N_i \, dV}$$



Temperature inhomogeneities *larger* in hydro simulations !

Conclusions

Since extragalactic PNe belong to stellar populations with very different chemical compositions

⇒ *Their general properties, i.e. their structure & expansion speed may differ from galaxy to galaxy*

⇒ *Depending on their evolutionary stage, PNe may be severely out of thermal equilibrium & standard methods of plasma diagnostics may fail !*

More work on hydrodynamic effects & metallicity dependences of PNe properties needed *before* PNe can be regarded as reliable probes for determining chemical abundances of stellar populations