Modeling X-ray Emission from Planetary Nebulae

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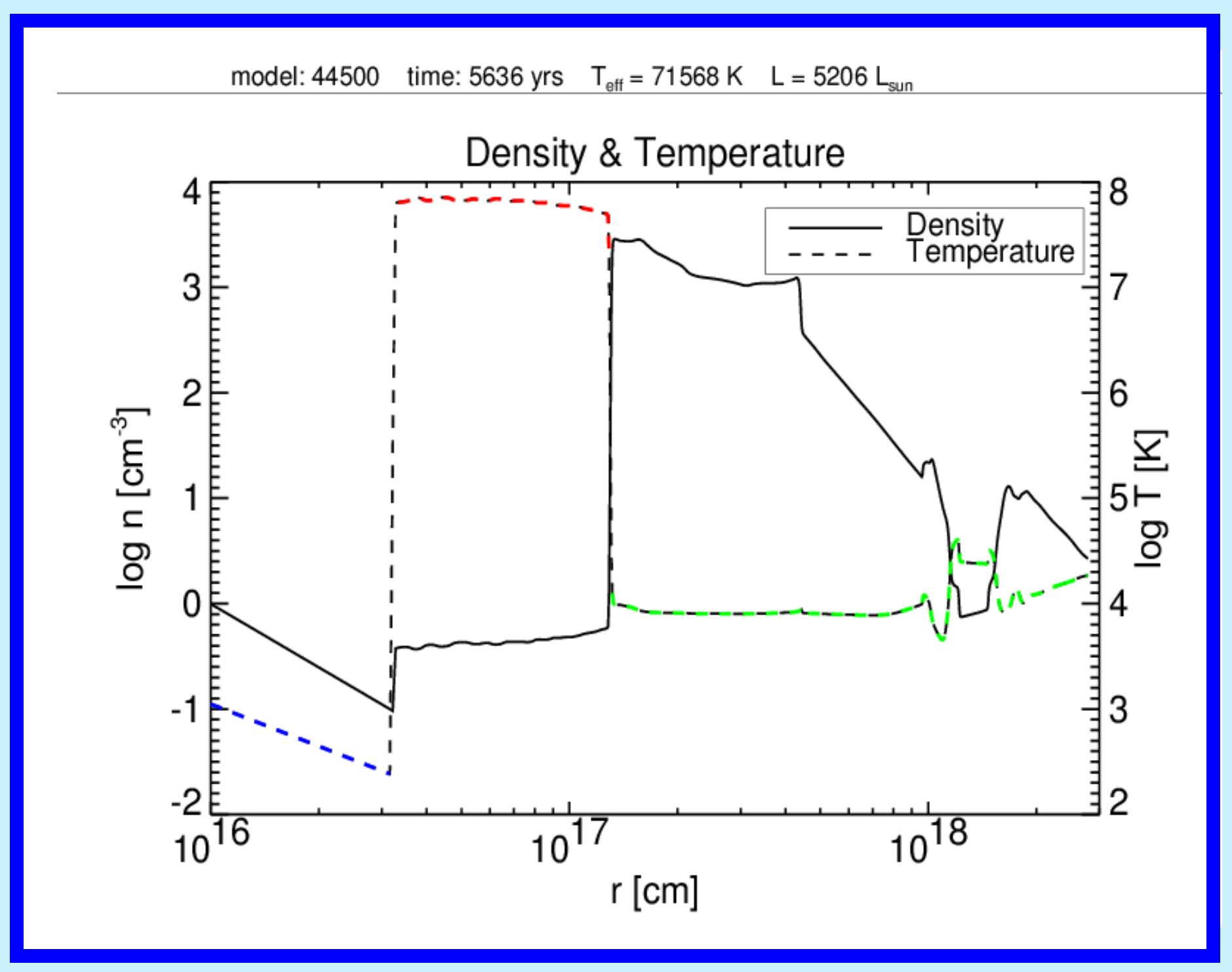
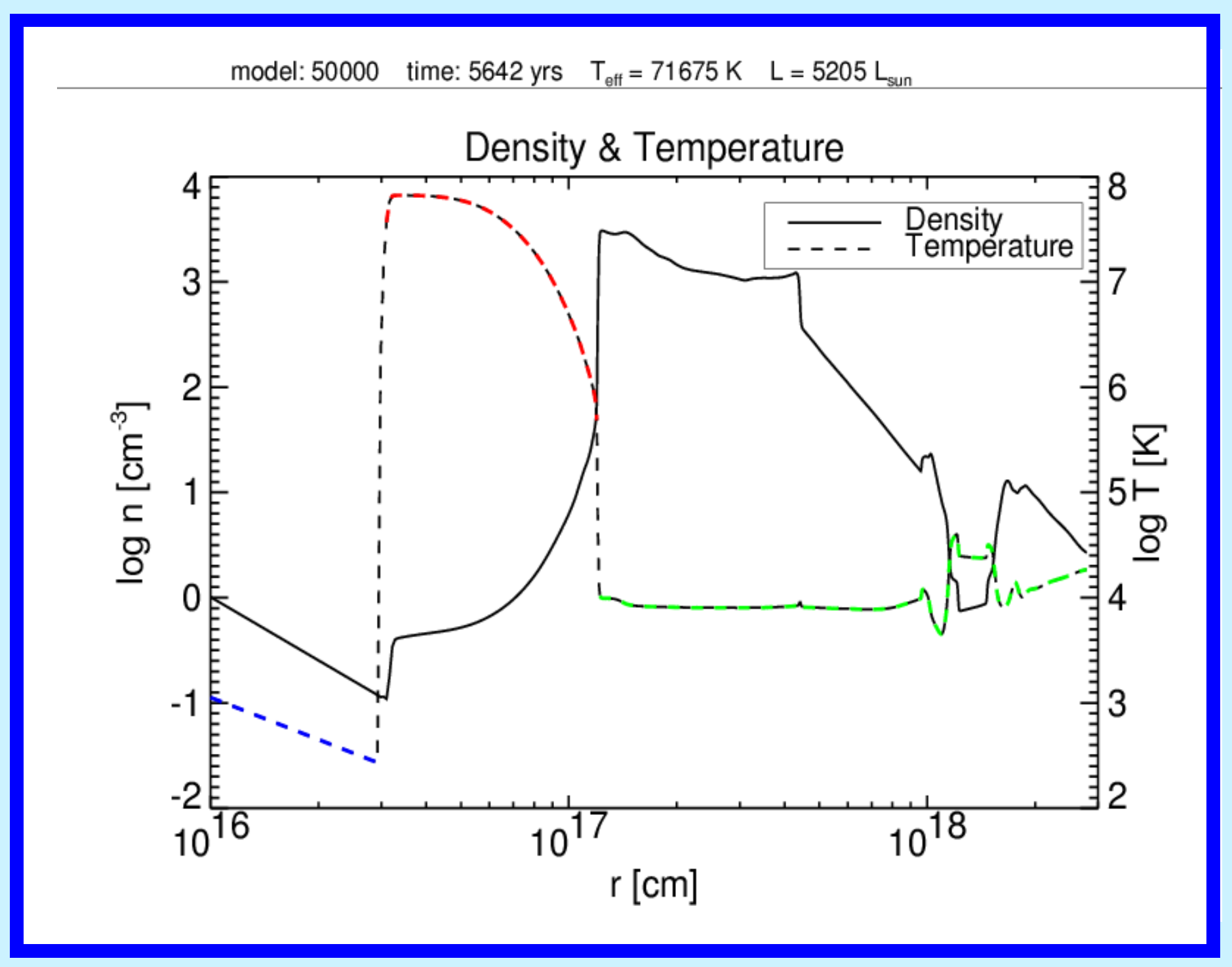
Introduction. Recent observations using the Chandra X-ray Observatory and XXM Newton revealed without doubt diffuse X-ray emission from the shock-heated wind gas in planetary nebula interiors. Typical properties of the emitting gas are temperatures of a few 10^6 K and electron densities of the order of 100 cm^{-3}. According to current hydrodynamical models, the shocked gas becomes too hot ($T \approx 10^7 \ldots 10^8$ K) and too tenuous ($n_e \approx 1$ cm^{-3}) to produce the observed X-ray emission. However, the hot gas is confined by the rather cool ($T \approx 10\,000$K) nebular gas, and thermal heat conduction across the interface between the hot and cool gas becomes important. It changes the contact discontinuity into a more extended transition layer covering the temperature range where the observed X-ray emission is thought to arise. To date, only similarity solutions for the hydrodynamical problem of PN evolution including heat conduction have been derived (Zhekov & Perinotto 1996, A&A 309, 654). **We present first results from new numerical simulations of the PN evolution, taking into account the additional heat flux due to thermal conduction by electrons.**

First Results



Density and temperature structure of an exemplary model PN, after 5640 years of post-AGB evolution. At this time, the central star ($M = 0.595\, M_\odot$) has $T_\mathrm{eff} = 71\,600$ K, $L = 5200\, L_\odot$, and the 'hot bubble' consisting of shocked wind matter is well established (marked in red). Heat conduction strongly influences the structure, and hence the X-ray emission of the 'hot bubble': $T \approx 5\, 10^7$ K and $n < 1$ cm^{-3} are nearly constant when heat conduction is ignored (**left**), while temperature falls by 2 orders of magnitude towards the outer edge of the 'hot bubble', and density increases by the same amount, when heat conduction is taken into account (**right**). Wind and PN proper are not affected!



Physical description. Electron heat conduction is described as a diffusion process, with the heat flux $\vec{q}$ given by

$$\vec{q} = -D\, \nabla T_e \qquad (1)$$

Following Spitzer (1962) and Cowie & McKee (1977, ApJ 211, 135), the electron mean free path λ can be written as

$$\lambda = 2.625 \cdot 10^5\, T_e^2 / n_e / \ln\Lambda \quad [\mathrm{cm}] \qquad (2)$$

where the Coulomb Logarithm $\ln\Lambda$ can be approximated as

$$\ln\Lambda = \begin{cases} 9.425 + 3/2\, \ln T_e - 1/2\, \ln n_e & \mathrm{for} T_e \leq 4.2 \cdot 10^5\ \mathrm{K} \\ 22.37 + \quad \ln T_e - 1/2\, \ln n_e & \mathrm{for} T_e > 4.2 \cdot 10^5\ \mathrm{K} \end{cases} \qquad (3)$$

for a pure hydrogen plasma. The diffusion coefficient D is then

$$D = 7.04 \cdot 10^{-11}\, \lambda\, n_e\, T_e^{1/2} \quad [\mathrm{erg/s/K/cm}] \qquad (4)$$

At high T_e and low n_e, λ becomes very large, and the diffusion approximation is no longer valid. Rather, the heat flux saturates at

$$\vec{q}_\mathrm{sat} = 1.72 \cdot 10^{-11}\, T_e^{3/2} n_e \quad [\mathrm{erg/cm^2/s}] \qquad (5)$$

Numerical Treatment. Each time step Δt of the simulation is divided into 3 successive update steps (operator splitting):

(a) $\vec{Q}(t) \rightarrow$ advection $\rightarrow \vec{Q}_1(t+\Delta t)$
(b) $\vec{Q}_1(t+\Delta t) \rightarrow$ diffusion $\rightarrow \vec{Q}_2(t+\Delta t)$ energy update at constant ρ
(c) $\vec{Q}_2(t+\Delta t) \rightarrow$ radiation $\rightarrow \vec{Q}\,(t+\Delta t)$ energy update at constant ρ

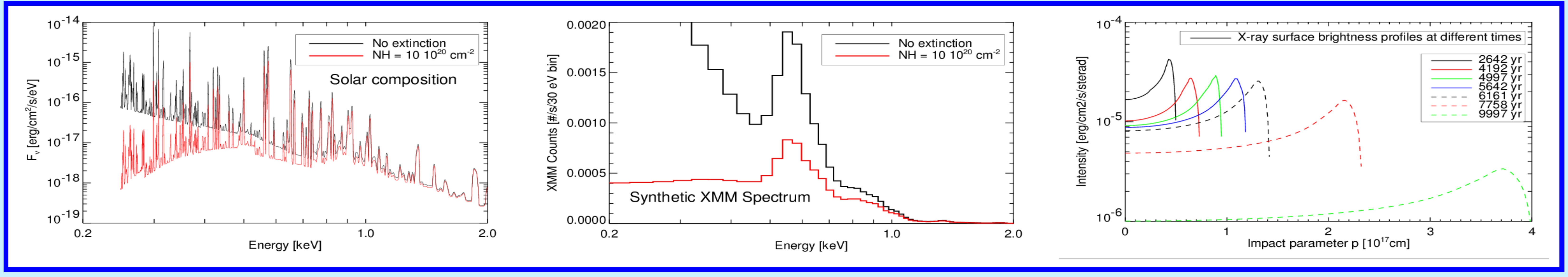
For step (b), we solve the diffusion equation in spherical coordinates

$$\frac{\partial E}{\partial t} = \rho c_v \frac{\partial T}{\partial t} = \frac{1}{r^2} \frac{\partial}{\partial r} \left(r^2\, D\, \frac{\partial T}{\partial r} \right) \qquad (6)$$

with a fully implicit, standard numerical method. No additional constraints are imposed on the time step. The diffusion coefficient D is evaluated from the local physical conditions according to Eq.(4), with

$$\lambda = \min\{0.244 \cdot \Delta r,\ 2.625 \cdot 10^5\, T_e^2 / n_e / \ln\Lambda\}, \qquad (7)$$

where Δr is the local spacing of the numerical grid. This limits the diffusive heat flux to the saturation value given by Eq.(5). Ionization is frozen during step (b), being updated subsequently in step (c).

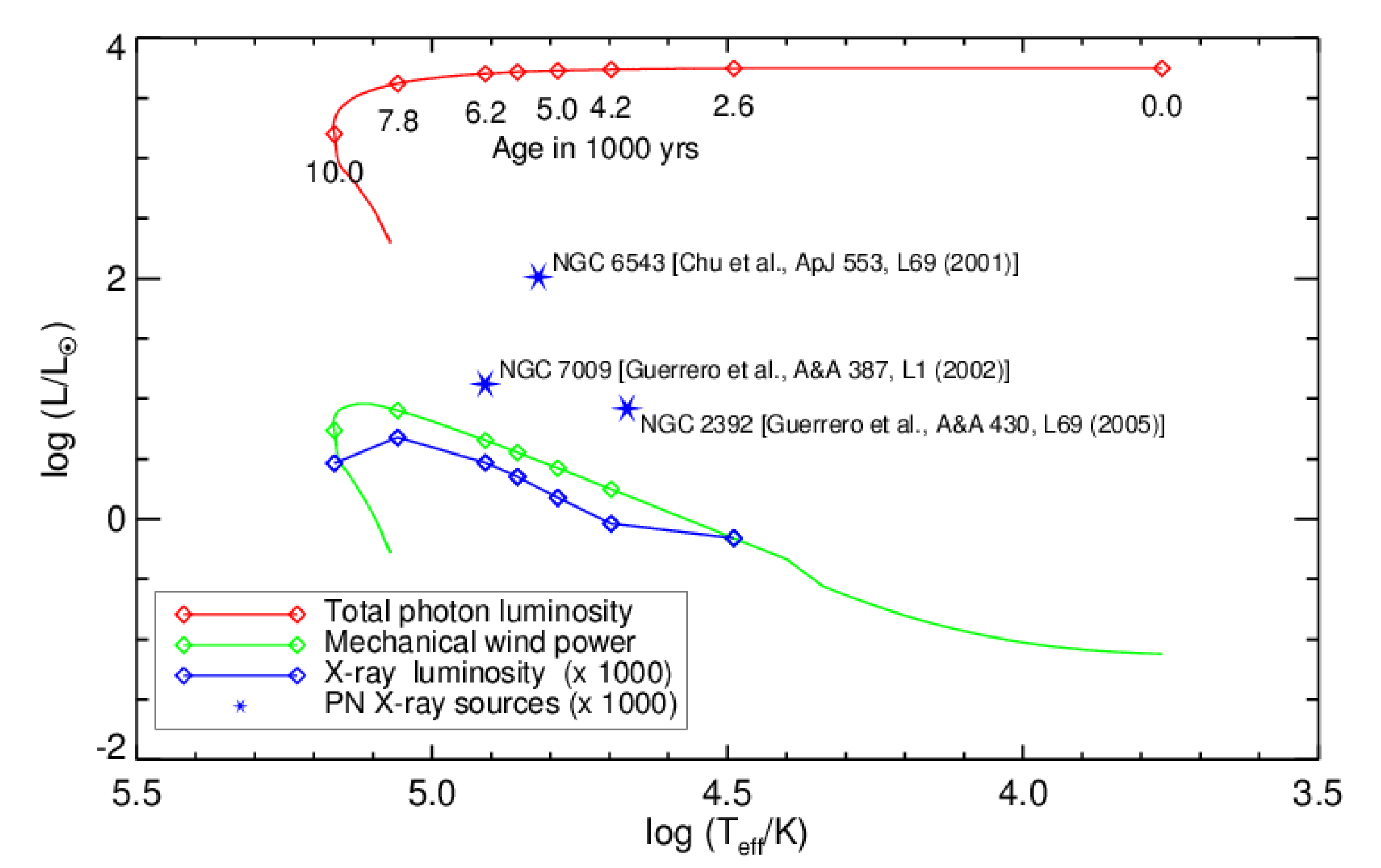


Top: Synthetic X-ray spectrum computed with the CHIANTI code before (**black**) and after (**red**) extinction, assuming a hydrogen column density of NH=10^{21} cm^{-2} and a distance of 1 kpc (**left**), together with the corresponding XMM count rate spectrum (**middle**) for the snapshot from our hydrodynamical PN simulation with electron heat conduction shown above. According to this model, the spectral energy distribution peaks near 0.5 keV, and the radial surface brightness profile of the X-ray emission is distinctly limb-brightened (**right**). The total X-ray luminosity is $8.62\, 10^{30}$ [erg/s] (5 to 50 Å) at this time of evolution. **Bottom:** Hertzsprung-Russell-Diagram showing the evolutionary track of the central star (red), the corresponding evolution of the wind power $\dot{M}V^2/2$ (green), and the X-ray luminosity (integrated from 5 to 50 Å, blue) for our hydrodynamical model sequence. Blue stars represent PN X-ray sources observed by XMM / Chandra; errors due to uncertain distances are eliminated by plotting the observed X-ray luminosity as $L_X = L_\mathrm{phot}^\mathrm{model} \times (L_X^\mathrm{obs} / L_\mathrm{phot}^\mathrm{obs})$. All X-ray luminosities scaled by a factor 1000.

Conclusions:

Electron heat conduction affects our dynamical PN models as follows:

- The total mass of the 'hot bubble' increases by at least a factor of 10
- The outer edge of the 'hot bubble' becomes cooler and denser by typically 2 orders of magnitude
- The X-ray luminosity ($5-50$ Å) increases more than 10 times
- The stellar wind remains cool, it is *not* affected by heat conduction
- Comparison with recent observations indicates that X-ray luminosities predicted by our hydrodynamical models are still too low by ≈ a factor of 10
- Assuming a faster evolution of the central star will lead to a more compact 'hot bubble', presumably resulting in a better match of the X-ray observations



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