AGB evolution with overshoot:
Hot Bottom Burning versus Dredge-Up

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1. Introduction

In recent stellar evolution calculations Herwig et al. (1997) have considered diffusive overshoot for all convective boundaries which leads to a considerable change in the models. This method provides for Asymptotic Giant Branch (AGB) stars a sufficient amount of dredge-up (DUP) to form low-mass carbon stars as required from observations. Additionally it leads to the formation of ^{13}C as neutron source to drive the s-process in these stars. However the consequences for massive AGB stars, which suffer from hot bottom burning, remains to be investigated in detail. Hot bottom burning (HBB) provides lithium-rich AGB stars and may prevent the carbon star stage for almost the whole AGB lifetime by turning ^{12}C into ^{13}C and ^{14}N. We continue to extend our computations to HBB models including a coupled treatment of nucleosynthesis and mixing.

2. Model input

- Stellar evolution code based on Blöcker (1995).
- Nuclear network with 30 isotopes and 74 reactions.
- Initial masses $M = 3 \ldots 7\,\mathrm{M}_\odot$ and $(X, Y) = (0.70, 0.28)$ from the pre-main sequence (PMS) stage through the thermal pulses.
- Convection treatment within the mixing length theory with $\alpha = 1.7$.
- Mass loss according to Reimers (1975) with $\eta = 1.0$.
- Opacities according to Iglesias & Rogers (1996) and Alexander & Ferguson (1994).
- The overshoot prescription is that of Herwig et al. (1997) based on the hydrodynamical calculations of Freytag et al. (1996) with an efficiency parameter $f = 0.016$. Diffusive overshooting has been taken into account in all convective regions during the complete evolution.
- Abundance changes have been treated self-consistently by coupling time-dependent mixing and nuclear burning of all chemical elements. This is necessary to follow, e. g., the $^7\mathrm{Li}$-production in luminous AGB stars via the Cameron-Fowler mechanism (Cameron & Fowler 1971, see also Sackmann & Boothroyd 1992).

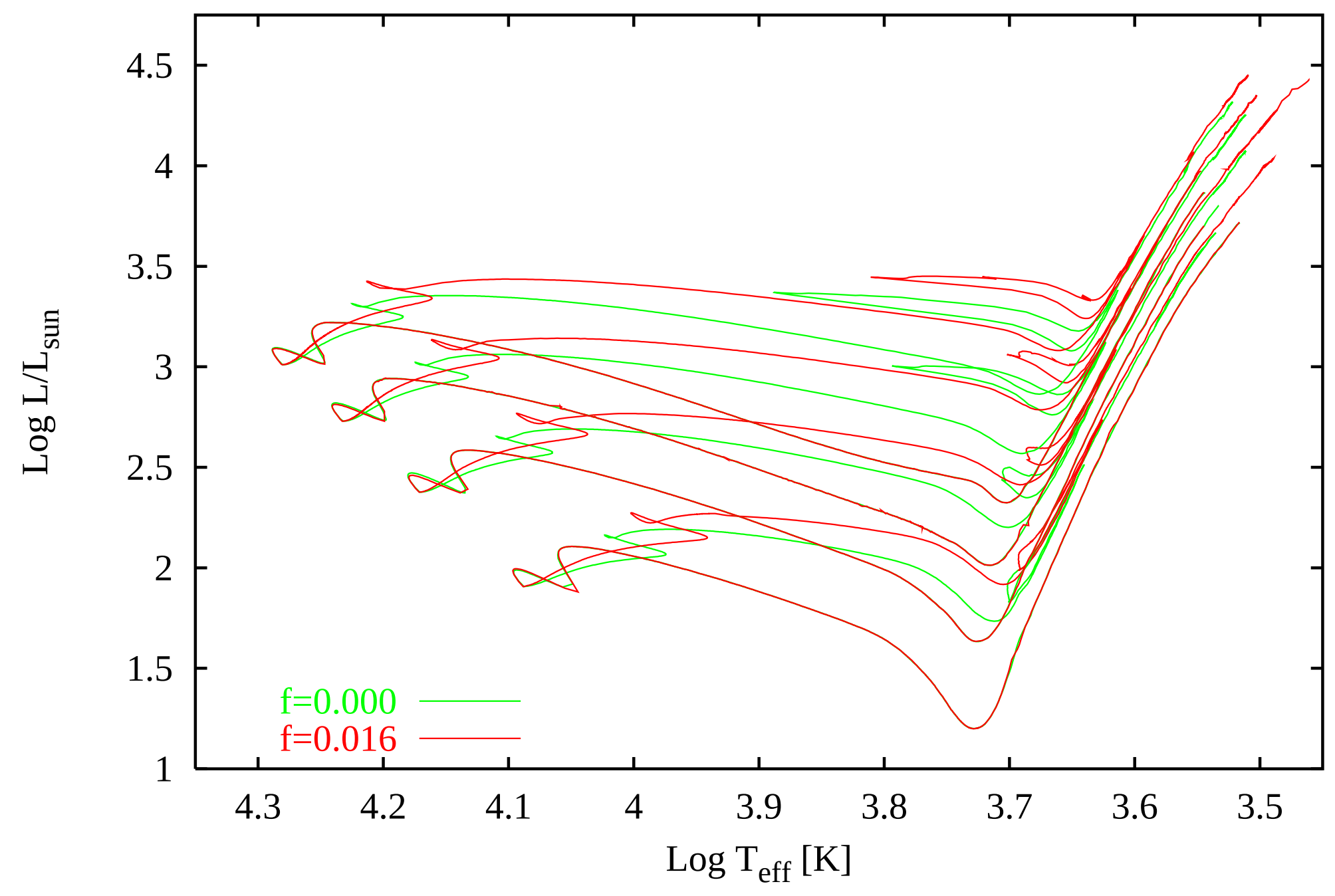

Figure 1: Hertzsprung-Russell-diagram with evolutionary tracks for $M = 3, 4, 5$ and $6\ \mathrm{M}_\odot$ with ($f = 0.016$, red lines) and without ($f = 0.000$, green lines) overshoot from the fully convective PMS-stage up to the AGB.

Main effects of overshoot during the evolution prior to the AGB are

- a prolongation of the main-sequence lifetime,
- a lower minimum initial mass for a central helium flash to occur ($M_{\mathrm{min,He-flash}} \approx 1.7\ \mathrm{M}_\odot$ for $f = 0.016$),
- a shortening of the duration of central helium burning,
- larger core masses before and after 1^{st} and 2^{nd} DUP.

3. Third Dredge-Up

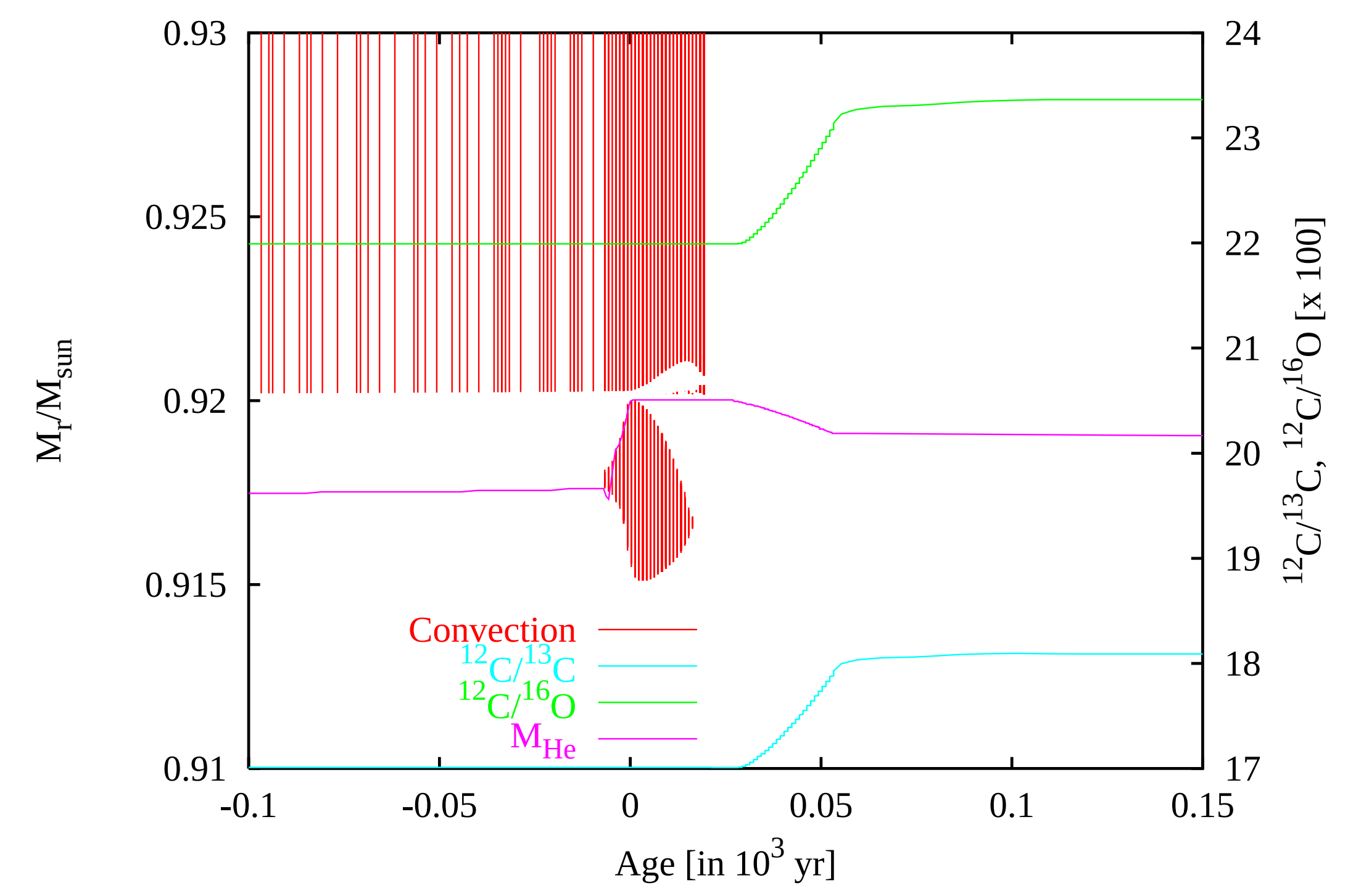

Figure 2: Evolution of convection zones (red hashed areas) during a thermal pulse for $M = 6\ \mathrm{M}_\odot$. The figure shows the lower boundary of the envelope convection as well as the pulse-driven convection zone (PDCZ). During the pulse hydrogen burning ceases. First, the flash-driven convection zone mixes carbon (and oxygen) into the layers between both shells (intershell region). Then, after the pulse, when hyrdogen burning is still off, the envelope convection penetrates the intershell region and mixes the carbon enriched material towards the surface. As an example, the green and blue line show the $^{12}\mathrm{C}/^{16}\mathrm{O}$ and $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio at the surface which increase due to the DUP of $^{12}\mathrm{C}$. M_{He} marks the position where the $^4\mathrm{He}$ content has dropped to $Y = 0.49$.

During a thermal pulse a pulse-driven convection zone (PDCZ) temporarily establishes (see Fig. 2). The lifting of the layers above the helium shell causes a temporary exhaustion of the hydrogen burning shell. Then, the convective envelope can penetrate the intershell region, mix up processed material and therefore change the surface composition (= third dredge-up (3^{rd} DUP), e.g. $^{12}\mathrm{C} \longrightarrow$ carbon star formation).
The overshoot treatment provides 3^{rd} DUP even for low-mass AGB stars (see Herwig et al. 1997) and in addition very efficient DUP for higher masses. With the DUP parameter λ being the ratio of material mixed up during the DUP and the material burnt during two consecutive thermal pulses we find $\lambda > 1$ already during the first pulses (see Fig. 3).

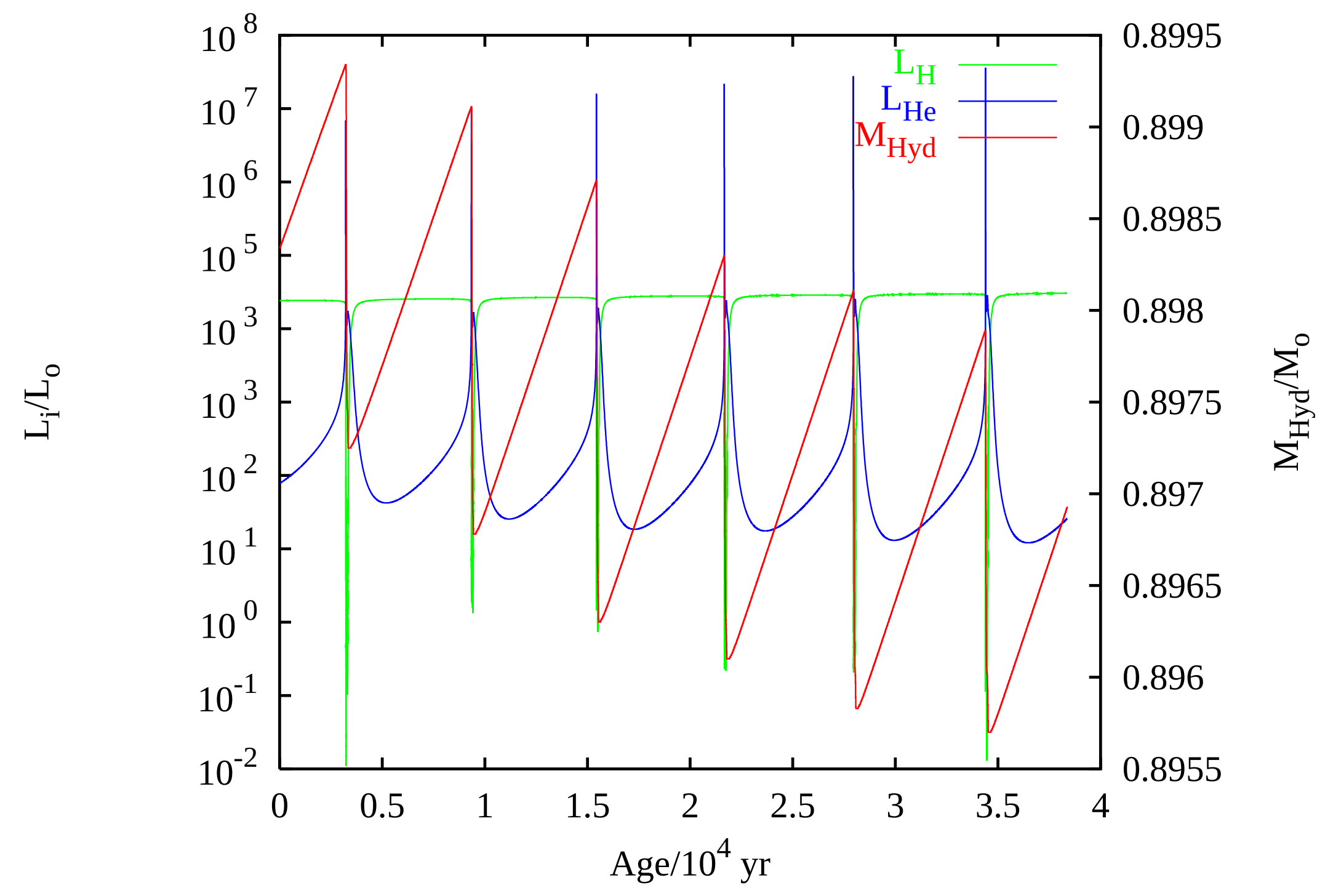

Figure 3: Evolution of luminosity due to hydrogen (L_{H}, green) and helium burning (L_{He}, blue) and the mass of the hydrogen exhausted core (M_{Hyd}, red) for $M = 5\ \mathrm{M}_\odot$. We found very efficient DUP due to the overshoot treatment. It is $\lambda > 1$ from the beginning of thermal pulse evolution and accordingly M_{Hyd} decreases.

4. Hot Bottom Burning

In more massive AGB stars ($M_{\mathrm{initial}} \geq 4\ \mathrm{M}_\odot$) the convective envelope cuts into the hydrogen burning shell during the interpulse phase leading yo CNO cycling of the envelope. Then, $^{12}\mathrm{C}$ is transformed into $^{13}\mathrm{C}$ and $^{14}\mathrm{N}$. Therefore, HBB may prevent AGB stars from becoming carbon stars (see Fig. 5).

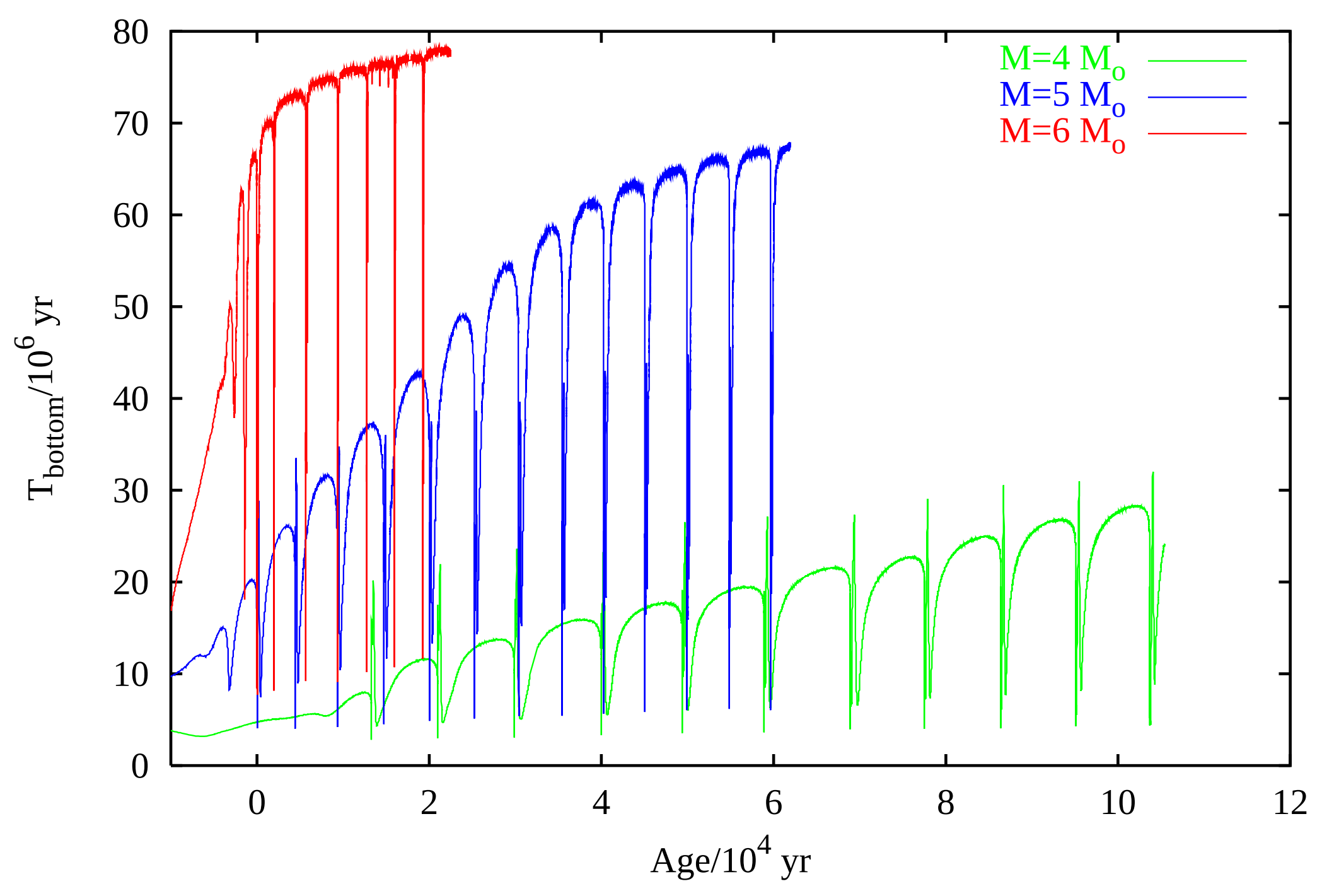

Figure 4: Evolution of the temperature at the bottom of the envelope convection for the overshoot sequences with $M = 4, 5$ and $6\mathrm{M}_\odot$. The strong increase of T_{bottom} indicates the efficiency of HBB. $t = 0$ refers to the L_{He} maximum of the first thermal pulse.

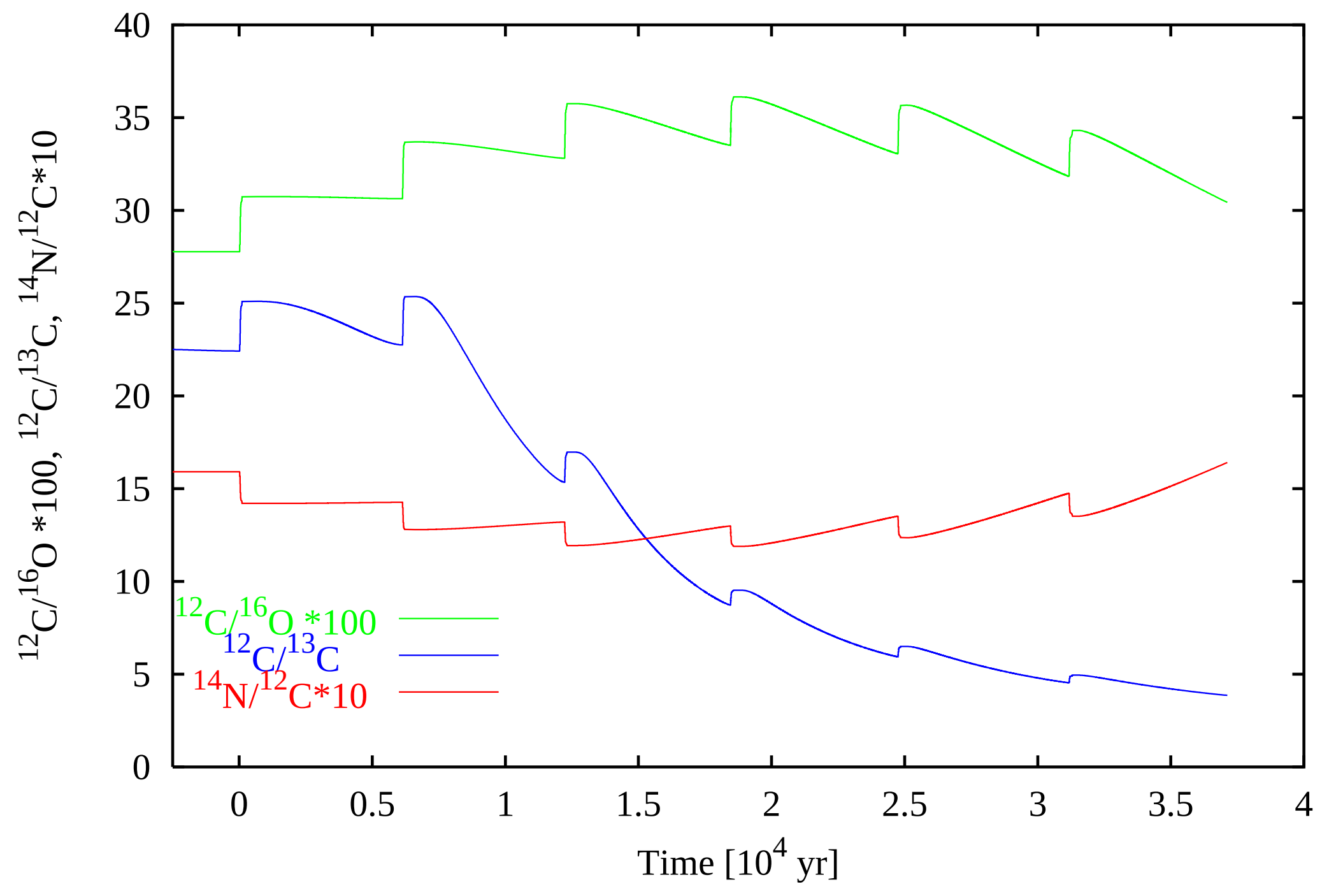

Figure 5: Evolution of the different isotope ratios at the surface of our 5 $\mathrm{M}_\odot$ sequence ($t = 0$ as in Fig. 4). As can be seen HBB efficiently prevents the formation of a carbon star by conversion of $^{12}\mathrm{C}$ into $^{13}\mathrm{C}$ and $^{14}\mathrm{N}$. The $^{12}\mathrm{C}/^{13}\mathrm{C}$ ratio (blue) reaches its equilibrium value after the first pulses and $^{14}\mathrm{N}/^{12}\mathrm{C}$ (red) starts to increase whereas $^{12}\mathrm{C}/^{16}\mathrm{O}$ (green) decrease.

5. Li stars

The significant $^7\mathrm{Li}$ enrichment observed in luminous AGB stars (see e. g. Smith & Lambert 1990) is well explained by the Cameron-Fowler mechanism (Cameron & Fowler 1971) which operates when HBB is present: The timescale of the β-decay of $^7\mathrm{Be}$ which is produced at the bottom of the envelope convection is comparable to the convective timescale. Therefore, before $^7\mathrm{Be}$ is burnt in the lower part of the envelope it can be mixed up to upper cooler layers where it decays to produce $^7\mathrm{Li}$. This mechanism is effective for temperatures $T_{\mathrm{bottom}} \approx 30 \ldots 80 \cdot 10^6\,\mathrm{K}$ at the bottom of the envelope (see Fig. 6).

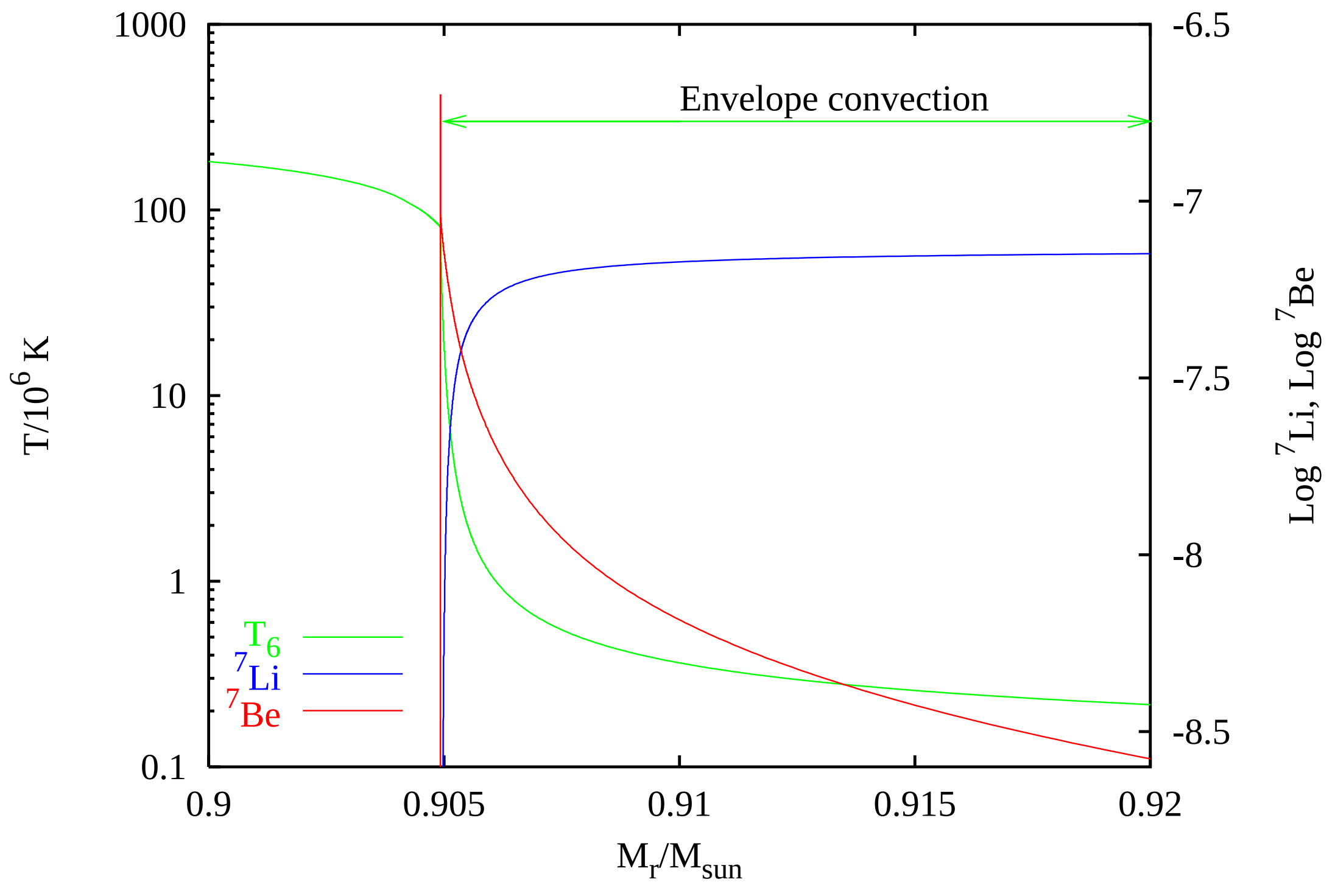

Figure 6: $^7\mathrm{Li}$ and $^7\mathrm{Be}$ profile along the lower part of the convective envelope in a $M = 5\mathrm{M}_\odot$ model. The green lines gives the corresponding temperature. Since nuclear and convective turn-over timescale are comparable the profiles are not constant within the convection zone. Therefore, $^7\mathrm{Be}$ can be transported to the upper envelope regions where it decays to produce $^7\mathrm{Li}$ (Cameron-Fowler mechanism).

Figure 7 illustrates the considerable $^7\mathrm{Li}$ enrichment during the first thermal pulses for $M = 6\mathrm{M}_\odot$. The maximum lithium abundance is $\epsilon(^7\mathrm{Li}) = \log\left[n(^7\mathrm{Li})/n(\mathrm{H})\right] + 12 \approx 4.4$ which is in very good agreement with the results of Sackmann & Boothroyd (1992). The production of Li-rich AGB stars can only be followed with a simultaneous treatment of mixing and burning. Otherwise, $^7\mathrm{Be}$ would be burnt at the bottom of the envelope before it can be mixed up.

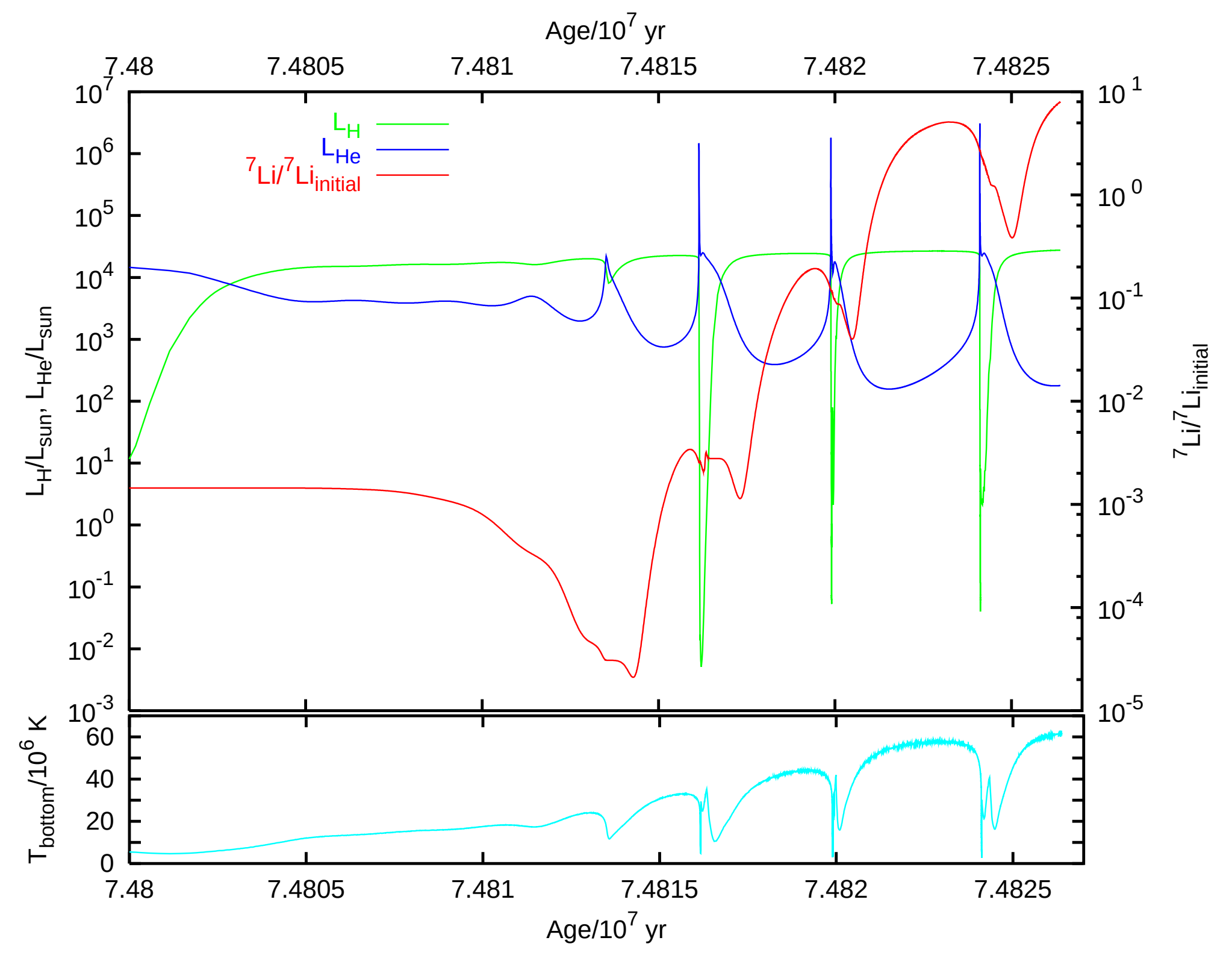

Figure 7: Upper panel: Evolution of hydrogen luminosity (L_{H}, green), helium luminosity (L_{He}, blue) and surface $^7\mathrm{Li}$ abundance (red) in terms of the initial value ($^7\mathrm{Li}_{\mathrm{initial}} = 9.35 \cdot 10^{-9}$) during the first thermal pulses of our $M = 6\ \mathrm{M}_\odot$ model. Within the first 3 pulses the Li abundance increases by more than 5 orders of magnitude to reach almost 10 times the main sequence value. Lower panel: Corresponding evolution of the temperature at the bottom of the envelope convection. $^7\mathrm{Li}$ is effectively destroyed for $T_{\mathrm{bottom}} \approx 10 \ldots 30 \cdot 10^6\,\mathrm{K}$ and effectively built up for $T_{\mathrm{bottom}} \gtrsim 30 \cdot 10^6\,\mathrm{K}$.

6. Summary

- ⇒ We calculated models of massive AGB stars with a self-consistent coupling of time-dependent mixing and nuclear burning for 30 isotopes and 74 reactions.
- ⇒ Treating exponential overshoot (Freytag et al. 1996) as in Herwig et al. (1997) we find very efficient 3^{rd} dredge-up with $\lambda > 1$.
- ⇒ Hot bottom burning occurs for $M \geq 4\ \mathrm{M}_\odot$ within our sequences with overshoot.
- ⇒ Carbon star formation in more massive AGB stars is delayed or even prevented by hot bottom burning despite very efficient dredge-up.
- ⇒ With the simultaneous treatment of mixing and burning we followed the formation of Li-rich AGB stars due to the Cameron-Fowler mechanism. For $M = 6\ \mathrm{M}_\odot$ the maximum Li abundance is $\epsilon(^7\mathrm{Li}) =\approx 4.4$

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