Mixing and Thermonuclear Processes in Stars

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Abstract. According to standard wisdom, six different nuclear burning stages, from hydrogen to silicon burning, can occur during the hydrostatic evolution of stars. However, several instabilities can lead to the mixing of layers with different compositions and produce non-standard composition mixtures. Those — when at high enough temperatures — burn due to nuclear reactions which are unimportant otherwise. We provide various examples of such occurrences, for different ratios of burning over mixing time scale.

INTRODUCTION

The vast majority of heavy elements is produced in stars, either during their hydrostatic nuclear burning processes or in explosive burning events (e.g., Woosley & Weaver 1995). Due to the relatively long time scale of the hydrostatic burning stages, they do not involve nuclei far from the valley of stability in the nuclear chart. Thus, both, from the stellar physics and the nuclear physics point of view, hydrostatic nuclear burning is "easy" compared to explosive processing. However, as we shall see in the course of this article, there is one property of stars disturbing this simplicity: often, the chemical stratification in a star is *unstable*, and as a consequence layers with different composition are mixed, which may open up non-standard nuclear reaction channels.

To illustrate the term non-standard, we recall the "standard" onion skin model for stellar structure (cf. Fig. 1), where the ashes of the various nuclear burning stages are layered above each other, well separated by sharp boundaries which usually coincide with active nuclear shell sources. Indeed, active nuclear shell sources provide strong entropy barriers which do not allow any mixing process to penetrate them. However, in response to expansion and contraction of the various layers in the course of evolution, shell sources may become weak or even extinct (e.g., the

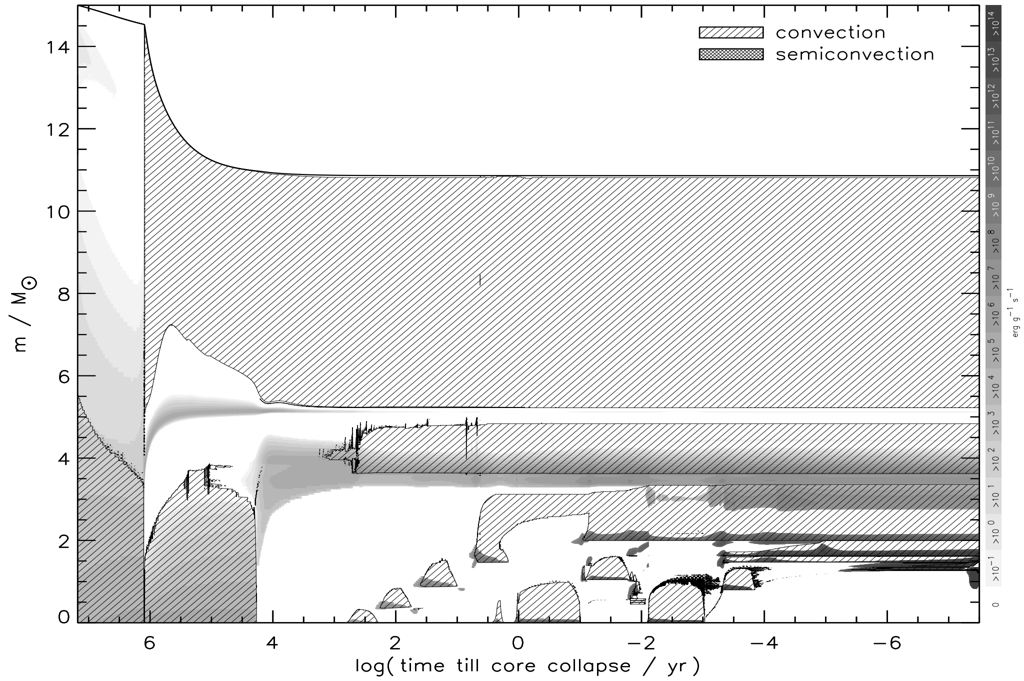

FIGURE 1. So called Kippenhahn-diagram, describing the evolution of the internal structure of a star with an initial mass of $15\,M_\odot$, from core hydrogen ignition until the onset of iron core collapse (cf. Heger et al. 2000). The X-axis gives the logarithm of the time (in years) with t=0 defined at the onset of iron core collapse. The Y-axis is a spatial coordinate; however, instead of a radius coordinate, the Lagrangian mass coordinate is used. Hatched areas are convectively unstable, and the convective cores of hydrogen, helium, carbon, neon, oxygen and silicon burning can be identified, successively. Gray shading denotes nuclear energy generation. After core burning, all burning stages develop shell sources, which give rise to the "onion skin model".

hydrogen burning shell in Fig. 1). In such a situation, the stage is set for mixing the ashes of neighbouring burning phases, which, if this mixture is exposed to high enough temperatures, gives rise to non-standard nuclear processes in stars.

MIXING PROCESSES

The list of instabilities which can lead to mixing processes in stars is very long (cf., Pinsonneault 1997); let us briefly consider the most important ones. Most important is certainly thermal convection. Fig. 1 shows that at any time a significant fraction of a massive star is convectively unstable; after the hydrogen burning stage even most of it. Convection is a dynamical instability, caused either by local nuclear energy production (note the nuclear energy production at the base of all convection zones in Fig.1, except for the convective envelope) or a low photon transmissivity.

While convection mixes on the local dynamical time scale, composition gradients in stars are typically such that light nuclei are lying on top of heavier ones. I.e., it costs energy to mix these layers in the gravitational potential of the star. Convection often is not able to mix in this situation; however, an instability confusingly named semiconvection may develop if the temperature stratification is superadiabatic. But, in contrast to convection, this instability acts only on the local thermal time scale, which is orders of magnitude larger than the local dynamical time scale.

Then, in particular as a result of mass transfer in binary systems, the situation may occur that heavy nuclei are placed above lighter ones in a star. This situation is unstable even if the temperature gradient is subadiabatic. So called thermohaline convection develops, which proceeds on the thermal time scale, like semiconvection.

Finally, all stars rotate, which can bring along a series of instabilities. Most important are the so called Eddington-Sweet circulations, slow currents which work towards thermal equilibrium in an ablated star with hotter poles and cooler equatorial regions, and the shear instability which may mix layers if they contain a sufficiently strong gradient in angular velocity (cf. Heger et al. 2000).

If any of these processes mixes elements into a nuclear burning zone, it is important to compare the time scale of this mixing process with the corresponding nuclear burning time scale. If the mixing time scale is short compared to the burning time scale — as it is, e.g., in a convective core — one may assume that the mixed region remains chemically homogeneous, and mixing and burning can be decoupled, as done in most stellar evolution models. If the mixing time is long compared to the burning time, obviously mixing and burning can be decoupled as well. However, if both time scales are comparable the situation is different, and a numerically costly coupled solution of the equations describing mixing and burning is necessary (Herwig et al. 1999). In all three cases, as well as when the burning starts only after the mixing is over, we may find non-standard nuclear fusion processes.

LONG OR SHORT MIXING TIME SCALES

Example 1: ^{13}C-Production in AGB stars

It is known since several decades that the main component of the s-process is produced in so called thermally pulsing AGB stars (cf., Gallino et al. 1998, and references therein), i.e. in red giants which consist of an electron-degenerate CO-core, an extended hydrogen-rich envelope, and two nuclear shell sources, the hydrogen and the helium burning shell, which operate very close together and alternately switch on and off. The s-process is supposed to occur in the helium burning shell using neutrons liberated by the $^{13}\mathrm{C}(\alpha, n)$-reaction. The problem is: within standard assumptions, AGB stellar models do not have any significant amount of ^{13}C in the helium-rich layers (Gallino et al. 1998). Instead, one needs to invoke a non-standard mixing-process which transports protons into the helium burning region so that ^{13}C can be produced via proton capture on ^{12}C. I.e., not only the production

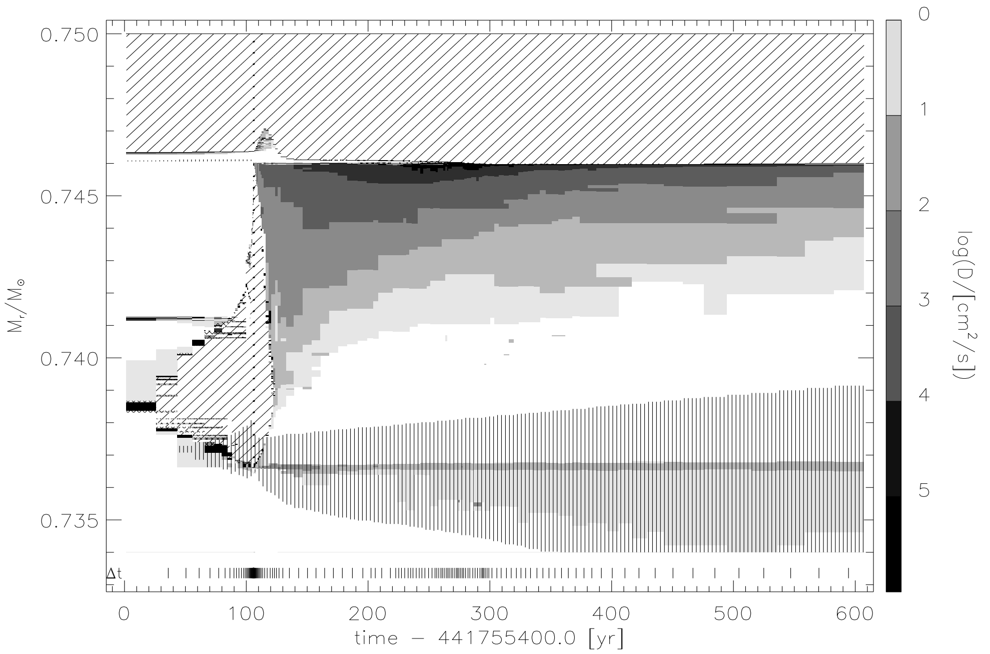

FIGURE 2. Section of the internal structure during and after the 25th thermal pulse of a rotating $3\,M_\odot$ sequence (Langer et al. 1999). Diagonal hatching denotes convection. The convective envelope extends down to $M_r \simeq 0.746\,M_\odot$. The pulse driven convective shell is located at $0.737\,M_\odot \lesssim M_r \lesssim 0.746\,M_\odot$ and $30\,\mathrm{yr} \lesssim t \lesssim 120\,\mathrm{yr}$. Vertical hatching denotes regions of significant nuclear energy generation, i.e., the hydrogen burning shell (at $M_r \simeq 0.746$ and $t \lesssim 100\,\mathrm{yr}$) and the helium burning shell ($0.734\,M_\odot \lesssim M_r \lesssim 0.739\,M_\odot$ and $t \gtrsim 40\,\mathrm{yr}$). Gray shading marks regions of significant rotationally induced mixing (see scale on the right side of the figure). Vertical marks at the bottom of the figure denote the time resolution of the calculation, where every fifth time step is indicated.

of ^{13}C, but the production of the whole main component of the s-process depends on non-standard mixing.

Very recently, two different approaches lead to significant ^{13}C production in AGB models: Herwig et al. (1997) found so called convective overshooting to be able to bring right amounts of protons into the helium-rich layers. Langer et al. (1999) have considered models of rotating AGB stars and found that shear mixing may also do the job (Figs. 2 and 3).

Mixing protons into helium burning layers may, however, involve further non-standard nuclear reactions, e.g. the production of fluorine or even of ^{15}N (cf. Jorissen & Arnould 1989). We note that this process may also occur in rotating massive stars with so far little explored consequences (Langer et al. 1997, Heger et al. 2000)

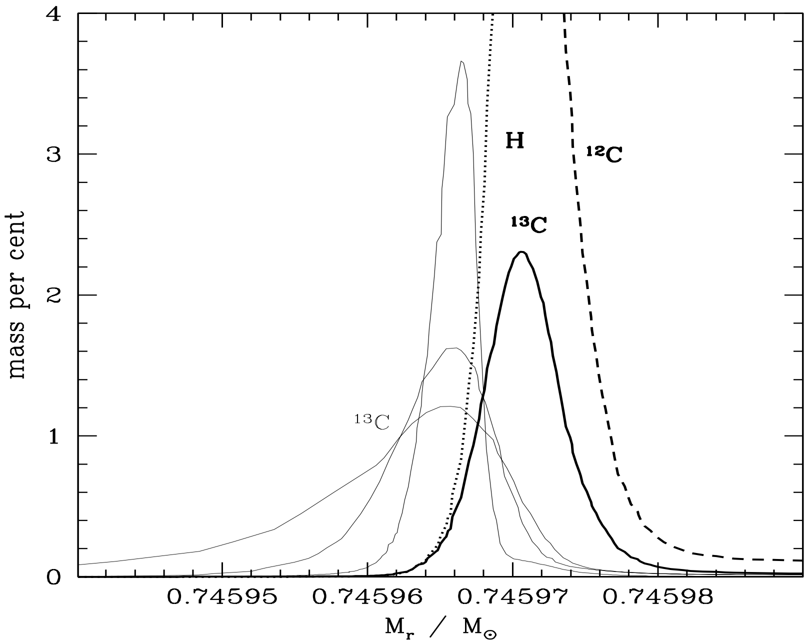

FIGURE 3. Chemical profiles at the location of the maximum depth of the convective envelope during the 25th thermal pulse (cf. Figure 2) of a rotating $3\,M_\odot$ AGB sequence (cf. Langer et al. 1999). The dotted and dashed lines mark the hydrogen and the ^{12}C mass fractions at $t = 1704$ yr, with $t = 0$ defined as in Figure 2. The fat solid line denotes the ^{13}C mass fraction at the same time. The three thin solid lines represent the ^{13}C mass fractions at $t = 2016$ yr, $t = 4155$ yr, and $t = 5139$ yr, with a later time corresponding to a smaller peak abundance. The maximum ^{13}C mass fractions of 3.6% occurs at $t = 2016$ yr. The ^{13}C peak moved inwards in the time interval from $t = 1704$ yr to $t = 2016$ yr due to continued proton captures on both, ^{12}C and ^{13}C.

Example 2: ^{26}Al-Production in Binaries

Most stars appear to be members of binary or multiple systems. The fraction of massive stars being members of *close* binaries — i.e. such in which mass overflow is expected to occur — is estimated to be of the order of 20...40% (cf., Podsiadlowski 1997, Mason et al. 1998). Langer et al. (1998) and Wellstein & Langer (1999) have studied the evolution and mixing processes in typical massive close binaries. Due to the transfer of most of the hydrogen-rich envelope of the primary to the secondary component, the primary becomes a helium star while the secondary evolves into a luminous blue supergiant. In both cases, the core masses evolve differently compared to single stars of the same initial mass (i.e., 20 or $18\,M_\odot$ in our example); the primaries' core masses are smaller, that of the secondaries larger.

The secondary star, which accretes the envelope of the primary during its core hydrogen burning evolution, is commonly assumed to evolve after accretion exactly like a single star of the corresponding new mass ($\sim 32\,M_\odot$ in our example).

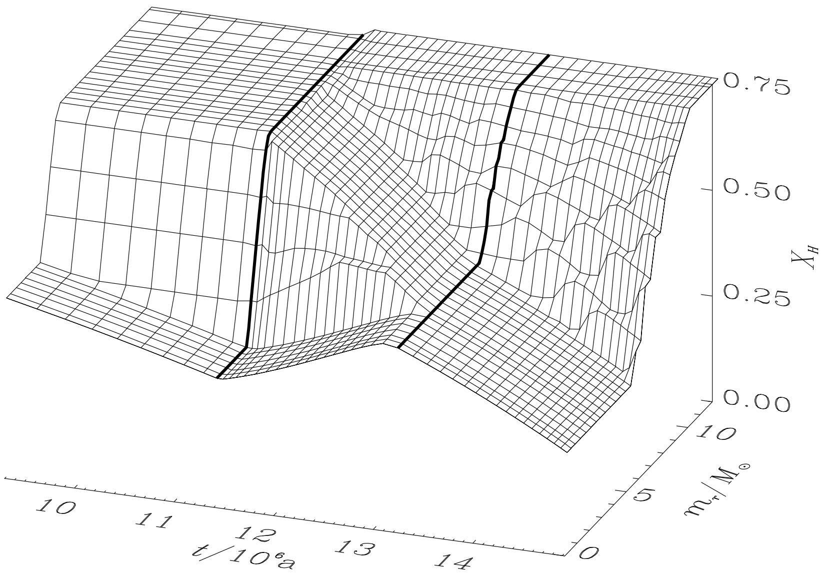

FIGURE 4. Hydrogen profile as function of time in a $12\,M_\odot$ star which accreted $8\,M_\odot$ at t$\simeq 11.4\,10^6$ a (left thick drawn line). At t$\simeq 13.1\,10^6$ a (right thick drawn line), the semiconvection controlled "rejuvenation process" is finished. The star has then adjusted its convective core size to its new mass (cf., Braun & Langer 1995). Note that were the accretion occurring later in the evolution of the $12\,M_\odot$ star, the time for rejuvenation might be too short.

However, Braun & Langer (1995) found that secondaries may retain significant structural differences compared to single stars (cf. Fig. 4), e.g. with the consequence that the supernova explosion occurs in the blue supergiant stage — as in the case of the progenitor of SN 1987A — rather than in the red supergiant stage.

Independent of this phenomenon, Langer et al. (1998) found that substantial differences in the synthesis of secondary CNO isotopes do occur in the secondary components of massive close binaries, due to the interplay between CNO burning and so called thermohaline mixing. This mixing process does occur in the whole hydrogen-rich envelope of the secondary from the surface down to the convective H-burning shell since the star accretes helium enriched matter from the primary component (i.e. matter with a higher mean molecular weight is lying above matter with lower mean molecular weight). As the time scale for thermohaline mixing — which is for the first time treated as a time dependent process in our models — and CNO processing at the bottom of the mixed zone are comparable, the production particularly of ^{13}C and ^{14}N is boosted in the whole H-rich envelope, increasing the yield of these isotopes by factors of the order of 2...3.

The synthesis of ^{26}Al in secondary components of close binaries was found to deserve special attention. The reason is that for ^{26}Al, as it is β-unstable with a mean life time of $1.03\,10^6$ yr ($\tau_{1/2} = 7.2\,10^5$ yr), not only the amount which is synthesised matters, but also the time of the synthesis if one wants to explain the observed γ-ray line emission from the decay of ^{26}Al in the Galaxy. We can only see the decay of ^{26}Al nuclei in the interstellar medium; the decay inside stars is unobservable. Therefore, the ^{26}Al which is observed should either be produced during supernova explosions or shortly before. From the spatial distribution of the γ-ray line emission (Prantzos & Diehl 1996) we know that it originates from massive stars. Supernovae are in fact the currently favoured production site, although the corresponding yields are very uncertain (Weaver & Woosley 1993, Woosley & Weaver 1995, Timmes & Woosley 1997).

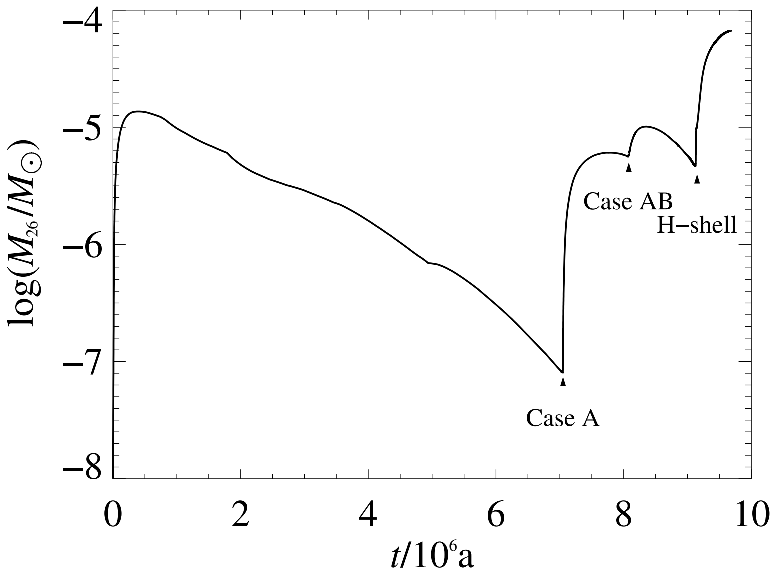

FIGURE 5. Evolution of the total mass of ^{26}Al inside the secondary component of a 20+18 $M_\odot$ close binary system as a function of time (in 10^6 yr). The beginning of the so called Case A and Case AB mass transfer phases is indicated, as well as the beginning of hydrogen shell burning which marks the end of the core helium burning evolutionary phase. When the star explodes as a supernova of Type SN 1987A ($t = 9.68\,10^6$ yr) it contains almost $10^{-4}\,M_\odot$ of 26Al. Note that the initial metallicity of the stars is $Z_\odot/4$.

However, ^{26}Al is also produced during hydrostatic hydrogen burning, by proton capture on ^{25}Mg. Although very massive stars, through extremely strong stellar winds, can eject ^{26}Al generated during H-burning and contribute to the Galactic ^{26}Al (Langer et al. 1995, Meynet et al. 1997), the hydrogen burning contribution of less massive stars (say 10...30 $M_\odot$) is not considered as important since the major fraction of the ^{26}Al decays inside the star before it is released in the course of the supernova explosion.

Langer et al. (1998) found this to be different in massive close binary secondaries. Fig. 5 shows the time dependence of the amount of ^{26}Al generated by hydrogen burning in the interior of the secondary component of a 20+18 $M_\odot$ system. Obviously, the ^{26}Al mass, although $10^{-5}\,M_\odot$ initially, would be of the order of $10^{-8}\,M_\odot$ at the end of the evolution if no mass accretion would occur. However, since fresh fuel — i.e. also fresh ^{25}Mg — is mixed into the core due to the mass accretion process (cf. Fig. 4) the amount of ^{26}Al is increased by orders of magnitude at that time.

This would already be sufficient to produce as much as $\sim 10^{-6}\,M_\odot$ ^{26}Al from this star of initially 18 $M_\odot$ — two orders of magnitude more than expected from single star calculations at $Z_\odot/4$ (cf. Langer et al. 1995). However, we find the H-burning shell source in the secondary component to be much more efficient than in corresponding single stars. This leads to the coupling of an extended convection zone to the hydrogen burning shell, and consequently to the enrichment of the whole convection zone with ^{26}Al. In the end, our secondary star contains almost $10^{-4}\,M_\odot$ of ^{26}Al which will be liberated during the supernova explosion. As the chosen example appears to be a rather typical case, the Galactic ^{26}Al production may in fact be dominated by massive close binary systems.

COMPARABLE MIXING AND NUCLEAR TIME SCALES

Example 3: ^{7}Li-Production in Giants

As mentioned above, when mixing and nuclear time scale are comparable one needs to solve the equations describing both processes simultaneously in order to obtain the correct result. An example is the so called Cameron-Fowler mechanism for lithium production in red giants (Cameron & Fowler 1971). The mixing process involved is convection, which acts in the hydrogen-rich envelope of red giants. Under certain circumstances, the bottom of this convective envelope can be hot enough for thermonuclear processes to occur in it.

When the reaction $^3\mathrm{He}(\alpha,\gamma)^7\mathrm{Be}$ is enabled (with ^{3}He being produced by the pp-chain) we have a nuclear time scale involved which is of the same order as the convective mixing time scale ($\sim 1\,\mathrm{yr}$), namely the β-decay of ^{7}Be to ^{7}Li ($\tau_\beta \simeq 50\,\mathrm{d}$). As the beryllium is transported out of the hot region into cooler layers by convection, the lithium which forms as its decay product may survive instead of being almost immediately destroyed.

The Cameron-Fowler mechanism may lead to considerable lithium production, and there is observational evidence for its operation in Li-rich red giants and AGB stars (cf. Charbonnel & Balachandran 2000).

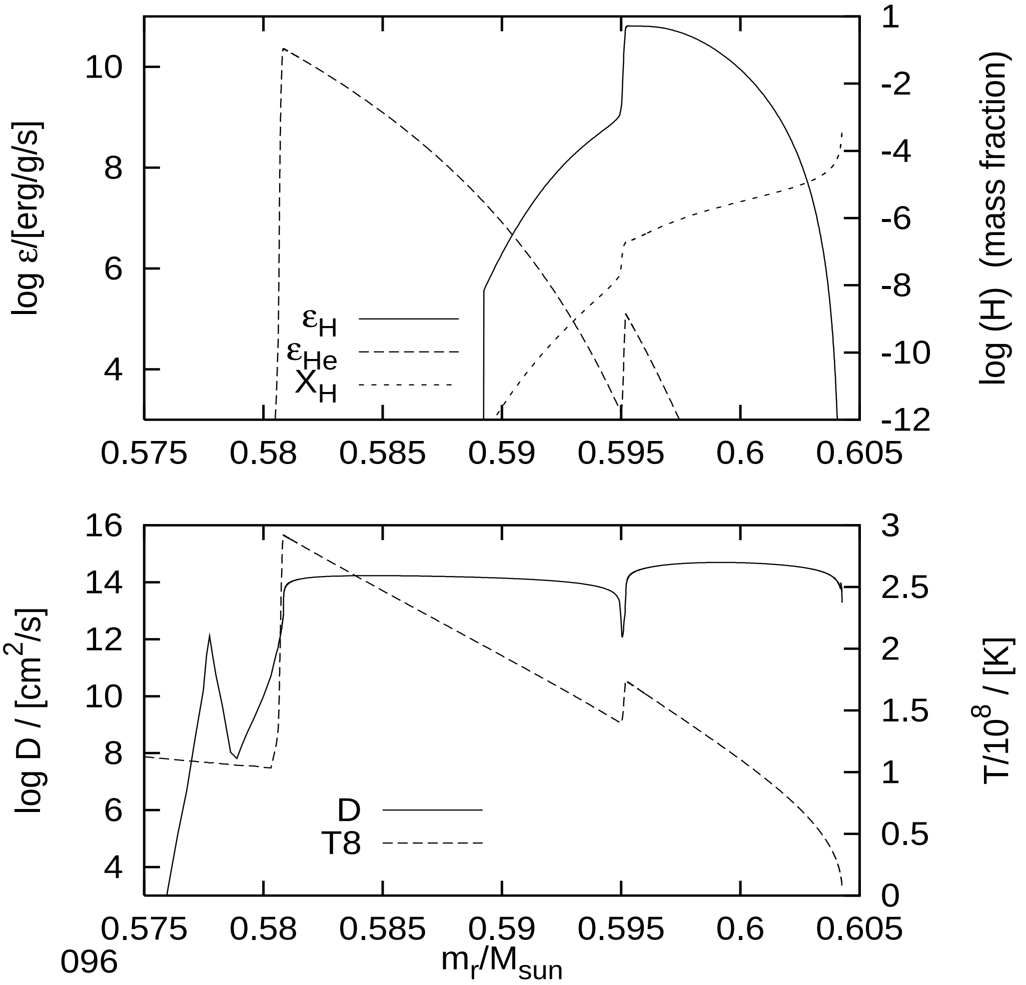

FIGURE 6. Profiles of various quantities in the nuclear burning region in post-AGB star during a late thermal pulse at the time of maximum energy generation (see text, and Herwig et al. 1999). The top panel shows nuclear energy generation rates due to proton and alpha captures, and the hydrogen mass fraction X_{H}. The bottom panel shows the diffusion coefficient D and the temperature in units of 10^8 K.

Example 4: Very Late Thermal Pulses

When AGB stars (see above) have lost all but a small fraction of their hydrogen-rich envelope due to their strong winds, they evolve within a short time scale into proto-white dwarfs. At this stage the hydrogen burning shell is practically extinct. However, there is evidence for some of these stars to undergo a so called "late thermal pulse" at this stage, i.e. the helium shell re-ignites violently. As the hydrogen burning shell is extinct, no entropy barrier prevents the convective mixing caused by this energetic event to penetrate into the remaining hydrogen-rich layers.

This is a most precarious situation, as convection brings the protons straight down into the helium burning layers. I.e., simultaneous hydrogen and helium burning occurs in the convection zone.

Fig. 6 describes this situation (cf. Herwig et al. 1999), which can not be modelled with standard stellar evolution codes. Protons survive up to temperatures of $\sim 2\,10^8$ K where they react with the products of helium burning. These, on the other hand, are mixed up into the cooler hydrogen-rich layers where they can react with protons. In the example shown in Fig. 6, all available protons are consumed, and the result is a hydrogen-free carbon-rich pre-white dwarf. We note that such objects are observed, as are stars which currently undergo a late thermal pulse.

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