

The survival of ^{205}Pb in intermediate-mass AGB stars

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Abstract. The now extinct ^{205}Pb is a pure s-process radionuclide ($t_{1/2} = 1.5 \cdot 10^7$ y) of possible substantial cosmochemical interest. As a necessary complement to the detailed theoretical study of the nuclear physics and astrophysics aspects of the $^{205}\text{Pb} - ^{205}\text{Tl}$ pair carried out by Yokoi et al. (1985), and to the recent calculation of the ^{205}Pb production in Wolf-Rayet stars by Arnould et al. (1997), this paper addresses for the first time in some detail the question of the survival of this radionuclide in thermally pulsing AGB stars. This problem is made difficult by the high sensitivity to temperature and density of the rates of the weak interaction processes that are able to produce or destroy ^{205}Pb . In view of this sensitivity, a recourse to detailed stellar models is mandatory. With the help of some simplifying assumptions concerning in particular the third dredge-up characteristics, some of which (like its depth) being considered as free parameters, predictions are made for the ^{205}Pb contamination of the stellar surface at the end of a pulse-interpulse cycle following a series of a dozen of pulses in three different intermediate-mass stars ($M = 3 M_{\odot}, Z = 0.02$; $M = 6 M_{\odot}, Z = 0.02$; $M = 3 M_{\odot}, Z = 0.001$). It is concluded that the chances for a significant ^{205}Pb surface enrichment are likely to increase with M for a given Z , or to increase with decreasing Z for a given M . More specifically, following the considered pulses at least, the enrichment appears to be rather unlikely in the $3 M_{\odot}$ star with $Z = 0.02$, while it seems to be much more probable in the other two considered stars. It is also speculated that the ($3 M_{\odot}, Z = 0.02$) star could possibly experience some ^{205}Pb enrichment following later pulses than the ones considered in this paper.

Key words: nuclear reactions, nucleosynthesis – stars: abundances; stars: AGB – stars: giant

1. Introduction

There is at present ample observational evidence that some meteoritic material of solar system origin carries the signature of

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the in-situ decay of by now extinct radionuclides with half-lives from about 10^5 to approximately 10^8 y. These observations have far-reaching implications for our knowledge of the history of the forming solar system, and provide in particular a key information about the time span between the last nucleosynthetic events that have modified the composition of the solar nebula and the formation of the solar system solid bodies. For a recent review, the reader is referred to e.g. Swindle (1993) and references therein.

Among the extinct radionuclides of potential cosmochemical interest, ^{205}Pb ($t_{1/2} = 1.5 \cdot 10^7$ y) exhibits the distinctive feature of being of pure s-process nature. If its signature in meteorites could be identified, it would thus very usefully complement the information provided by the other extinct radionuclides. Unfortunately, its abundance at the start of the solidification process in the early solar system is very poorly known. In fact, just an upper limit on this quantity is available (Huey & Kohman 1972).

A detailed theoretical study of the nuclear physics and astrophysics aspects of the $^{205}\text{Pb} - ^{205}\text{Tl}$ pair has been carried out by Yokoi et al. (1985, hereafter YTA85). These authors have shown that, in contradiction with an earlier estimate (Blake & Schramm 1979), enough ^{205}Pb could be produced in certain s-process conditions to allow the development of a s-process chronometry. This of course requires a renewed search for the signature of this radionuclide in meteorites (a step in this direction has been taken by Chen & Wasserburg 1994), as well as a reliable enough prediction of the ^{205}Pb yields from all possible s-process sites.

In order to explore the latter question, YTA85 have considered simple parametric models that can at best mimic the complex conditions prevailing in the stellar interiors. The first quantitative attempt to evaluate ^{205}Pb stellar yields has been conducted by Arnould & Prantzos (1986) on grounds of detailed models of massive mass-losing stars of the Wolf-Rayet type. Their early predictions, confirmed recently by Arnould et al. (1997), reinforce the view already expressed by YTA85 that indeed ^{205}Pb could be a valuable s-process chronometer. Asymptotic Giant Branch (AGB) stars, on the other hand, have also been considered by YTA85 as potential sites for the ^{205}Pb enrichment of the interstellar medium (see also Wasserburg et

al. 1994). Their estimate, however, is based on a very schematic representation of the recurrent thermal pulse - interpulse cycles characterising these objects. In addition, the very important question of the survival of ^{205}Pb during the interpulse phases has been left unanswered, nor has it been tackled by Wasserburg et al. (1994) either.

The aim of this paper is to fill this gap by following quantitatively the decay of ^{205}Pb in essentially neutron-free locations of AGB stars during their interpulse phases. These computations are based on the β -transition rates derived by YTA85 and on detailed AGB models for three different stars ($M = 3 M_{\odot}$, $Z = 0.02$; $M = 6 M_{\odot}$, $Z = 0.02$; and $M = 3 M_{\odot}$, $Z = 0.001$) whose layers experiencing the pulse - interpulse episodes are supposed to be enriched with s-process products, and in particular with ^{205}Pb . It is then assumed that the third dredge-up (hereafter 3DUP) is responsible for the transport of the surviving ^{205}Pb to the surface of the AGB stars before being ejected into the interstellar medium by their winds.

Some generalities about the AGB features of interest here (pulses and s-process nucleosynthesis) are briefly reviewed in Sect. 2. The specific aspects of the β -decay of ^{205}Pb in AGB conditions are described in Sect. 3, and the prescriptions adopted for the calculation of its abundance evolution in neutron-free AGB layers are presented in Sect. 4. The predictions of the survival of ^{205}Pb in the three considered model stars are presented in Sect. 5 and discussed in Sect. 6. Some conclusions are drawn in Sect. 7.

2. The AGB stars

2.1. Thermal instabilities

The structural evolution of the H- and He-burning shells (denoted hereafter HBS and HeBS, respectively) during a thermal instability (pulse) characteristic of the AGB stars is displayed in Fig. 1. For the sake of further discussion, four distinct cycle phases are identified, the main characteristics of which are summarized below (more details can be found in Mowlavi 1995):

Phase 1: *The interpulse phase.* Hydrogen burns in a thin layer of a few $10^{-4} M_{\odot}$ located at mass fractions M_r increasing with time. The H-burning products, including ^{13}C and ^{14}N , are left behind in the intershell region (layers between the HBS and the HeBS). The HeBS, whose mass is about $10^{-2} M_{\odot}$, is almost extinct, and the luminosity of the star is essentially provided by the HBS. As the mass of the He-rich layers increases, a thermal instability is triggered in the HeBS (Schwarzschild & Härm 1958), leading to the development of a convective pulse;

Phase 2: *The growth of the convective pulse.* A convective zone develops just above the location of the maximum energy production of the HeBS, its upper boundary coming close to the H-rich layers. The ashes left behind by the HBS during the interpulse period are engulfed into the pulse. The pulse duration is about 500 times shorter than the interpulse one;

Phase 3: *The decay of the pulse.* The energy accumulated in the HeBS escapes through the now extinct HBS, and the convective pulse recedes;

Phase 4: *The afterpulse phase.* Following the pulse, the structural and energetic evolution is complex and dominated by thermal relaxations. The temperature and density in the He-rich layers first drop as a result of the expansion of the intershell region, and then increase due to the structural readjustment. At the same time, the convective envelope reacts to the thermal relaxations by deepening into the H-depleted layers, possibly reaching zones containing the ashes of the convective pulse. The mixing of these ashes into the envelope and their transport to the surface constitute the 3DUP. This dredge-up is required by the observation of the surface composition peculiarities of AGB stars, and is predicted by some models after a sufficient number of pulse/interpulse cycles (Mowlavi 1997). The model pulses dealt with in this paper (Sect. 5) are not accompanied with the 3DUP, which appears to develop only at later pulses in the considered stars. However, some observations suggest that the 3DUP might occur much earlier than predicted (Mowlavi et al. 1996). In view of the uncertainties still affecting the precise time of occurrence and extent of the 3DUP, we simply assume in the following that it indeed takes place at the time of deepening of the convective envelope in all the pulses to be discussed later. This time also defines the end of the afterpulse phase, and correspondingly the start of the following interpulse period.

2.2. The s-process

While observation demonstrates that the s-process can develop in AGB stars, its modelling remains a warmly debated question. This concerns more specifically the precise mechanism of production and the amount of neutrons made available for the process. The two classically envisioned neutron sources, $^{13}\text{C}(\alpha, n)^{16}\text{O}$ and $^{22}\text{Ne}(\alpha, n)^{25}\text{Mg}$, have an efficiency that is expected to depend very much on the considered stars, as well as on the precise evolutionary phase of a given star. The reliability of the predictions in this field is drastically limited by astrophysics and nuclear physics uncertainties (Drotleff et al. 1993, Frost & Lattanzio 1995).

In the models considered in the present paper, the temperatures limit the neutron production to $^{13}\text{C}(\alpha, n)^{16}\text{O}$. The available ^{13}C is found to come from the CN cycle exclusively. This amount is well known to be insufficient for producing the neutrons required for the development of a full s-process. This problem classically encountered in the modelling of the s-process in AGB stars is circumvented by assuming that some protons from the envelope are brought “semi-convectively” into the underlying ^{12}C -rich layers during the afterpulse phase (Iben & Renzini 1982). Recent evolutionary calculations (Herwig et al. 1997) predict similar mixing to occur by convective overshoot at the base of the envelope. In both cases, after reignition of the HBS in the early interpulse phase, some ^{13}C could be produced by $^{12}\text{C}(p, \gamma)^{13}\text{C}$. Part at least of this ^{13}C of “primary” nature could be subjected to $^{13}\text{C}(\alpha, n)^{16}\text{O}$ either during the interpulse phase or later after ingestion in the subsequent pulse. These two burning modes will be referred to in the following as the “Interpulse Scenario (IS)” and the “C Pulse Scenario (CPS)”, respectively. Of course, the s-process abundances emerging from a pulse may

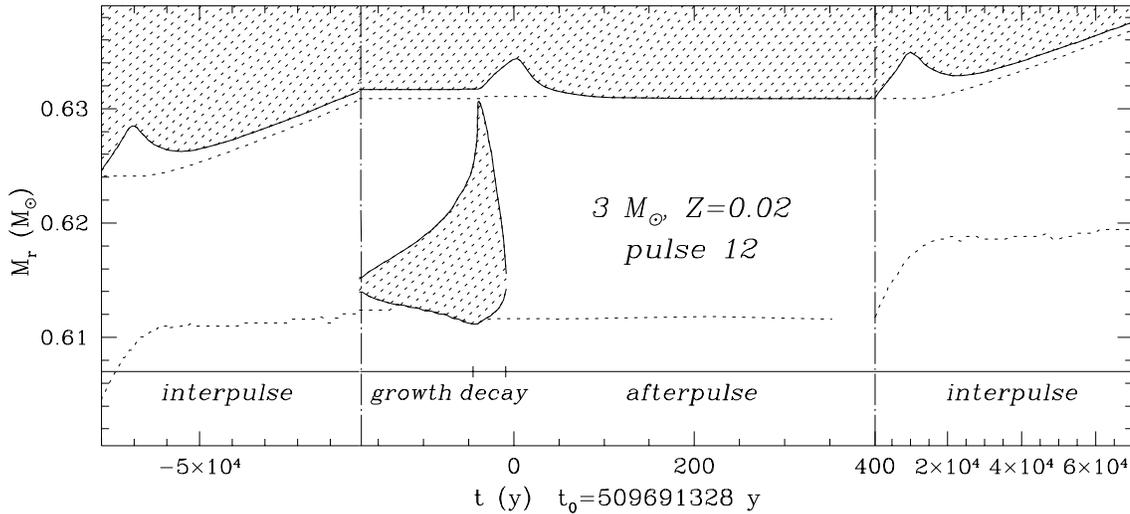


Fig. 1. Structural evolution of the intershell regions of the $3 M_{\odot}$ star with $Z = 0.02$ around the 12th pulse. The origin of the abscissa is arbitrarily set to time t_0 , the value of which is indicated in the figure. Filled regions correspond to convective zones. The dotted lines identify the location of maximum energy production in the H-burning (top) and He-burning (bottom) layers. The different phases of an instability cycle described in the main text are also indicated

result from the complementary and sequential action of the IS and of the CPS. We define this scenario as the IS+CPS.

Even if the $^{13}\text{C}(\alpha, n)^{16}\text{O}$ neutron source is currently believed to be responsible for the s-process in AGB stars, it remains that the amount of neutrons that can be produced in such a way is still highly uncertain, and its dependence on stellar mass and metallicity is unknown.

3. The production and destruction of ^{205}Pb

As emphasized in Sect. 1, ^{205}Pb has the distinctive feature of being of pure s-process origin, and could thus be synthesized in the IS and/or CPS. The produced quantities depend of course on the amount of available neutrons, which cannot be estimated self-consistently and reliably at the present stage of development of the models.

A complementary question, which has not been addressed properly yet, concerns the survival of ^{205}Pb in the essentially neutron-free layers in which the radionuclide may reside after its production by the s-process. Obviously, the level of ^{205}Pb destruction in such conditions depends on the relative values of the relevant stellar evolutionary lifetimes and of the timescales of production or destruction of this radionuclide through weak interaction processes¹. As demonstrated by YTA85, the latter lifetimes may depend drastically on the stellar conditions. This makes the question of the survival of ^{205}Pb a non-trivial problem. More specifically, in a stellar plasma the thermal population of low-lying nuclear excited states, ionization, and the possibility of capture of free electrons can modify substantially the experimentally known ^{205}Pb half-life, and even open the

possibility for the laboratory stable ^{205}Tl to become β -unstable and to transform into ^{205}Pb . Fig. 2 illustrates the impact of the stellar conditions on the ^{205}Pb and ^{205}Tl decay rates. Let us just emphasize that

(1) the ^{205}Pb e^- -capture half-life gets much shorter than its terrestrial value of $1.5 \cdot 10^7$ y at temperatures that are high enough (typically in excess of a few 10^6 K) for the first excited state of ^{205}Pb (excitation energy of only 2.3 keV) to be significantly populated;

(2) when its level of ionization is high enough, ^{205}Tl can transform into ^{205}Pb via bound-state β -decay, its corresponding half-life depending very sensitively on both temperature and density. Its lifetime is shorter than the ^{205}Pb one for temperatures $T \gtrsim 1.3 \cdot 10^8$ K at a density $\rho \approx 300 \text{ g cm}^{-3}$, this critical temperature increasing with increasing densities.

On such grounds, YTA85 predict that ^{205}Pb is in danger of being transformed into ^{205}Tl by electron captures in neutron-free regions at $10^6 \lesssim T \lesssim 10^8$ K, the level of destruction being highly sensitive in this temperature range to the free electron number density and to the evolutionary timescales. In hotter locations, this destruction is prevented by the reverse transformation $^{205}\text{Tl}(\beta^-)^{205}\text{Pb}$. Finally, at $T \lesssim 10^6$ K, the ^{205}Pb e^- -capture lifetime gets longer than the typical interpulse period ($\lesssim 10^6$ y) expected in AGB stars, so that ^{205}Pb has no time to decay in significant amounts before the occurrence of the next pulse. Of course, these temperature limits are only indicative since the rates are density dependent.

In view of the above considerations, it appears hopeless to evaluate in a reliable way the level of destruction of ^{205}Pb in stellar neutron-free locations following the CPS or IS without recourse to a self-consistent abundance calculation conducted in the framework of AGB models. The first computation of this kind is described below.

¹ In the considered neutron-free stellar environments, charged particle reactions or photodisintegrations cannot affect the ^{205}Pb abundances.

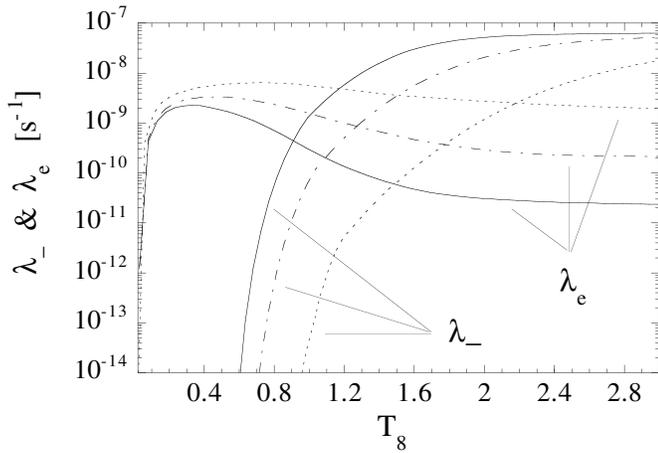


Fig. 2. YTA85 rates λ_e of ^{205}Pb electron capture and λ_- of ^{205}Tl β -decay versus temperature for the electron number densities N_e (in cm^{-3}) of 10^{25} (full line), 10^{26} (dot-dashed line) and 10^{27} (dashed line). The uncertainties of nuclear origin affecting these predictions are discussed in detail by YTA85. They concern mainly some experimentally unknown β -decay matrix elements, as well as the $^{205}\text{Pb} - ^{205}\text{Tl}$ mass difference

4. The stellar models and numerical assumptions

The time variations of the ^{205}Pb abundance is followed during some characteristic pulse – interpulse cycles through detailed model calculations of three AGB stars with different masses and metallicities referred to in the following as M3Z02 ($M=3 M_{\odot}, Z=0.02$), M6Z02 ($M=6 M_{\odot}, Z=0.02$), and M3Z001 ($M=3 M_{\odot}, Z=0.001$), the evolution of these stars being computed all the way from the pre-main sequence phase. Details about these evolutionary models, as well as about the computer code being used can be found in Mowlavi (1995) and Mowlavi et al. (1996).

These detailed AGB models fail to predict self-consistently the s-processing and the 3DUP, so that some assumptions have to be made in order to compute the ^{205}Pb surface enrichment that may follow from a thermal pulse phase. More specifically, we suppose that

- (i) all the considered stars can produce ^{205}Pb . This possibility is substantiated by the fact that the considered model stars are found to produce neutrons through the CPS or IS+CPS (see Sect. 5);
- (ii) in line with assumption (i), a ^{205}Pb number density equal to unity is imposed in the whole convective pulse region at the moment of its maximum extension in mass, considered as the initial time t_{in} in the abundance calculations reported below. This choice of initial abundances is justified by the fact that we are not interested here in the *absolute* level of ^{205}Pb production, but rather in the extent of its survival after its synthesis;
- (iii) the 3DUP occurs at the time t_{dredge} of deepest extent of the convective envelope (see Sect. 2.1). It is considered to mix homogeneously part of the remaining ^{205}Pb into the whole convective envelope up to the surface. The fraction of ^{205}Pb that is

Table 1. Some characteristics at the given pulse number of the three cases for which the ^{205}Pb abundance calculations are performed. T_{bp}^{\max} is the maximum temperature reached at the base of the given pulse and T_{be} the temperature at the base of the envelope during the following interpulse. The temperatures are expressed in units of 10^6 K. The last column identifies the scenario assumed to be responsible for the ^{205}Pb abundance production (see main text)

case	pulse	T_{bp}^{\max}	T_{be}	scenario
M3Z02	12	265	~ 5	CPS
M6Z02	13	285	~ 80	IS+CPS
M3Z001	14	308	~ 30	IS+CPS

effectively transported to the surface depends on the depth of the 3DUP, taken here as a free parameter. In addition, the mixing is assumed to take place during a time interval that is short compared to the lifetimes of the ^{205}Pb production or destruction mechanisms. These processes are thus frozen during the 3DUP; (iv) after the 3DUP, the ^{205}Pb abundance is followed in the convective envelope over the time t_{inter} of duration of the interpulse. In absence of a self-consistent 3DUP model, the physical conditions in the envelope are assumed to recover their pre-dredge-up values;

(v) in the $t_{in} \leq t \leq t_{dredge}$ time interval, the layers loaded with ^{205}Pb following assumptions (i) and (ii) are neutron-free, so that the ^{205}Pb abundance is governed by the simultaneous action of just $^{205}\text{Pb}(e^{-}\nu)^{205}\text{Tl}$ and $^{205}\text{Tl}(\beta^{-})^{205}\text{Pb}$. The phase of decay of the modelled pulses (see Sect. 5) is indeed found to be neutron free, the ^{13}C possibly engulfed in the pulse convective tongues being fully destroyed at $t = t_{in}$, while ^{22}Ne cannot burn.

On grounds of the above assumptions, the calculation of the evolution of the ^{205}Pb abundance profile from t_{in} up to the end of a given interpulse is then fully coupled to the detailed modelling of the pulse decay, afterpulse, and interpulse phases. For each stellar model, we limit ourselves to the consideration of a single pulse-afterpulse-interpulse cycle identified in Table 1. This simplification is justified by the absence of self-consistent 3DUP phases in the computed models. It will be dropped in future models if they succeed to predict such a dredge-up. Even if the number of studied cycles is limited, they cover a quite large variety of situations ^{205}Pb can face after its production.

In radiative neutron-free layers, the ^{205}Pb abundances follow from

$$N_{205\text{Pb}}(t + \Delta t) = \left(N_{205\text{Pb}}(t) - N_{205} \frac{\lambda_-}{\lambda} \right) \exp^{-\lambda \Delta t} + N_{205} \frac{\lambda_-}{\lambda}, \quad (1)$$

with $\lambda = \lambda_- + \lambda_e$, and

$$\begin{aligned} N_{205} &= N_{205\text{Pb}}(t) + N_{205\text{Tl}}(t) \\ &= N_{205\text{Pb}}(t + \Delta t) + N_{205\text{Tl}}(t + \Delta t). \end{aligned} \quad (2)$$

In these equations, $N_i(t)$ is the abundance of nucleus i at time t , Δt the time step over which the abundance change is calculated. Following assumption (ii) of Sect. 4, $N_{205\text{Pb}}(t_{in}) = 1$

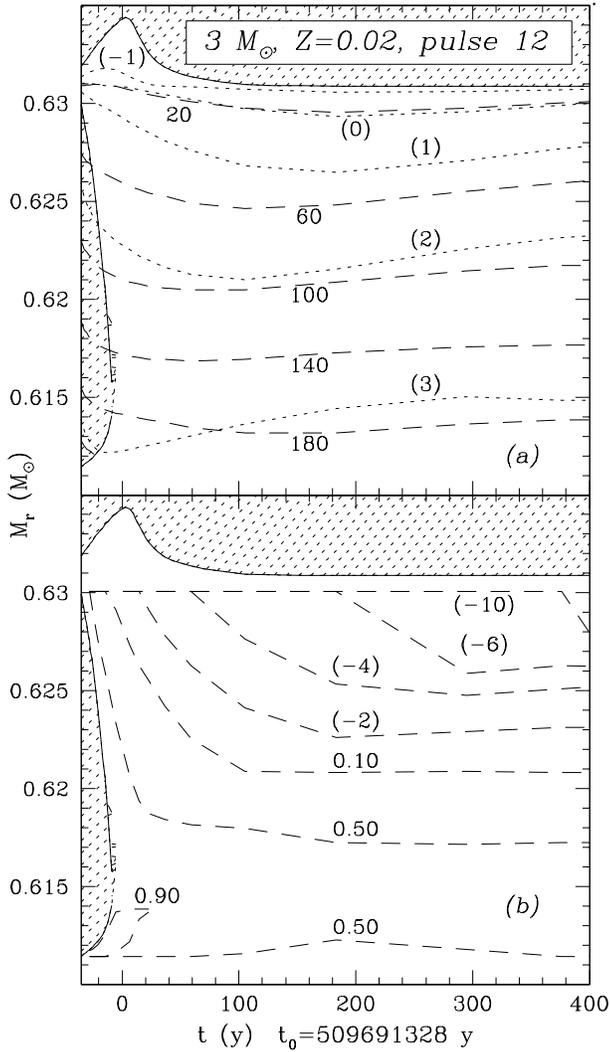


Fig. 3. **a** Structural evolution of the intershell regions during the decay of pulse 12 and during the afterpulse of the M3Z02 star. Filled areas have the same meaning as in Fig. 1. Long-dashed lines represent locations of constant temperature, labelled in units of 10^6 K. Short-dashed lines indicate locations of constant density (in g cm^{-3}). Values in parentheses indicate logarithms of the density. The origin of time is set at t_0 , the value of which is displayed on the abscissa. **b** Same as **a** but for contours of equal ^{205}Pb abundance. Numbers in parentheses refer to logarithms of the abundances

and $N_{205\text{Tl}}(t_{in}) = 0$ are adopted. On the other hand, λ_- and λ_e are the values of the ^{205}Tl β -decay and ^{205}Pb e^- -capture rates appropriate for the temperature, density and composition (and thus electron concentration) of the considered radiative layer. Eq. (2) expresses the constancy of the total amount of $A = 205$ isobars in absence of any other transformation than the considered β -transitions.

In convective regions, instantaneous mixing is assumed. The evolution of their ^{205}Pb content is still given by Eqs. (1) and (2) in which λ_- and λ_e are interpreted as mass averages of the local β -decay and e^- -capture rates over the whole convective region.

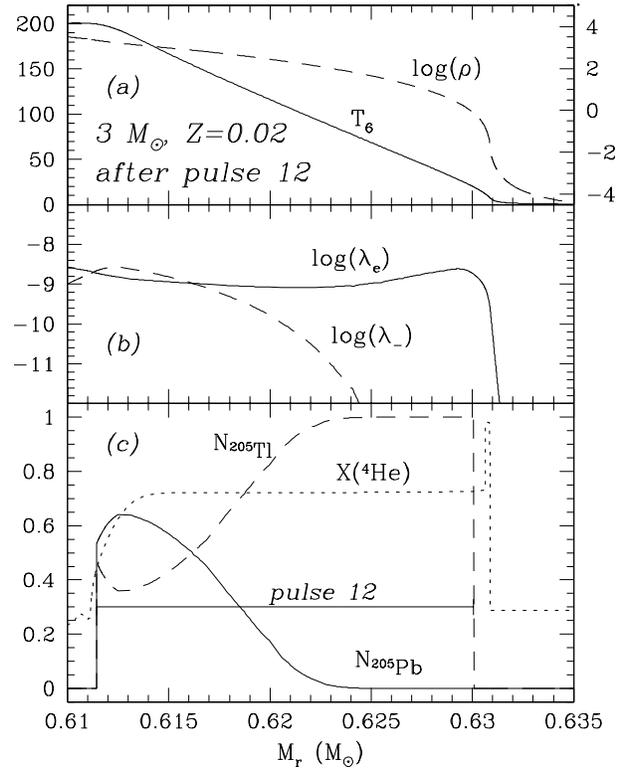


Fig. 4a–c. Mass profiles of some quantities in the M3Z02 star at the end of the 12th afterpulse, which occurs at $t = 408$ y in the time abscissa of Fig. 3; **a** Temperatures (in units of 10^6 K) and densities (in g cm^{-3}), to be read on the left- and right-hand ordinates, respectively; **b** ^{205}Pb e^- -capture (λ_e) and ^{205}Tl β^- -decay (λ_-) rates, expressed in s^{-1} ; **c** ^{205}Pb and ^{205}Tl abundances. The helium mass fraction profile (dotted line) helps locating the envelope. The extent of pulse 12 is also shown

5. Model predictions

5.1. The M3Z02 case

Up to at least pulse 12, CPS dominates the ^{205}Pb production. During the decay phase of this pulse, the thermodynamic conditions in the convective tongue are such that ^{205}Pb essentially survives. Though the typical (mass-averaged) lifetime of ^{205}Pb is of the order of the ≈ 30 y duration of the decay phase, the lifetime of ^{205}Tl is ≈ 12 y preventing great depletions of ^{205}Pb .

In the afterpulse phase, Figs. 3(b) and 4a–c(c) demonstrate that the destruction of ^{205}Pb is severe in layers experiencing temperatures $T \lesssim 10^8$ K, as already predicted by YTA85 (see also Sect. 3). This corresponds to about the upper half of the region formerly covered by pulse 12. In this mass region, λ_e is of the order of 10^{-9} s^{-1} [see Fig. 4a–c(b)], corresponding to a ^{205}Pb lifetime of about 30 y. This is roughly ten times shorter than the afterpulse duration, so that ^{205}Pb decays largely into ^{205}Tl . On the other hand, the reverse transformation is too slow to impede this destruction. The situation in this respect is quite different in deeper layers vacated by the pulse, where λ_- can be comparable to λ_e . In such conditions, the destruction of ^{205}Pb

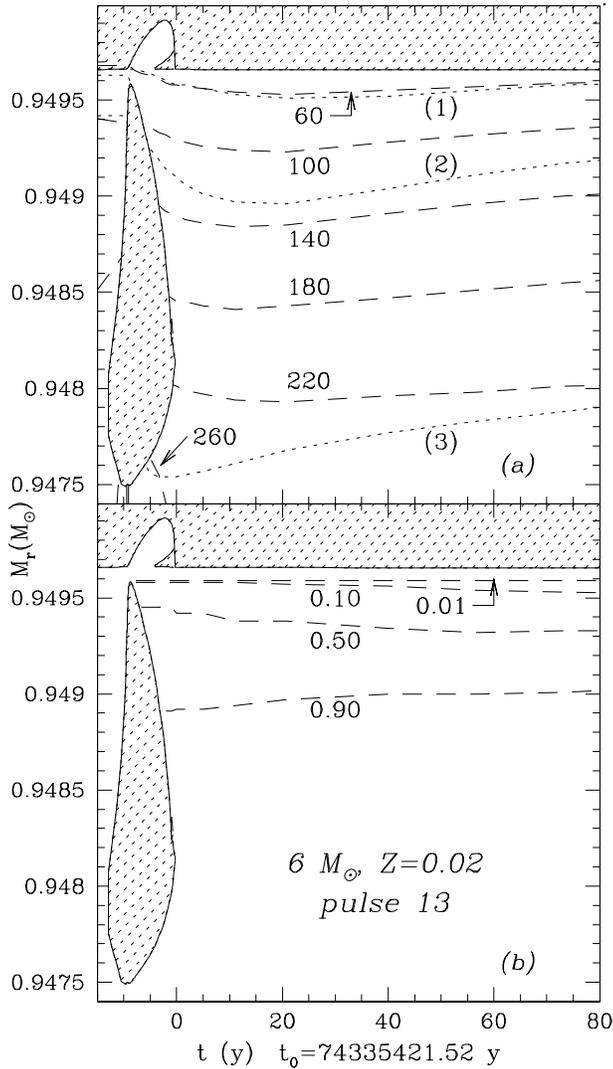


Fig. 5. Same as Fig. 3, but for pulse 13 of the M6Z02 star

is largely avoided, its abundance having time to reach its local equilibrium value $N_{205\text{Pb}}^{\text{eq}} = N_{205}\lambda_-/\lambda$.

The results just described imply that a very deep 3DUP of some $10^{-2}M_{\odot}$ is required at the end of the afterpulse phase in order to bring some ^{205}Pb to the surface of the M3Z02 star. Whether or not such a deep 3DUP can operate is still unknown.

5.2. The M6Z02 case

In contrast to the M3Z02 case, the M6Z02 star at its 13th pulse is the site of the IS+CPS. Neutrons are not produced anymore at times $t \geq t_{in}$, so that assumption (v) is fully valid.

As in the M3Z02 case, almost no ^{205}Pb can be destroyed during the pulse decay. This results from the fact that, at the time of maximum extension of pulse 13, ^{205}Pb has an effective (mass-averaged) lifetime of the order of 40 y, while the corresponding ^{205}Tl lifetime is of the order of 3 y. These lifetimes have to be compared with the approximate 10 y duration of the pulse decay.

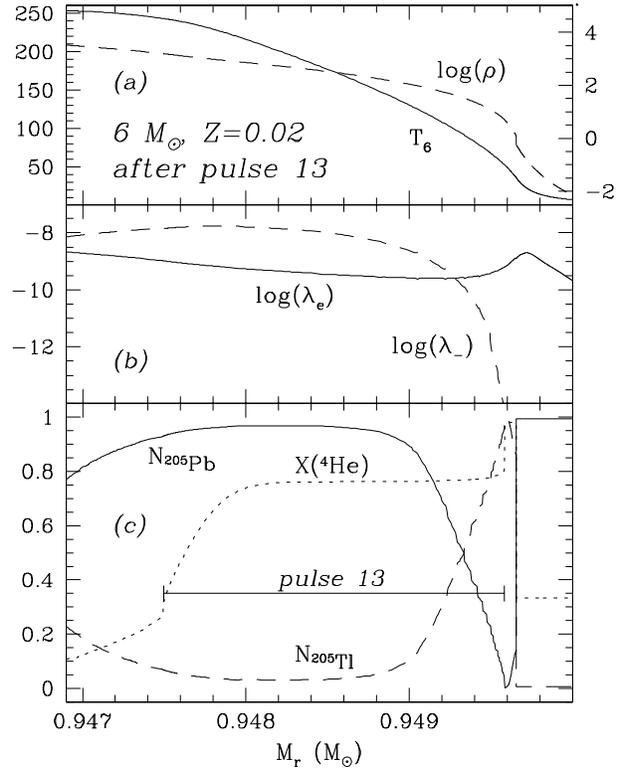


Fig. 6. Same as Fig. 4a–c, but at time $t = 40$ y (in the scale shown in the abscissa of Fig. 5) following pulse 13 of the M6Z02 star

The M6Z02 afterpulse ^{205}Pb abundance evolution differs in two ways from the M3Z02 one. First, the M6Z02 core mass is higher than the M3Z02 one. This implies much higher intershell temperatures in the former case, as demonstrated by comparing Figs. 3(a) and 5(a) or 4a–c(a) and 6(a). Because of the high sensitivity of λ_- to T (Fig. 2), this leads to ^{205}Tl β -decay rates exceeding the ^{205}Pb e^- -capture rates over a large fraction of the intershell region of the M6Z02 star. As a consequence, the ^{205}Pb destruction is prevented over more than the inner 80% of the intershell region [Figs. 5(b) and 6(c)]. Second, the response time of the envelope to the thermal relaxations following the decline of the pulse is about ten times shorter in the M6Z02 than in the M3Z02 case. This favours further the survival of ^{205}Pb before the eventual occurrence of the 3DUP.

In conclusion, large amounts of ^{205}Pb can emerge from massive AGB stars for moderately deep 3DUP events.

5.3. The M3Z001 case

There are many similarities between the 14th pulse-interpulse of this star and the M6Z02 case discussed above. In both stars, the s-processing is of the IS+CPS type, and no neutrons can be produced after the maximum extension of the pulse. In addition, Figs. 7(b) and 8(c) reveal that much of the initial ^{205}Pb survives the afterpulse, and can be brought to the surface by an eventual 3DUP.

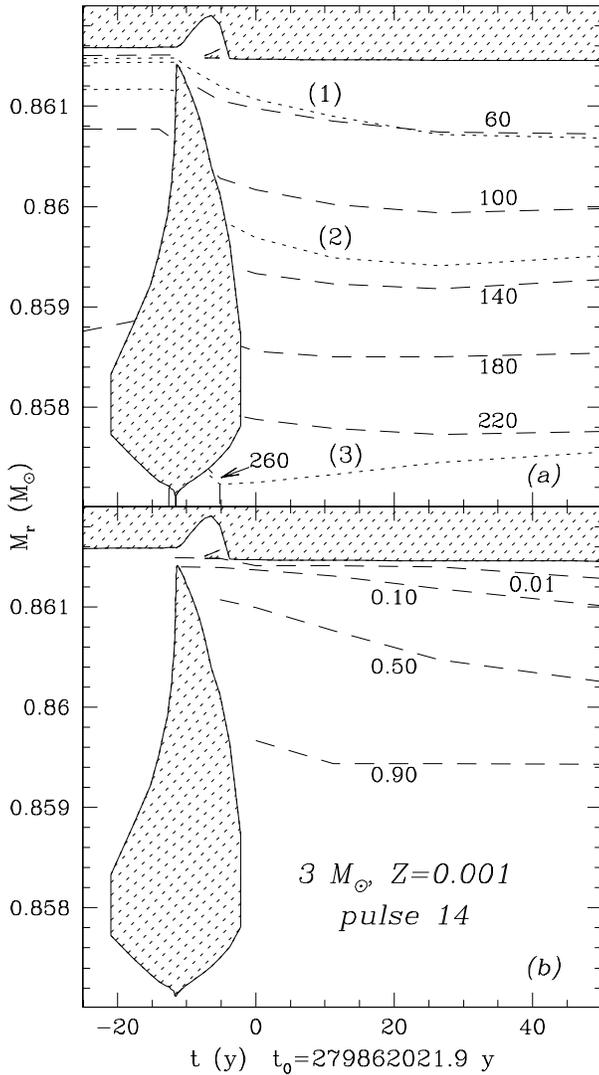


Fig. 7. Same as Fig. 3, but for pulse 14 of the M3Z001 star

5.4. The survival of ^{205}Pb in the envelopes

If indeed some ^{205}Pb can find its way to the stellar surface, it remains to be seen if it is able to survive there during the entire duration t_{inter} of the interpulse phase subsequent to the 3DUP. This is a non trivial question as the ^{205}Pb e^- -capture and ^{205}Tl β -decay rates depend on the detailed thermal structure of the envelope.

Table 2 indicates that no significant ^{205}Pb destruction occurs in the envelope of the three considered stars, in spite of the fact that the effective ^{205}Pb decay rate in the envelope, obtained by mass-averaging over all its convective layers, is increased over its terrestrial value due the high temperatures reached at the bottom of the envelope. Even so, Table 2 shows that the effective ^{205}Pb lifetime remains much longer than the interpulse duration, so that ^{205}Pb has no time to be destroyed significantly in the envelope between two successive pulses.

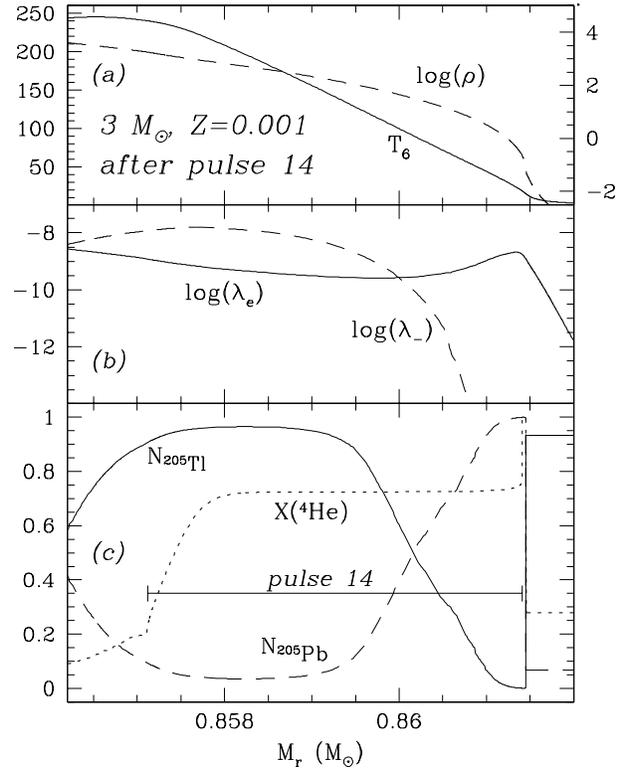


Fig. 8. Same as Fig. 4a–c, but at time $t = 60$ y (in the abscissa of Fig. 7) following pulse 14 of the M3Z001 star

6. Discussion

The following remarks are worth emphasizing:

- (i) the stellar models considered in this work lead to some neutron processing through the CPS or IS+CPS. Interpulses that are hot enough for allowing the development of a pure IS might well be obtained at later evolutionary phases. In such conditions, one might wonder if, following its IS production, ^{205}Pb could not be destroyed before the episode of maximum extension of the following pulse. This would of course invalidate our assumption of the presence of the considered radionuclide at this evolutionary phase and, as a consequence, make the calculations reported in the previous sections meaningless. In fact, we have performed some numerical tests which suggest that the IS-produced ^{205}Pb , even if transformed into ^{205}Tl after the IS neutron-production episode and before the end of the interpulse phase, could be fully replenished at an early stage of the following pulse growth by the fast $^{205}\text{Tl} (\beta^-) ^{205}\text{Pb}$ transformation taking place at the high temperatures encountered in the bottom layers of the convective pulse. In such conditions, the situation would be essentially the same as the one considered in this work, with ^{205}Pb uniformly distributed in the pulse at its maximum extent. Of course, more definite conclusions have to await the construction of detailed models leading to a pure IS production of ^{205}Pb ;
- (ii) in the CPS or IS+CPS scenarios encountered in this work, our ignorance of the precise mass location of the primary ^{13}C responsible for the neutron release is not likely to influence the

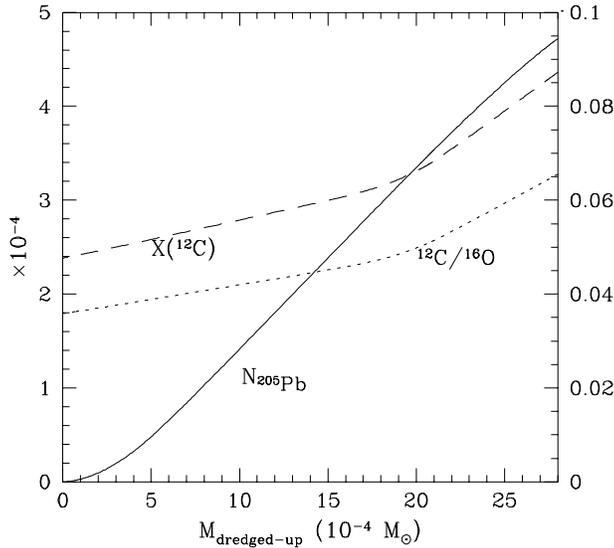


Fig. 9. Number density of ^{205}Pb and ^{12}C mass fraction (to be read on the left-hand ordinate) and $^{12}\text{C}/^{16}\text{O}$ ratio (to be read on the right-hand ordinate) at the surface of the M6Z02 star 40 y after its pulse 13 (see Fig. 6) as a function of the parametrized depth of the 3DUP within the ^{12}C -rich region left over by pulse 13. Note that hot bottom burning at the base of the envelope is responsible for the low ^{12}C abundance prior to the 3DUP

Table 2. Percentage $f_{\text{Pb},\text{surv}}^{\text{env}}$ of ^{205}Pb in the envelope which survives the interpulse of the given star. T_{be} is the approximate temperature (in 10^6 K) at the bottom of the envelopes, and t_{inter} the duration (in y) of the interpulse. The last column gives an estimate of the mass-averaged ^{205}Pb e^- -capture lifetime (in y) in the envelope.

case	interpulse	T_{be}	t_{inter}	$f_{\text{Pb},\text{surv}}^{\text{env}}$	τ_e
M3Z02	12-13	~ 5	~ 76000	100	$1.2 \cdot 10^7$
M6Z02	12-13	~ 80	~ 3000	99.4	$4.8 \cdot 10^5$
M3Z001	13-14	~ 30	~ 10700	93.3	$1.4 \cdot 10^5$

fraction of ^{205}Pb that can survive the thermal pulses. This results from the fact that the interpulse ^{13}C -loaded layers are efficiently mixed by the time of maximum extent of the next pulse;

(iii) in contrast, the fraction of surviving ^{205}Pb drastically depends on the specific conditions found in the intershell region during the afterpulse phase prior to the 3DUP;

(iv) the level of contamination of the stellar surface with ^{205}Pb is probably quite insensitive to the precise time of occurrence of the 3DUP. Indeed, Figs. 3(b), 5(b) and 7(b) reveal that, in regions where ^{205}Pb survives in large amounts, it reaches its equilibrium value on timescales of the order of the characteristic intershell thermal readjustment time, i.e. quite likely well before the occurrence of the 3DUP;

(v) the ^{205}Pb eventually dredged up to the surface would not be severely destroyed during the interpulse (Sect. 5.4).

Of course, the amount of ^{205}Pb finding its way to the stellar surface does depend on the depth of the 3DUP. Fig. 9 illustrates this dependence for the M6Z02 model displayed in Fig. 6. It is

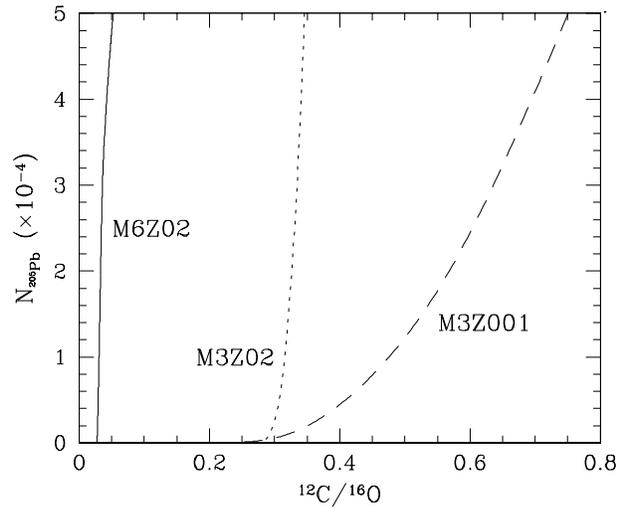


Fig. 10. Number density of ^{205}Pb as a function of the $^{12}\text{C}/^{16}\text{O}$ ratio at the surface of the three stars analysed in the text following the pulse indicated in Table 1. Each location on the curves corresponds to a given depth of the 3DUP, which is taken as a free parameter

also instructive to present the surviving ^{205}Pb at the stellar surface versus the surface $^{12}\text{C}/^{16}\text{O}$ abundance ratio. Fig. 10 shows this correlation after a single 3DUP following pulses 12, 13 and 14 in the M3Z02, M6Z02 and M3Z001, respectively. As in Fig. 9, the depth of the 3DUP is a free parameter. In addition, it is assumed that the stellar surface is free of ^{205}Pb before the considered 3DUP, while the ^{12}C and ^{16}O profiles are those provided by the models.

Fig. 10 demonstrates that substantial amounts of ^{205}Pb could pollute the stellar surface well before the considered stars become C-type stars, and that the ^{205}Pb amount increases much more dramatically with the increased depth of the 3DUP than the corresponding ^{12}C surface enrichment. Of course, it has to be stressed that the situation displayed in Fig. 10 is quite artificial, as the surface ^{12}C concentration most likely builds up progressively through successive, and possibly relatively shallow, 3DUPs. In $M \lesssim 3 M_{\odot}$ AGB stars, in which only very little ^{205}Pb survives in the outer layers of the intershell region, the succession of pulses could thus lead to an increase of the surface $^{12}\text{C}/^{16}\text{O}$ ratio without any associated ^{205}Pb enrichment.

7. Conclusions

This paper presents the first attempt to evaluate in a quantitative way the possibility of contamination with ^{205}Pb of the surface of thermally pulsing intermediate-mass AGB stars. We rely on detailed models of three different stars ($M = 3 M_{\odot}, Z = 0.02$; $M = 6 M_{\odot}, Z = 0.02$; $M = 3 M_{\odot}, Z = 0.001$), and on some simplifying assumptions concerning in particular the 3DUP characteristics, some of which (like its depth) being considered as free parameters. From the examination in each of the considered stars of a single pulse-interpulse cycle following a sequence of a dozen of pulses, we conclude that, during the afterpulse phase,

the ^{205}Pb destruction is prevented in the hottest ($T \gtrsim 10^8\text{K}$) parts of the intershell region. As a direct consequence, the chances for a significant ^{205}Pb surface enrichment are likely to increase with M for a given Z , and to increase with decreasing Z for a given M . More specifically, following the considered pulses at least, the enrichment appears to be rather unlikely in the $3 M_{\odot}$ star with $Z = 0.02$, while it seems to be much more probable in the other two considered stars. Of course, the older the AGB star (i.e. the larger the pulse number), the more ^{205}Pb is likely to survive during the afterpulse, as the temperatures in the intershell regions increase with the pulse number. It may thus be that the surface of a $3 M_{\odot}$ star of the M3Z02 type could be polluted with a significant ^{205}Pb amount at a more advanced stage of its AGB evolution, provided of course that the pulse sequence is not too drastically shortened by severe mass losses.

Quite clearly, the problem of the ^{205}Pb survival in AGB stars will have to be revisited more thoroughly once AGB models that predict self-consistently the development of the s-process and the occurrence of the third dredge-up become available. In such conditions, it will be meaningful to analyse in detail the surface ^{205}Pb enrichment resulting from a series of self-consistently computed pulse-interpulse cycles.

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