A BRIEF REVIEW OF THE S-PROCESS OF NUCLEOSYNTHESIS

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ABSTRACT. A brief overview is presented of the s-process of nucleosynthesis. Special emphasis is put on some of its nuclear physics aspects, and in particular on the uncertainties that still affect the rates of the $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ neutron producing reactions. We also briefly review the so-called "classical" s-process model, and put it in perspective with recent s-process calculations conducted in the framework of detailed models for massive stars or for thermally pulsing AGB stars.

1. Introduction

The synthesis of the stable nuclides heavier than iron is classically ascribed to three different stellar mechanisms referred to as the s-, r- and p-processes. The s-process is called for in order to explain those stable heavy nuclides located at the bottom of the valley of nuclear stability (s-nuclides), while the r- and p-processes have to account for the stable nuclides that are neutron-rich (r-nuclides) and neutron-deficient (p-nuclides), respectively.

The bulk solar-system abundances of the s-, r-, and p-nuclides are represented in Fig. 1. Those distributions exhibit some well known features, and in particular (i) well-developed s-nuclide abundance peaks at mass numbers A = 138 and 208, (ii) peaks in the r-nuclide distribution at A = 130 and 195, and (iii) p-nuclides that are 100-1000 times less abundant than the corresponding more neutron-rich isobars, while their distribution roughly parallels the s- and r-nuclei abundance curves (note, however, the very low abundances of the two odd-odd p-nuclides ^{138}La and ^{180}Ta, and the relatively large amounts of the ^{92}Mo and ^{94}Mo p-isotopes). Not represented in Fig. 1 are those heavy stable nuclides that can be produced in significant proportions by both the s- and r-processes (referred to as sr-nuclides). The distributions exhibited in Fig. 1 are used to separate their abundances into a s- and an r- component. Such a splitting, however, involves some uncertainty.

It has also been realized recently (essentially after 1973) that a minor fraction of the solar system material (mass $\leq 10^{-4}$ $M_\odot$) might have

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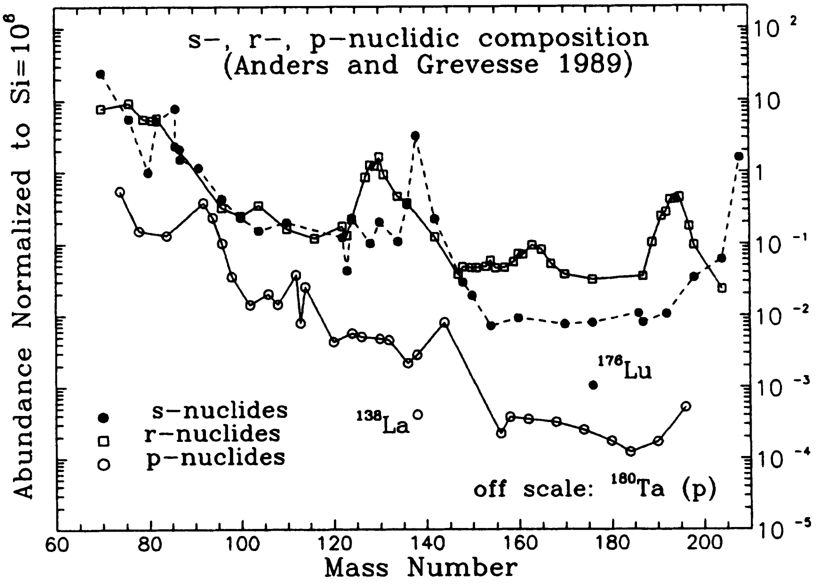

Fig. 1. The solar system abundances of the s-, r-, and p-nuclides. The sr-species for which the estimated s- or r-process contribution exceeds 10% are not represented.

an isotopic composition different from the bulk one, after due correction for the operation of the known mechanisms of isotopic fractionation.

The mounting evidence regarding the existence of those isotopic heterogeneities in the solar nebula just before the start of condensation of solids has far reaching consequences for many important astrophysical problems, and in particular for the modeling of the early solar system and for the evaluation of the last nucleosynthesis contributions to its material. It is in fact speculated that those "anomalies" might originate from a limited number of nearby or remote stars, particularly Asymptotic Giant Branch (AGB) stars, or exploding objects (novae, supernovae). This is in marked contrast to the situation envisioned for the bulk solar system material, which is made of the well mixed ashes of many nucleosynthetic events, and has to be interpreted in the framework of models for the chemical evolution of the Galaxy. Detailed discussions of the meteoritic isotopic anomalies and of their astrophysical and cosmochemical implications can be found in e.g. Wasserburg (1985), Anders (1987), or Arnould (1987), and need not be repeated here. Let us just emphasize that several anomalies are attributed to the s-, r- or p-processes, as reviewed recently by e.g. Lee (1988) (see also Ott et. al. 1988; Lewis et al. 1990; Ott and Begemann 1990).

The abundances of a variety of elements that are thought (from the analysis of the solar system bulk abundance distributions presented in

Fig. 1) to be produced mainly by the s-process or by the r-process have also been determined in stars of various metallicities and types (e.g. Lambert 1989; Smith 1989: Wheeler et al. 1989, for reviews). In contrast, no information is available concerning the p-nuclidic abundances outside the solar system.

Much effort has been devoted to the understanding of the very nature of the s-, r- and p-processes. In particular, many dedicated experimental and theoretical works have tried to provide the necessary nuclear physics input for the study of those heavy element build-up mechanisms, while stellar modeling has attempted to unravel the adequate astrophysical sites for the operation of those processes.

In spite of those efforts, it is fair to say that much remains to be done in order to gain a reliable picture of the s-, r- and p-processes, and of the observed abundances of the corresponding heavy nuclides in stars and in the solar system. It is beyond the scope of this paper to review all these problems in detail. Instead, we will limit ourselves to a brief overview of, and to some critical comments on the nuclear physics of the s-process (Sect. 3), on the so-called "classical" model (Sect. 4), and on the modeling of the s-nuclide build-up in realistic stellar models (Sect. 5). Further considerations about the s-process can be found in the reviews by Iben and Lambert (this Symposium), as well as in Käppeler et al. (1989) and in Arnould and Rayet (1990), where a brief overview of the r- and p-processes can also be found.

2. The s-Process: Some Generalities

The s-process results from the production of neutrons, and from their captures by preexisting ("seed") nuclei (most importantly iron, assumed to be produced in previous stellar generations) on time scales long compared with most β-decay lifetimes. This relative slowness of the neutron captures is at the origin of the identification of that process as the s-(for slow) process. In such conditions, a neutron capture path develops along which a β-unstable nucleus, once produced, has in general time to decay before capturing a neutron. For some nuclides, however, neutron captures can compete with β-decays. This leads to local "branches" along the main path. Even so, the s-process always flows very close to the bottom of the valley of nuclear stability, and "hits" on its way s- or sr- nuclides, while the r- and p-nuclei stay out of its reach. Typical s-process flow paths are obtained for neutron densities n_n in the approximate $10^7 \le n_n \le 10^9$ range.

One of the key questions raised by the s-process of course relates to the possibility of producing such neutron concentrations. It now appears that $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ are likely to be the most important neutron producing reactions in stars. Additional reactions, like $^{18}O(\alpha,n)^{21}Ne$, $^{21}Ne(\alpha,n)^{24}Mg$, $^{25,26}Mg(\alpha,n)^{28,29}Si$, or $^{16}O(^{16}O,n)^{31}Si$ have occasionally been considered as possible neutron producers. The other key aspect of the s-process modeling concerns the precise characterization of the astrophysical sites where the various neutron producing reactions can operate.

3. The Nuclear Physics Aspects of the s-Process

As stated above, a question of prime importance for the study of the s-process concerns the rate at which $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ can produce neutrons in stellar plasmas.

The situation concerning $^{13}C(\alpha,n)^{16}O$ has been discussed by Descouvemont (1987). Various experiments have been carried out at (c.m.) energies $E \gtrsim 350$ keV. These data have been extrapolated linearly (e.g. Caughlan and Fowler 1988) in order to provide the rate at lower energies that are of interest in astrophysical applications. A study relying on a microscopic model (Descouvemont 1987) raises instead the possibility of an increase of the astrophysical S-factor with decreasing energies as a result of the contribution from a state located 4 keV *below* the $\alpha+^{13}C$ reaction threshold. This leads to a stellar rate that is ≈2-3 times larger than the commonly accepted value (e.g. Caughlan and Fowler 1988) for the stellar temperatures $T \approx 10^8$-$2 x 10^8$ K at which $^{13}C(\alpha,n)^{16}O$ could operate during helium burning (see Sects. 4,5). At present, the conclusion of an increase of the S-factor with decreasing energies appears to be qualitatively reliable. Further work is, however, required in order to better evaluate the extent of that increase.

Even if the $^{13}C(\alpha,n)^{16}O$ rate is still somewhat uncertain at the energies of astrophysical interest, the situation concerning the rate of $^{22}Ne(\alpha,n)^{25}Mg$ is by far worse. In fact, the most recent analysis of this reaction (Wolke et al. 1989) provides lower and upper limits on that rate that differ by as much as a factor of ≈1000 at the temperatures ($T \approx 3.5 x 10^8$ K) that are generally considered as typical for the operation of $^{22}Ne(\alpha,n)^{25}Mg$. On top of that, the commonly used rate (Caughlan and Fowler 1988) for the $^{22}Ne(\alpha,\gamma)^{26}Mg$ channel is claimed by Wolke et al. (1989) to be underestimated by a factor of ≈5-50 at those same temperatures, so that the (α,γ) channel could be more probable than the (α,n) one. All in all, one is led to the conclusion that the nuclear physics uncertainties still affecting the $\alpha+^{22}Ne$ rates are so large that the efficiency and role of that neutron source cannot be established yet.

Another key nuclear physics input for the study of the s-process concerns the astrophysical rates of neutron captures by nuclides in the whole $12 \leq A \leq 209$ mass range. The situation in this respect has been discussed recently (Käppeler et al. 1989), and the reader is referred to that review for details[1]. Let us just stress here that most of the nuclides involved in the s-process neutron capture chain are β-stable, so that their ground-state neutron capture cross sections can be measured. However, some data of that type are still missing, while others remain, or have been until very recently, uncomfortably uncertain. In this respect, we want to emphasize the special and very important cases of the neutron captures by ^{12}C, ^{14}N and ^{22}Ne.

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[1] Some new experimental data have been obtained since the publication of the review by Käppeler et al. (1989), in particular with the Karlsruhe 4π BaF_2 detector (e.g. Wisshak et al. 1990)

The importance of $^{12}C(n,\gamma)^{13}C$ in some astrophysical scenarios has been stressed by Jorissen and Arnould (1986), and has been confirmed by further works (e.g. Hollowell and Iben 1990). While a mere 1/v extrapolation of the thermal cross section provides a value $<\sigma>_{30} \approx 0.003$ mb for the Maxwellian-averaged neutron capture cross section at a typical energy kT = 30 keV for the operation of the s-process (see Sects. 4,5), the value $<\sigma>_{30} = 0.2 \pm 0.4$ mb has been reported by Allen et al. (1971), and adopted in the recent compilation by Bao and Käppeler (1987). Quite unfortunately, some recent astrophysical s-process calculations have been conducted with $<\sigma>_{30} = 0.2$ mb. The blind adoption of that value without discussion of the effect of the reported 0.4 mb error bar on it is of course meaningless! The $^{12}C(n,\gamma)$ cross section has just been re-examined by Macklin (1990), who proposes $0.0032 \leq <\sigma>_{30} \leq 0.014$ mb. It is clearly of interest to investigate the case further, either experimentally or theoretically.

The $^{14}N(n,p)^{14}C$ or $^{14}N(n,\gamma)^{15}N$ reactions can also be of interest in some s-process models (Jorissen and Arnould 1986,1989). The cross section of the former reaction has been measured by Brehm et al. (1988), who claim a 30 keV value about 2.5 times smaller than the previously adopted value derived from extrapolation of the thermal data. This conclusion is questioned by Koehler and O'Brien (1989), who recommend the old value. This discrepancy has clearly to be understood. As far as $^{14}N(n,\gamma)$ is concerned, its $<\sigma>_{30}$ value is commonly derived from an extrapolation of the thermal data. This may lead to some uncertainty (Käppeler 1984).

Finally, let us mention that the saga of the $^{22}Ne(n,\gamma)^{23}Ne$ cross section appears at last to have come to an end! While $<\sigma>_{30} \approx 0.03$ mb was proposed by Fowler et al. (1967), Almeida and Käppeler (1983) measured $<\sigma>_{30} = 0.9 \pm 0.7$ mb. This revision led to a flurry of new s-process calculations that emphasized the role of ^{22}Ne not only as a neutron producer, but also as a neutron *poison*. This conclusion is largely invalidated by new measurements (Beer et al. 1989) leading to $<\sigma>_{30} = 0.060 \pm 0.005$ mb.

While further measurements of some neutron capture cross sections on stable nuclides still appear desirable, theoretical estimates will certainly remain for quite a while the only source of information for the vast majority of the neutron captures on radioactive isotopes involved in "branched" s-process models. In addition, model predictions are also required in order to evaluate the contribution of thermally populated excited states to the net stellar reaction rates (e.g. Arnould 1972, Thielemann et al. 1986). In the intermediate-mass range as well as for heavy nuclides, the necessary reaction rates can be calculated with the aid of a statistical model of the Hauser-Feshbach type. A global model of this kind that fits quite satisfactorily the neutron capture and other reaction data is described by Thielemann et al. (1986).

Beta-decay rates are the indispensable complement to the neutron capture rates in order to model the s-process, and in particular to describe in a proper way the various branchings that can develop along its path. In a stellar plasma, various mechanisms conspire to modify the laboratory lifetimes of unstable species, and even to make possible the decay of terrestrially stable nuclides. The effects of this type that can be of importance in s-process conditions have been studied with great care by Takahashi and Yokoi (1987), and are reviewed by Käppeler et al. (1989).

The problem of a proper evaluation of the stellar β-decay lifetimes and, to some extent, of the neutron capture rates as well is intimately related to the question of the thermal population of excited nuclear states in stellar plasmas. This problem is especially acute when dealing with isomeric states. Some isomers of importance for the s-process modeling and for its chronometry have been identified, and are reviewed by e.g. Käppeler et al. (1989).

In conclusion, a large body of nuclear physics input is required in order to model the s-process. Even if these nuclear data are, generally speaking, much more reliably known than those called for in the study of the r- and p-processes, various quite vexing uncertainties remain, and have to be eradicated by further experimental and theoretical effort.

4. The "Classical" s-Process Model

This model represents a purely phenomenological approach of the s-process that takes detailed account of the necessary nuclear physics input, but avoids any reference to specific astrophysical environments. In fact, the only astrophysical requirements are that neutrons have to be produced in amounts compatible with the definition and aim of the s-process (see Sect. 1), and that the s-process nuclear flow is just made of (n,γ) reactions and β-decays. In particular, (γ,n) photodisintegrations have to be slow enough to have negligible effects on the abundance patterns. This is equivalent to constraining the stellar temperatures to values lower than about 10^9 K.

In addition to those basic constraints, the classical model makes the following assumptions: (i) (n,p) and (n,α) reactions play no role, (ii) temperature, density and neutron concentration n_n are constant during the whole neutron irradiation period t_{irr}, and (iii) ^{56}Fe is the only initial seed for neutron captures, this assumption being justified by the large solar system ^{56}Fe abundance relative to all the other $A \gtrsim 50$ nuclides (e.g. Anders and Grevesse 1989). These simplifying assumptions make the s-process amenable to a purely analytical treatment, even when due account is taken of branches along the s-process path.

Apart from its simplicity, the classical s-process owes its success to its ability to reproduce quite satisfactorily the solar system s-nuclide abundance distribution (Fig. 1). As reviewed by e.g. Käppeler et al. (1989), this fit is obtained if different fractions of ^{56}Fe seeds are exposed to different neutron doses. In fact, at least two distinct s-process components, referred to as the "weak" and "main" components, are called for in order to account for the solar system s-nuclides in the $A \gtrsim 90$ and $90 \lesssim A \leq 204$ mass ranges, respectively. In addition, a "strong" component appears to be required in order to fit the $204 < A \leq 209$ abundances at best.

Another important conclusion of the many studies devoted to the classical s-process is that the main component is able to provide a good fit to the solar system abundances only if a distribution $\rho(\tau)$ of neutron exposures $\tau = \int n_n v_T dt$ (where v_T is the neutron thermal velocity) of the form

$$\rho(\tau) = [fN_{56}(0)/\tau_0]\exp(-\tau/\tau_0) \qquad (1)$$

is adopted, where the fraction f of irradiated seeds [with initial abundance $N_{56}(0)$] and τ_0 are free parameters. In such conditions, the s-process abundances can be expressed analytically as $N_s = F(f,\tau_0; n_n,T,t_{irr})$, where the n_n, T, and t_{irr} dependence results from the presence of branching points along the s-process path. Various sets of free parameters that best fit the $90 \lesssim A \leq 204$ solar system abundances have been proposed recently (Käppeler et al. 1989,1989a; Beer, 1990b). The latest best fit for the main component (Beer 1990b) predicts in particular $f = (0.063 \pm 0.004)\%$, $kT = (25 \pm 2)$ keV, $\tau_0(kT{=}25 \text{ keV}) = (0.276 \pm 0.0098)$ mb^{-1}, and $n_n = (2.0^{+1.4}_{-0.8})10^8$ cm^{-3}.

In contrast to the conclusions derived for the main component, the analyses conducted for the weak (Beer 1990b) and strong (Beer 1990a) components indicate that the best fits to the solar system data are not obtained with an exponential distribution of the form (1), but instead with a single neutron exposure. In this framework, Beer (1990b) obtains a best fit for the weak component with kT = 20 keV and $n_n = 1.8 \times 10^8$ cm^{-3}.

Most analyses of *stellar* s-element abundances have also been performed in the framework of the classical model. However, an unambiguous choice between a single neutron exposure and an exponential distribution of exposures is often prevented by the remaining abundance uncertainties. This is especially the case when dealing with chemically peculiar Red Giants (e.g. Jorissen 1990). In spite of this, some general tendencies can be identified. In particular, Ba and CH stars seem to exhibit quite a wide range of exposures (e.g. Jorissen 1990; Luck and Bond 1982). This is also the case for MS and S stars. In fact, the adoption of Eq. (1) for the neutron exposure distribution leads to $0.1 \lesssim \tau_0 \lesssim 1$ mb^{-1} for those objects, with some sign of clustering around the solar system main component value $\tau_0 \approx 0.3$ mb^{-1} (e.g. Smith 1989; Smith and Lambert 1990). It remains to be seen if this clustering has really far reaching implications. The answer to this question is made especially difficult in view of the uncertainties that remain in the calculation of the AGB s-process yields, as briefly discussed in Sect. 5.2.

5. The s-Process in "Real" Stars

The classical s-process model is generally considered to provide some kind of "effective" s-process conditions that have to be obtained either in a single star (in order to account for its surface abundance) or in a collection of stars of possibly different masses and metallicities (in order to account for the solar system abundances through a model for the chemical evolution of the Galaxy). It now remains to be seen if detailed stellar models can provide conditions compatible with the requirements of the classical model, or, much more modestly, to identify stellar sites where some s-processing has a chance to develop.

Various such studies have been conducted recently. It is clearly beyond the scope of this contribution to review all of them in detail. We will instead limit ourselves to some comments about the s-process studies in massive stars (Sect. 5.1) and in low- or intermediate-mass stars (Sect. 5.2).

5.1. The s-Process in Massive Stars

Several studies of the s-process during central He burning in massive stars of different masses and metallicities have been published recently (e.g. Prantzos et al. 1987, 1988, 1989; Langer et al. 1989). They demonstrate that the neutrons produced in those sites by ^{22}Ne(α,n)^{25}Mg could be responsible for a significant production of the A $\lesssim$ 90 s-process nuclides, while the heavier species cannot be synthesized substantially. This essentially results from the rather low density ($n_n \lesssim 3\times10^7$ cm^{-3}) of the produced neutrons.

Those computations suggest that central He burning in massive stars is a plausible site for the solar system weak s-process component identified by the classical model (Sect. 4). This identification is, however, not free from difficulties, as exemplified by the predicted ^{80}Kr overabundance that results from the calculated rather low neutron concentrations. It has also to be noted that the s-process calculations performed in the framework of detailed central He-burning stellar models predict s-process characteristics (especially neutron exposures) that differ significantly from those providing the best fit for the weak component in the classical model. The meaningfulness of a comparison between those two different approaches to the weak component has in fact to be questioned.

The neutron capture nucleosynthesis during central carbon burning and shell helium burning in massive stars has also been studied in the framework of detailed stellar models (Arcoragi et al. 1990). It is concluded that the s-process that can develop in such sites is so limited that it does not affect in any significant way the conclusions based on central He burning alone.

The effects of metallicity on the central He-burning s-process associated with the operation of ^{22}Ne(α,n)^{25}Mg in massive stars have been studied recently (Prantzos et al. 1989). This study emphasizes in particular that the efficiency of the s-process in such conditions results from a subtle balance between variations of the ^{22}Ne/^{56}Fe source to seed ratio and of the efficiency of the "primary" neutron poisons ^{12}C or ^{20}Ne during the galactic evolution. The competition between these two effects leads to an optimum s-process efficiency for metallicities that are ≈1%-10% solar. In order to complete this study, an examination of the efficiency of the ^{13}C(α,n)^{16}O neutron source versus metallicity remains to be performed in the framework of detailed stellar models.

Finally, let us mention that the suspected Ba (and possibly also Sr) overabundances claimed to exist in SN1987A (e.g. Hillebrandt and

Höflich 1989) have been studied by Prantzos et al. (1988). Their calculations rely on the operation of $^{22}Ne(\alpha,n)^{25}Mg$ during central He burning in a specific model for the SN1987A progenitor. Prantzos et al. (1988) predict some Ba overabundance, without, however, being able to account for the largest values compatible with the observations. If these large Ba overabundances are real and not an artifact of the photospheric models, then another neutron capture process had to be at work in the SN1987A progenitor. This could also be true for other massive stars.

5.2. The s-Process in Low- and Intermediate-mass Stars

This question has already been addresses by Iben and by Sackmann and Boothroyd at this Symposium, and the reader is referred to their contributions for details. Here, we limit ourselves to some brief comments and remarks on this subject.

Since the demonstration by Ulrich (1973) that successive and partly overlapping thermal pulses in AGB stars can provide in a natural way the exponential distribution of neutron exposures given by Eq. (1) (if indeed *neutrons can be generated during the pulses!*), much work has been devoted to the unraveling of the details of that neutron producing mechanism.

A decade ago, an impressive series of computations by Iben (e.g. this Symposium, or Iben and Renzini 1983, for reviews) set up a quite appealing picture: thermal pulses in intermediate-mass ($3 \lesssim M \lesssim 8\ M_\odot$) AGB stars can generate neutrons through $^{22}Ne(\alpha,n)^{25}Mg$, and synthesize s-nuclides in amounts that compare rather satisfactorily to the solar system s-process main component. In addition, that material was found to be transported to the stellar surface by the third dredge-up, this providing a natural explanation for the chemical peculiarities observed in certain classes of Red Giants. Through their winds, those objects could also be major agents for the galactic s-process enrichment.

Pessimism about this appealing picture grew, however, after the realization that it was far from obvious to observe counterparts of those theoretical intermediate-mass objects, or to identify stellar spectra with the ^{25}Mg excess expected from the operation of $^{22}Ne(\alpha,n)^{25}Mg$. Further stellar and s-process modeling brought some additional touch of pessimism about the ability of $^{22}Ne(\alpha,n)^{25}Mg$ in intermediate-mass stars to account for stellar chemical peculiarities and for the solar system main s-process component.

The $^{13}C(\alpha,n)^{16}O$ neutron source operating in low-mass AGB stars has recently become a viable contender through a series of modeling experiments (e.g. the reviews by Iben and by Sackmann and Boothroyd at this Symposium). However, it clearly appears that the efficiency of that source as well as the occurence of the dredge-up to the stellar surface of the possibly irradiated material depend on many aspects of a very complex physics, and that the predictions in that field remain a matter of warm debate and active research.

To make a long and complicated story short, let us just state that the observed enrichment of s-elements at the surface of chemically peculiar Red Giants remains a puzzle. It is also our opinion that any *detailed discussion* of the solar system main component (e.g. Käppeler et al. 1989a) or of s-process isotopic anomalies (e.g. Gallino et al. 1990) in terms of the $^{13}C(\alpha,n)^{16}O$ in low-mass AGB stars *is by far premature*. In fact, we consider it as meaningless to draw subtle conclusions from the consideration of a *single* pulse-interpulse model and of a series of *identical* pulse-interpulse episodes in a *single* model star. This is even more so if, for fitting purposes, key quantities, like the amount of ^{13}C burned during a pulse, are, after all, taken as free parameters, as done in some recent computations.

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