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Distributions of Neutron Exposures in AGB Stars and the Galaxy *

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Abstract Based on the s-process nucleosynthesis model with the ^{13}C$(\alpha, n)^{16}$O reaction occurring under radiative conditions in the interpulse phases, we investigate the characteristics of the distribution of neutron exposure in low-mass Asymptotic Giant Branch (AGB) stars. We introduce a new concept, the distribution of neutron exposures of the Galaxy (NEG), to study the chemical evolution characteristics of the Galaxy for s-process elements. Using a chemical evolution model of the Galaxy, we develop a model for the NEG and obtain the evolution results of the NEG in different epochs. The present results appear to reasonably reproduce the distribution of neutron exposures of the solar system (hereafter NES). The main component and the strong component in the NES are built up in different epochs. The strong component of the s-process is mainly synthesised in the low-mass and metal-poor AGB stars, and the main component is produced by the s-process in the low-mass AGB stars with higher metallicities.

Key words: Galaxy: evolution — stars: AGB and post-AGB— stars: abundances

1 INTRODUCTION

The dominant site of the slow neutron-capture process (s-process) is thought to be the Asymptotic Giant Branch (AGB) phase in low- and intermediate-mass stars $(0.8 \leq M(M_\odot) \leq 8.0)$, which can be investigated either through nucleosynthesis computations in stellar models (Straniero et al. 1995; Gallino et al. 1998) or by the phenomenological models, mostly by the so-called classical model (Käppeler et al. 1989; Busso et al. 1999). The classical s-process was first outlined by Burbidge et al. (1957). Many efforts have been made to explain the solar-system abundance of elements associated with the s-process. Clayton et al. (1961) showed that the solar system abundances of the s-only isotopes cannot be reproduced by a single irradiation of an iron seed. Because the solar-like system s-element composition was assumed to be the result of a superposition of different distributions of neutron exposures, a satisfactory solution was found by Seeger et al. (1965) assuming an exponential decreasing distribution of neutron exposures.

To describe completely the observed s-process abundance of the solar system, three components had to be invoked to give a good fit, a main component for the bulk of isotopes between $A = 90$ and 200, and additionally a weak and a strong component for the abundances of the isotopes below $A = 90$ and for the very high ^{208}Pb abundance at the termination of the s-process. Each of these components is expressed as

$$\rho(\tau) = \Big(\frac{f_i N_{56}(0)}{\tau_0}\Big) \exp(-\tau/\tau_0), \tag{1}$$

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where f_i is the initial solar fraction of ^{56}Fe that has been irradiated, τ means the time-integrated neutron flux ($\tau = \int_0^t N_\mathrm{n} v_\mathrm{T} dt'$, where N_n is the neutron density and v_T is the mean thermal velocity) and τ_0 is the mean neutron exposure. These three components will be distinguished by indices 1, 2 and 3, in the parameters f_i and $\tau_{0,i}$. The current understanding of the s-process is supported by many observational and theoretical works (Clayton & Rassbach 1967; Clayton & ward 1974; Käppeler et al. 1982; Beer & Macklin 1985).

Ulrich (1973) showed that an exponential distribution of exposures follows naturally from repeated He-shell flashes during the AGB phase. If $\Delta\tau$ is the neutron exposure per pulse, and if r denotes the overlap of the nth and the $(n-1)$th convective shell, then after n pulses the fraction of material having experienced an exposure $\tau = n\Delta\tau$ is $\sim r^n \equiv \exp(-\tau/\tau_0)$, where $\tau_0 = -\Delta\tau/\ln r$ is the mean neutron exposure. During the AGB evolution, stars experience enough helium shell flashes to establish an exponential distribution. There, the s-process was assumed to occur in convective thermal pulses, the classical analysis was considered to yield "effective" conditions characterizing the stellar scenarios (Käppeler et al. 1990). In order to test the reliability of the classical model, Goriely (1997) developed a new s-process model based on the superposition of a large number of canonical astrophysical events, the abundance predictions of the multi-event model are in good agreement with those of the widely used exponential model.

The overabundances of elements heavier than iron observed at the surface of MS and S stars (Smith & Lambert 1990) clearly indicate that the s-process takes place during the AGB phase in the evolution of low- and intermediate-mass stars. Though the observations in the solar neighborhood exhibit a spread in the respective s-abundances, it is remarkable that the solar s-abundance distribution lies roughly at the center of the spread observed in MS and S stars (Busso et al. 1999), and most Galactic disk AGB stars in the mass range $1.5 \leq M(M_\odot) \leq 3.0$ can be considered as suitable sites for reproducing the main component. Recently, the knowledge of the last evolution stages of AGB stars was improved by a series of investigations originally based on the activation of the ^{13}C(α,n)^{16}O reaction in low-mass stars (Straniero et al. 1997; Gallino et al. 1998). According to the models, the ^{13}C neutron source is activated under radiative conditions during the intervals between successive He-shell burning episodes. The stellar models show that the distribution of neutron exposures is definitely non-exponential, and is actually very difficult to describe analytically (Arlandini et al. 1995; Zhang & Cui 2006). The mean physical conditions for producing the main component are found in AGB star models down to a metallicity slightly lower than $1/2Z_\odot$ by Gallino et al. (1998). In addition, Gallino et al. (1998) proposed that the strong component may be produced by low-mass AGB stars with low metallicities (Zhang & Cui 2006; Cui et al. 2007).

For the third dredge-up and the thermal pulse model, several important properties depend primarily on the core mass (Iben 1977; Groenewegen & de Jong 1993; Karakas et al. 2002). Taking account of the core-mass dependence relation and the initial-final mass relations of AGB stars (Zijlstra 2004), Cui & Zhang (2006) obtained the neutron exposure as a function of the initial mass and metallicity of AGB star, and such scatter of [Pb/hs] as found in metal-poor stars (see Straniero et al. 2006) can be explained naturally by varying the initial mass of the AGB stars. However, the solar system chemical composition is the result of a complex Galactic evolution mechanism, and depends upon the details of the stellar formation history, the initial mass functions, chemical yields, etc. Since the s-process distribution and the neutron exposure distribution vary strongly in TP-AGB stars with different metallicity (Busso et al. 1999; Travaglio et al. 1999; Raiteri et al. 1999; Du et al. 2003; Cui & Zhang 2006), a comparison with the solar distribution has to be complemented by the s-process distribution and the neutron exposure distribution of the TP-AGB stars with a fixed initial mass and metallicity. A quantitative understanding of the Galactic evolution of neutron exposure distribution has so far been a challenging problem. Although some of the basic tools of this task have been presented several years ago, the study of the solar-like system neutron exposure distribution was addressed in previous investigations only at a phenomenological level (Beer et al. 1997; Goriely 1997), the physical reasons of the assumptions made in the exponential model are seldom discussed. Because a large production of Pb derives from low-mass AGB stars with low metallicities, Gallino et al. (1998) introduced the idea that a separate astrophysical site for the strong component from the main component might be unnecessary. This expectation, however, must be substantiated with a detailed model for the Galactic enrichment to verify whether the production of strong component is really adequate.

In this work, we introduce a new concept, the distribution of neutron exposures of the Galaxy (NEG) $\rho_\mathrm{Gal}(t,\tau)$, to study the chemical evolution of the Galaxy for the s-process elements. This paper is organized as follows: in Section 2 we deduce the evolution equations of the NEG from the chemical evolution model; in Section 3 we discuss the distributions of neutron exposures in the AGB stars (hereafter the NEAGB); in Section 4 we show the model results for the NEG and compare them with those of two parameterized models, namely the multi-event model and the exponential model. Finally, in Section 5 we summarize the main conclusions.

2 THE NEG EQUATIONS: BASIC EQUATIONS

In the chemical evolution model there are four variables: the total mass of the system, M, the mass of 'gas' g, the mass existing in the form of stars (including compact remnants) s and the abundances X of the element(s) of interest, assuming certain initial conditions and laws governing the star formation rate (SFR) and the flow of material in and out of the system.

For the system mass, we have

$$M = g + s, \tag{2}$$

and

$$dM/dt = F - E, \tag{3}$$

where F is the rate of accretion of material from outside the system and E the rate of ejection by galactic wind.

The change rate of the mass of gas is governed by

$$dg/dt = F - E + e - \psi, \tag{4}$$

where ψ is the star formation rate (by mass) and e the ejection rate of matter from stars, and the change rate of mass of stars by

$$ds/dt = \psi - e, \tag{5}$$

where

$$e(t) = \int_{m_l(\tau_m=t)}^{m_U} (m - m_{\rm rem})\psi(t - \tau_m)\phi(m)dm, \tag{6}$$

where the integration is from $m_{l,\min} = 0.1$ to $m_U = 62\,M_\odot$ (Miller & Scalo 1979), $\phi(m)$ being the initial mass function (IMF) adopted from Miller & Scalo (1979) too, $m_{\rm rem}$, the remnant mass for a star of initial mass m that dies at an age τ_m. Assuming a homogeneous interstellar medium (ISM), the abundance of a stable element in the gas is governed by

$$\frac{d}{dt}(gX_i) = e_X - X_i\psi + X_F F - X_E E, \tag{7}$$

where the first term on the right represents the total amount of the element ejected from stars, the second, the loss to the ISM by star formation, the third, the addition from any of the element that may exist in inflowing material and the fourth, the loss by galactic wind (if any).

The term e_X is given by

$$e_X(t) = \int_{m_l(\tau_m=t)}^{m_U} [(m - m_{\rm rem})X_i(t - \tau_m) + m_i]\psi(t - \tau_m)\phi(m)dm, \tag{8}$$

where the first term in square brackets represents recycling without change in abundance and the second, fresh product by nuclear processes in stellar evolution followed by ejection. For a homogeneous galactic wind with $X_i = X_E$, we combine Equation (4) with Equation (7) and have

$$\frac{dX_i}{dt} + (X_i - X_F)\frac{F}{g} = \frac{e_X}{g} - X_i\frac{e}{g}. \tag{9}$$

In fact, the Galactic chemical composition is the result of a complex Galactic evolution, and depends on the details of the stellar formation history, the initial mass functions, chemical yields, etc. We define a new concept,namely the distribution of neutron exposures of the Galaxy, to study the chemical evolution of the Galaxy for s-process elements. Let $\rho_{\rm Gal}(t,\tau)d\tau$ represent the number of iron seed nuclei (per 10^{12} H atoms) that have received a neutron exposure between τ and $\tau + d\tau$ in the Galaxy before time t. The abundance of an s-process nucleus i at time t can be written as

$$N_i(t) = \frac{1}{\sigma_i} \int_0^{\infty} \Psi_i(\tau) \rho_{\rm Gal}(t, \tau) d\tau, \tag{10}$$

where $\Psi_i(\tau)$ is the solution of single exposure (see Clayton 1961). In addition, we define the distribution of neutron exposures of an AGB star as $\rho_{\rm AGB}(Z, \tau)$ (hereafter NEAGB). Then, the abundance of an s-process nucleus i in the AGB star with initial metallicity Z is given by an expression of the form

$$N_i^{'}(Z) = \frac{1}{\sigma_i} \int_0^{\infty} \Psi_i(\tau) \rho_{\rm AGB}(Z, \tau) d\tau. \tag{11}$$

Combining Equations (10) and (11) with Equation (9), the rate of the NEG can be written as

$$\frac{\rho_{\rm Gal}(t,\tau)}{dt} + [\rho_{\rm Gal}(t,\tau) - \rho_F(t,\tau)]\frac{F}{g} + \rho_{\rm Gal}(t,\tau)\frac{e}{g} = \frac{1}{g}\int_{m_l(\tau_m=t)}^{m_U} [(m - m_{\rm rem})\rho_{\rm Gal}(t-\tau_m,\tau) + m_{\rm Dup}\rho_{\rm AGB}(t-\tau_m,\tau)]\psi(t-\tau_m)\phi(m)dm. \tag{12}$$

Based on Equation (12), the NEG can be computed as a function of time up to the present epoch. Stars are born with an initial composition equal to that of the gas from which they formed. The formation of the Sun takes place at the epoch when the metallicity of the Galaxy is equal to that of the solar system ($Z_\odot$).

3 THE DISTRIBUTION OF NEUTRON EXPOSURE IN THE AGB STARS (NEAGB)

3.1 Convective He Burning Model (Case A)

There is a possibility of synthesis of s-process elements in the AGB stars, i.e., with nucleosynthesis taking place during thermal pulses (Aoki et al. 2001; Zhang et al. 2006). In this case, the neutron irradiation is derived primarily by the ^{13}C(α, n)^{16}O reaction, with a minor contribution from the marginal burning of ^{22}Ne. During the AGB evolution, stars experience enough helium shell flashes to establish an exponential distribution (Allen & Barbuy 2006)

$$\rho_{\rm AGB}(Z, \tau) = \frac{N_{56}(Z)}{\tau_0(Z)} \exp(-\tau/\tau_0(Z)). \tag{13}$$

The resulting pattern of AGB nucleosynthesis and its dependence on the initial metallicity of the star have been discussed by Gallino et al. (1999). Since the ^{13}C neutron source is primary, typical neutron density in the nucleosynthesis zone scales roughly as $1/Z^{0.6}$, from $Z_\odot$ down to $0.02Z_\odot$. At lower metallicities, the effect of the primary poison prevails (Gallino et al. 1999; Busso et al.1999).

3.2 Radiative ^{13}C Burning Model (Case B)

We adopt the 25th pulse computed by Gallino et al. (1998), corresponding to an initial mass $M = 3M_\odot$ at solar metallicity, as typical, and assume that all the pulses are identical. In fact, the overlap factor *r* at a given pulse is not very model dependent, being roughly the same in different authors once the other parameters (especially the core mass) are fixed (see Iben 1977; Gallino et al. 1998). However, in each model *r* actually changes from pulse to pulse as long as the core mass increases, and is slightly affected also by the initial metallicity. The major effects of neglecting small structural changes from one cycle to another are on the neutron density, $N_{\rm n}(t)$. Indeed, for a given amount of ^{13}C, $N_{\rm n}(t)$, which is strongly variable in time during an interpulse, has a maximum value determined by the rate of the ^{13}C(α, n)^{16}O reaction (Arlandini et al. 1999). Fortunately, the $N_{\rm n}(t)$ variations only affect the few nuclei that are strongly dependent on branchings in the s-process path, and since here we are interested mainly in the neutron exposure, which depends only on the average value of neutron density, we think that our simplified hypothesis of identical pulses is acceptable.

We first analyze the irradiation history of the $1 - r$ of fresh matter (He-shell-burning ashes with fresh Iron seed nuclei) that has moved from the envelope into the He intershell (the region between the H- and

He- burning shells) at the end of the nth thermal pulse. According to the s-process stellar models of Gallino et al. (1998, for schematic illustration see their fig. 7), among the $1 - r$ of fresh matter, $(1 - r)r$ can experience the $(n + 1)$th thermal pulse, but only $(1 - r)q$ (q is the mass fraction of ^{13}C pocket in the He intershell) can suffer the subsequent neutron irradiation in the q layer during the interpulse period under radiative conditions. That is to say, $(1 - r)r$ can be written as

$$\begin{aligned}(1 - r)r &= (1 - r)[(r - q) + q] \\ &= (1 - r)(r - q) + (1 - r)q,\end{aligned} \tag{14}$$

where the first and second terms in the right side of Equation (14) are the fractions of matter not irradiated and irradiated once, respectively. At the occurrence of the $(n + 1)$th convective instability, the irradiated $(1 - r)q$ and the unirradiated $(1 - r)(r - q)$ are all diluted over the whole intershell region. Then a faction r of the mixture, namely $(1 - r)r^2$ of original fresh matter goes on to experience the $(n + 2)$th cycle, with $(1 - r)rq$ being irradiated and $(1 - r)r(r - q)$ un-irradiated. Similar to the previous cycle, we can rewrite $(1 - r)r^2$ as

$$\begin{aligned}(1 - r)r^2 &= (1 - r)r[(r - q) + q] \\ &= (1 - r)[(r - q) + q]^2 \\ &= (1 - r)(r - q)^2 + 2(1 - r)(r - q)q + (1 - r)q^2.\end{aligned} \tag{15}$$

Thus among $(1 - r)r^2$ of original fresh matter, the part irradiated not at all is $(1 - r)(r - q)^2$, irradiated once is $2(1 - r)(r - q)q$ and twice, $(1 - r)q^2$. It is clear that the matter that has experienced a same number of pulses may have experienced irradiation at different of times. Among the aforementioned $(1 - r)$ of fresh matter, the part that can continuously experience m pulses is $(1 - r)r^m$. Based on the above discussion, $(1 - r)r^m$ can be rewritten as $(1 - r)[(r - q) + q]^m$. Expanding it using the binomial theorem, we obtain

$$(1 - r)[(r - q) + q]^m = \sum_{k=0}^{m} (1 - r)\frac{m!}{(m - k)!k!}(r - q)^{m-k}q^k, m = 0, 1, \cdots, m_f. \tag{16}$$

In the right side of Equation (16), each term and the power of its factor q just represent the fraction of matter and the corresponding number of irradiation times, respectively. That is because the s-process only occurs in the q layer for any cycle.

After a sufficient number of thermal pulses, the material of the He intershell is a mixture of materials that have experienced varying numbers of pulses. Collecting all the terms with the same number of irradiation times, k, in the above m_f+1 expansions, we obtain the total fractional number of Fe nuclei in the He intershell that has suffered irradiation k times in all after m_f pulses, $\frac{\Delta N(k)}{N_0}$(N_0 is the total number of Fe seed nuclei in the He intershell). The main neutron source allowing s-processing to take place in AGB stars is the reaction ^{13}C(α, n)^{16}O. Its activation requires penetration of a small amount of protons from the envelope into the He intershell during each third dredge-up event (repeated downward extensions of envelope convection). Studies on the required mixing mechanisms have made use of diffusive or hydrodynamical simulations. Although a consensus is emerging that partial mixing must indeed occur, there are still large uncertainties. The amount of ^{13}C that forms in a pocket at the top of the He intershell and its mass profile must be represented by free parameters (Busso et al. 2001). Since here we are interested mainly in the total distribution of neutron exposure in the AGB star, which, in general, depends weakly on the mass profile of ^{13}C, so in this work we suppose that the q layer contains a ^{13}C pocket of uniform composition and undergoes a fixed neutron exposure, $\Delta\tau$, per interpulse . Then the above $\frac{\Delta N(k)}{N_0}$ would be the fraction of Fe seed nuclei with exposure $k\Delta\tau$, namely,

$$\frac{\Delta N(k\Delta\tau)}{N_0} = \frac{\Delta N(k)}{N_0} = (1 - r)q^k \sum_{m=k}^{m_f} \frac{m!}{(m - k)!k!}(r - q)^{m-k}, k = 0, 1, \cdots, m_f. \tag{17}$$

When m_f is large enough, Equation (17) will give the discrete asymptotic distribution of neutron exposure in AGB star. In fact, in the first cycle a small difference of $\Delta\tau$ in the different zones of the q layer gives rise to a huge difference in the production factors of the s-process isotope. However, the ratio of the production factors between two selected zones is progressively smoothed in the subsequent thermal pulses. This smoothing effect is due to the repeated averaging of the s-process products by the thermal pulses, which dilute the s-enriched layers over a stellar zone that contains about 20 times more mass than the one in which neutrons are produced. Because of these extreme and repeated dilutions, even large variations in local details of the pocket have only small effects on the final distribution of the s-process elements (see Busso et al. 2001), hence on the distribution of neutron exposures.

We note that, when $q = r$, the right side of Equation (17) will become $(1 - r)r^k$, which gives the exponential exposure distribution according to the Ulrich mechanism of recurrent overlapping thermal pulses. From the analyses at the beginning of this section we can also find that, after m pulses, the total fraction of Fe seed nuclei in the He intershell that have both experienced k pulses and suffered irradiation episode at least once is $(1 - r)r^k - (1 - r)(r - q)^k$, which gives the result of Gallino et al. (1998).

Since in the case of radiative nucleosynthesis model, the seed nuclei in different layers of the q layer will receive different exposures after suffering one-time irradiation, the exposure distribution for those irradiated nuclei is a continuous function, and so it is for those nuclei irradiated any k times in all (in the case of convective nucleosynthesis model they are all δ functions). Considering the significance of such distributions, we define a new concept, namely multi-order distribution of neutron exposures. Let $\rho_k(\tau)d\tau$ represent the probability that an iron nucleus has received a neutron exposure between τ and $\tau + d\tau$, after experiencing irradiation episode k times, and $\rho_k(\tau)$ is called the "kth-order distribution of neutron exposures".

Actually, the first-order distribution of neutron exposures is derived from the ^{13}C abundance profile in the ^{13}C-pocket (see Gallino et al. 1998, figure 1), which can be roughly regarded as a two-region linear distribution. The neutron density $N_{\rm n}$ in each layer scales as the ^{13}C local abundance, i.e., the profile of the neutron exposure τ, when all ^{13}C has burnt, is about the same as that of the initial ^{13}C abundance, so we can regard the ordinate $X(^{13}\text{C})$ as τ, and have

$$\rho_1(\tau) = \frac{dM(\tau)}{M_q d\tau}, \tag{18}$$

where $dM(\tau)$ is the mass of matter that has received a neutron exposure τ, in the interval τ to $\tau + d\tau$ after one irradiation episode, and M_q is the mass of q layer (i.e. the ^{13}C-pocket). The calculated result is shown by curve 1 in Figure 1, where $\tau_{\rm max}$ represents the maximum value of neutron exposure achieved in each interpulse period. Because of the two line-like distributions of ^{13}C mass fraction in the q layer (see Gallino et al. 1998, figure 1), $\rho_1(\tau)$ consists of two uniform distributions. The Fe seeds with lower value of τ ($\tau < 0.5\tau_{\rm max}$) account for a relatively large percentage, and those with higher values of τ also account for a certain percentage. The first-order distribution of neutron exposures, $\rho_1(\tau)$, plays a fundamental role in the study of the exposure distribution in AGB stars (see following discussion). It is completely determined by the ^{13}C abundance profile in the ^{13}C-pocket.

We next calculate the multi-order distribution with $k \geq 2$. According to the model, the repeated occurrence of neutron source bursting causes the same distribution characteristics of neutron density in the q layer. So, during the second irradiation the probability that an iron nucleus can receive a neutron exposure τ_2, in the interval τ_2 to $\tau_2 + d\tau_2$ is $\rho_1(\tau_2)d\tau_2$. Since all the neutron irradiation episodes are independent, the probability that an iron nucleus can receive a neutron exposure between τ_1 and $\tau_1 + d\tau_1$ during the first irradiation, as well as an exposure between τ_2 and $\tau_2 + d\tau_2$ during the second one, is $\rho_1(\tau_1)\rho_1(\tau_2)d\tau_1 d\tau_2$, and the probability that an iron nucleus has received an accumulated exposure between τ and $\tau + d\tau$ after two irradiation episodes is,

$$\rho_2(\tau)d\tau = \iint_{\tau \leq \tau_1 + \tau_2 \leq \tau + d\tau} \rho_1(\tau_1)\rho_1(\tau_2)d\tau_1 d\tau_2. \tag{19}$$

For the same reason, the probability that an iron nucleus has received an accumulated exposure between τ and $\tau + d\tau$ after experiencing irradiation k times is,

$$\rho_k(\tau)d\tau = \int \cdots \int_{\tau \leq \tau_1 + \tau_2 + \cdots + \tau_k \leq \tau + d\tau} \rho_1(\tau_1)\rho_1(\tau_2)\cdots\rho_1(\tau_k)d\tau_1 d\tau_2 \cdots d\tau_k. \tag{20}$$

Equation (20) gives the formula for calculating the multi-order distribution of neutron exposures for $k \geq 2$. In practice the exact solution of the Equation (20) is difficult to evaluate for large k due to the multiple integral. Nevertheless, we can calculate the $\rho_k(\tau)$ using the Monte Carlo method. The calculated results of $\rho_k(\tau)$ for k between 2 and 10 inclusive are shown by the curves labelled 2 to 10 in Figure 1. The figure shows that all the multi-order distribution curves show a peak (the peak position of curve 1 is at the middle point of its first segment). As the irradiation time k increases, the maximum in the distribution moves to larger values of τ, while its height decreases and its width increases. In principle, using the Monte Carlo method we can obtain any kth-order distribution.

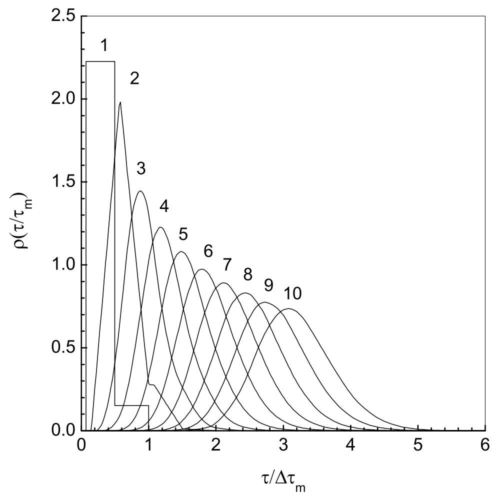

Fig. 1 Multi-order distribution of neutron exposures.

Generally, once $\frac{\Delta N(k)}{N_0}$, the total fraction number of seed nuclei in the He intershell that have suffered irradiation k times in all after m pulses, and $\rho_k(\tau)$, the kth-order distribution of neutron exposures, have been determined, the exposure distribution in the He intershell region of an AGB star can be calculated by

$$\rho_{\mathrm{AGB}}(\tau) = \sum_{k=1}^{m} \rho_k(\tau) \frac{\Delta N(k)}{N_0}. \tag{21}$$

There are four parameters in this model, i.e., the overlap factor r, the mass fraction q, the temperature T and the maximum of neutron exposure $\Delta\tau_{\max}$ in the q layer. Since in this paper we are particularly interested in the exposure distribution which can reproduce the solar s-abundance distribution, we adopt the ^{13}C abundance profile labelled "standard" (ST) by Gallino et al. (1998, see their figure 1). We take $r = 0.45$ and $q = 0.05$. Figure 2 shows the resulting asymptotic distribution of exposures in the ^{13}C burning scenario. As Figure 2 shows, even in the above simplified scenario, the distribution of neutron exposures is much more complex than the usually exponential form.

4 EVOLUTION OF THE NEG

4.1 Input Quantities

Instantaneous recycling cannot be used to describe the formation of elements, such as the s-process elements, to which there is a significant contribution from stars that take a non-negligible time to complete the evolution, so that any analytic solution of Equation (12) is not possible. We adopted the chemical evolution model developed by Pagel & Tautvaišienė (1995) for the disc of the Galaxy assuming no Galactic wind (i.e. $E = 0$) and the inflowing material to be unprocessed ($X_F = 0$, i.e. $\rho_F(t, \tau) = 0$). We adopt the forms of basic functions of the model, such as $F(t)$, $g(t)$, $\psi(t)$ and so on, given by Pagel & Tautvaišienė (1995). In the present work we concentrate on the influence of the initial metallicity of low-mass AGB stars on the NEG. More massive AGB stars, in the range $4 - 8M_{\odot}$, do not give a relevant contribution to the main and strong components (see Travaglio et al. 1999).

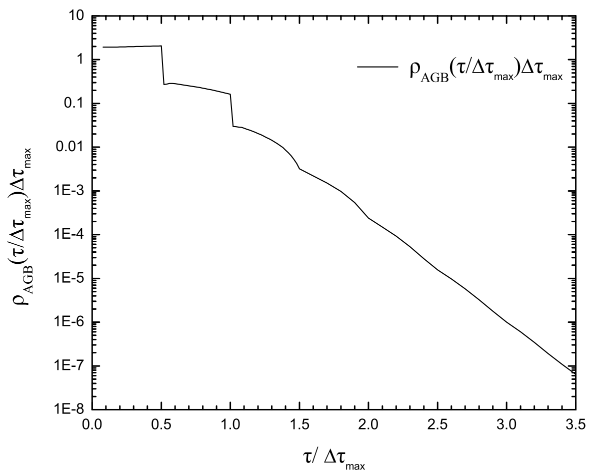

Fig. 2 Distribution of neutron exposures inside a low-mass AGB star that can reproduce the main s-component in a solar-like system, according to the radiative nucleosynthesis model of Gallino et al.(1998).

At the end of the TP-AGB phase, the s-process contributions to the ISM are determined by the amount of matter cumulatively dredged-up from the He shell to the surface and lost by stellar winds. For simplicity, in all cases the total mass dredged up into the envelope of the low-mass AGB stars is taken to be $M_{\rm Dup} = 10^{-2}M_\odot$ (Busso et al. 1992), independent of the initial stellar mass. The remnant masses are taken from Iben & Renzini (1983), and the stellar lifetimes from Larson (1974).

Gallino et al. (1998) have pointed out that the neutron density is relatively low, reaching $\sim 10^{\,7}\,{\rm cm}^{-3}$ in the q layer at $Z_\odot$ and the thermal energy $kT = 8\,$keV. For convenience of comparing with others' results, we take the thermal energy as $kT = 30\,$keV both in Case A and in Case B. We choose $\tau_0 = 0.296(kT/30)^{1/2}{\rm mb}^{-1}$ (Arlandini et al.1999) for $3MZ_\odot$ AGB stars with [Fe/H] $= -0.3$ in Case A, which corresponds to a mean neutron exposure of the solar-like system. According to Gallino et al.'s (1998) standard ^{13}C profile, we take the maximum neutron exposure $\Delta\tau_{\rm max} = 1.79(kT/30)^{1/2}{\rm mb}^{-1}$ for the $3MZ_\odot$ AGB stars with [Fe/H]$= -0.3$ in Case B. For other metallicities, we use the neutron exposure as a function of the initial mass and metallicity of AGB stars for Case A and Case B presented by Cui & Zhang (2006).

4.2 Results and Discussion

In Figures 3 and 4, we present our calculated results of the evolution of the NEG as a function of neutron exposures (τ) for Case A and Case B. The solid lines show respectively the resulting NEG at $Z = 1/30$, $1/15, 1/5, 1/3, 1/2$ and 1 $Z_\odot$. The [Fe/H] scale here is indicative of a time scale, albeit a non-linear one. It is evident from Figures 3a and 4a that there is a strong dependence of the NEG on the metallicity (or time t) of the Galaxy, and we can also derive that the s-process contribution becomes important starting from [Fe/H] $= -1.5$. At lower values of [Fe/H], the contribution of s-process nucleosynthesis rapidly decreases due to the strong dependence of stellar yields on metallicity. The low-mass and metal-poor AGB stars are the dominant contributors for the larger neutron exposures of the NEG with a complex dependence on metallicity, and a maximum efficiency is achieved at [Fe/H] $= -1.0$ or so for the strong component. With their increasing metallicities, the low-mass AGB stars become the dominant producers of lower neutron exposures of the NEG, with a maximum efficiency at [Fe/H]$= -0.6$. We also compare, respectively in Figures 3b and 4b, our results with the previous studies by Beer et al. (1997), obtained with the so called classical approach and the results obtained by Goriely (1997) with the mult-events model. Note that our results are in good agreement with both of these.

Our calculations succeed in reproducing the strong component of the solar system, due to the large role played by the larger neutron exposures in low-mass and low-metallicity AGB stars. Despite the large

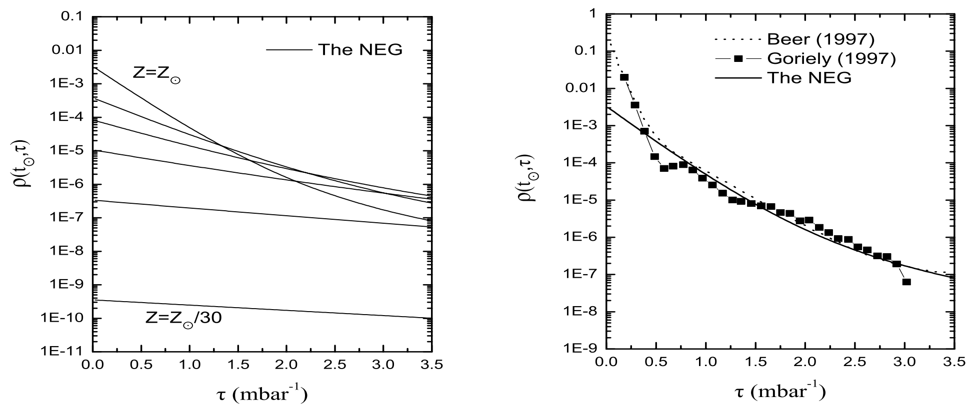

Fig. 3 Evolution of the NEG as a function of neutron exposure (τ) for Case A. Left (3a): Solid lines show respectively the resulting NEG at $Z = 1/30$,$1/15$,$1/5$,$1/3$,$1/2$ and 1 $Z_{\odot}$. Right (3b): NEG at $Z = Z_{\odot}$. The analytical exposure distribution predicted by the exponential model of Beer et al. (1997) and the exposure distribution predicted by the canonical multi-event s-process model of Goriely (1997) are also shown for comparison.

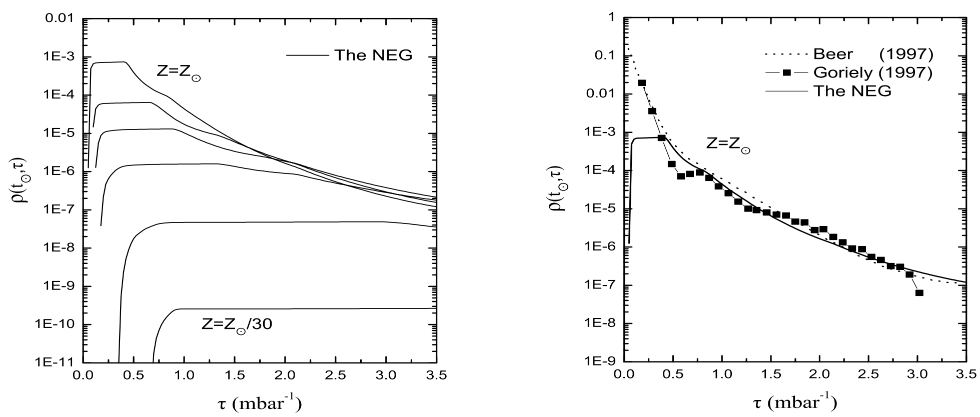

Fig. 4 Same as Figure 3, but for Case B.

number of approximations (the total amount of dredged-up material, the parametrization on the ^{13}C pocket and the dependence on the initial mass of low-mass AGB stars for the s-process nucleosynthesis, etc.), the present results appear to reasonably reproduce the main component and the strong component of the NES. The agreement of the model results with the NES provides a strong support for the validity of the evolution equations of the NEG and the NEAGB prescriptions adopted in this work. In turn, the NEG obtained from our model at various metallicities can be used to determine the distribution characters of s-process element abundances at earlier Galactic epochs. From Figures 3b and 4b, we can see that the NEG are slightly overestimated as compared to the results given by Beer et al. (1997) for the lower neutron exposures. The origin of the discrepancies might be attributed to specific characteristics of the Galactic evolution model (e.g. the age-metallicity relation). The uncertainty in this evaluation may depend on the set of prescriptions adopted when estimating the s-process yields from the AGB stars with varying the metallicity and on the general prescriptions adopted in the Galactic chemical evolution model.

Further, from the solutions of the NEG, we can obtain the total number of iron seed nuclei which have been irradiated in all AGB stars in the Galaxy before evolution time t (see Fig. 5). Beer et al. (1997) defined

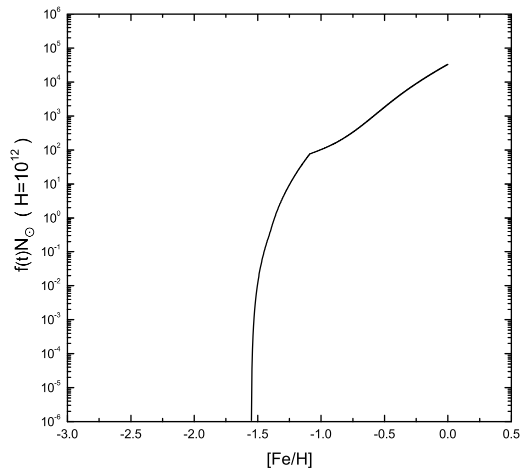

Fig. 5 Derived from Case A, $f(t)N_\odot$ as a function of metallicity.

a seed abundance that is proportional to the solar abundances $N_\odot$, i.e. $fN_\odot$, where f is the fraction of solar seed abundances. In this work, we extend f to $f(t)$, corresponding to different epochs of the Galaxy. In Figure 5 we present Case A's calculation results for the evolution of the $f(t)N_\odot$ as a function of the metallicity. The value of $f(t)N_\odot$ that we predicted for the NES is close to the usually used one by Beer et al. (1997). It is evident from Figure 5 that the contributions of the s-process become important starting from [Fe/H] $= -1.5$, which is agrees very well with the evolution of Ba predicted by Travaglio et al. (1999, see their figure 4).

5 CONCLUSIONS

We studied the evolution of NEG in the interstellar gas of the Galaxy, adopting a new NEAGB for s-process in AGB stars with different metallicities and initial masses. We calculated the NEAGB based on AGB models and applied these NEAGB in the framework of a Galactic model. Taking into account the important role played by different generations of low-metallicity AGB stars for the production of the higher neutron exposure in the Galaxy, both the main and strong components of solar system are matched by our model results with $Z = Z_\odot$.

The new neutron exposure distribution presented is in relatively good agreement with the exponential model and the multi-event s-process model predictions. This indicates that the exposure distribution in the solar system can be interpreted by the Galactic evolution theory and the distribution for the low-mass TP-AGB stars with different metallicities. Theoretically, a fixed s-process pattern should correspond to a fixed neutron exposure distribution. Some deviations between the new neutron exposure distribution and the exponential model are unavoidable since s-process events are thought to take place at different temperatures and n_n. From a comparison of the best fit by the classical analysis to the main component and the strong component by Beer et al. (1997) with the outcome of our NEG, one can obtain a clear indication that neither a unique AGB stellar model, nor the classical analysis, can explain the main and strong component in the solar system, which must be considered as the outcome of different generations of AGB stars prior to the formation of the solar system. As a matter of fact, our NEG calculations confirm in a quantitative way what was anticipated by Gallino et al. (1998), i.e., that the role previously attributed to the strong component is actually played by low-mass AGB stars with low metallicities. It is evident that the s-process contribution dominates the Galaxy chemical evolution of the strong component starting from [Fe/H]= –1.5 and the main component starting from [Fe/H]= –1.0, respectively. At lower values of [Fe/H], independent of the characteristics of the Galaxy chemical evolution model, the contribution of s-process nucleosynthesis rapidly decreases as a result of the long lifetimes of low-mass AGB stars. This confirms the previous results of the Galaxy chemical evolution for elements from Ba to Eu (Travaglio et al. 1999; Zhang et al. 2002) and Pb (Travaglio et al. 2001).

The neutron exposure distribution of the Galaxy presented in the present paper is therefore believed to be an interesting tool to study the s-process abundance distributions in the Galaxy at different metallicities and the Galactic chemical evolution of the neutron-capture elements. It presents new features in comparison with the exponential model. Hopefully, the new distribution can help us to improve our understanding of the exposure distribution in the solar-like system and open new perspectives in this topic.

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