The origin of the lead-rich stars in Galactic halo: investigation of the model parameters for the s-process

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1 INTRODUCTION

The elements heavier than the iron peak are made through neutron capture via two principal processes: the r-process (for rapid process) and the s-process (for slow neutron capture process) \cite{Burbidge1957}. The observations have confirmed that, indeed, Asymptotic Giant Branch (AGB) stars show overabundances of elements heavier than iron at their surface \cite{Smith1990}, which clearly indicate that the s-process takes place during the AGB phase in the evolution of low- and intermediate-mass stars \cite{Thielemers1989}. Low-mass AGB stars are usually thought as the main nuclear production site of the s-process elements \cite{Gallino1998, Lugaro2003, Herwig2004}. By now, the generally favoured s-process model is associated with the partial mixing of protons (PMP) into the radiative C-rich layers during thermal pulses \cite{Straniero1995, Gallino1998, Lugaro2003, Herwig2004}. PMP activates the chain of reactions \[ ^{12}\text{C}(p,\gamma)^{13}\text{N}(\beta)^{13}\text{C}(\alpha,n)^{16}\text{O} \] which likely occurs in a narrow mass region of the He intershell (i.e. \[ ^{13}\text{C}-\text{pocket} \]) during the interpulse phases of an AGB star. The s-elements thus produced in the deep interior by successive neutron captures are subsequently brought to the surface by the third dredge-up. Using the primary-like neutron source \[ ^{13}\text{C}(\alpha,n)^{16}\text{O} \] and starting with a very low initial metallicity, most iron seeds are converted into \[ ^{208}\text{Pb} \]. When the third dredge-up episodes mix the neutron capture products into the envelope, the star will appear s-enhanced and lead-rich. If the standard PMP scenario holds, all s-process-enriched AGB stars with metallicities \[ \text{[Fe/H]} \leq -1.3 \] are thus predicted to be lead(Pb) stars \[ \text{[Pb/hs]} \geq 1 \], where hs denotes the 'heavy' s-process elements such as Ba, La, Ce, independently of their initial mass and metallicity \cite{Gallino1998, Goriely2006, Gorlely2001}.

The first three such lead stars (HD187861, HD224959, HD196944), have been later confirmed by \cite{VanEck2001}. At the same time, \cite{Aoki2001} found that the slightly more metal-deficient stars LP 625-44 and LP 706-7 are enriched in s-elements, but cannot be considered as lead stars \[ \text{([Pb/Ce]<0.4)} \], in disagreement with the standard PMP predictions. Recently, more spectroscopic data of s-rich and lead-rich stars are reported \cite{Aoki2002, Cohen2003, Lucatello2003, VanEck2003, Johnson2002, 2004, Sivarani2004}. The large observation data spreads of \[ \text{[Pb/hs]} \] are strong indication to suspect a large intrinsic spread of integrated neutron irradiations. In order to explain the spreads of \[ \text{[Pb/hs]} \], a large spread of \[ ^{13}\text{C}-\text{pocket} \] efficiencies is subsequently proposed by \cite{Straniero2004}. However, it should be stressed here that the predictions of the standard PMP scenario are rather robust \cite{Goriely2006}. In the framework of the PMP scenario, there is no obvious degree of freedom that could be used to reduce the lead production in low-metallicity AGB stars \cite{VanEck2003}. At present, the physical explanation for the different \[ ^{13}\text{C}-\text{pocket} \] strengths, which perhaps should not be consistent with the primary nature of the neutron source, is not yet found \cite{Reyniers2004}. Thus the

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*\[ \text{[X/Y]} = \log(N_X/N_Y) - \log(N_X/N_Y)_{\odot} \], \( \odot \) refers to the Solar System abundances.
fundamental problems, such as the formation and the consistency of the \(^{13}\text{C}\)-pocket, the neutron exposure signature in the interpulse period, currently exist in the models of AGB stars.

For the third dredge-up and the thermal pulse model, several important properties depend primarily on the core mass \(M_c\), while the dependence on the other stellar parameters is negligible or marginal (Iben 1977; Groenewegen & de Jong 1993; Karakas et al. 2002). Zijlstra (2004) reported that the initial-final-mass relation steepens at low metallicity, due to low mass-loss efficiency. This may cause the degenerate cores of low-\(Z\), high-mass AGB stars to reach the Chandresekhar mass, leading to an Iben & Renzini-type-1.5 supernova (Iben & Renzini 1983). On the other hand, this can obviously affect model parameters of the AGB stars, e.g. the overlap factor \(r\), which is the fraction of material that remains to experience subsequent neutron exposures, and the neutron irradiation time \(\Delta t\), in particular at low metallicity.

In this paper we will present a calculation which indicates that at low metallicity, large core mass of AGB stars may allow the overlap factor and the duration of neutron irradiation to reach small values for a fixed initial mass of AGB stars. This will affect the characters of the \(s\)-process nucleosynthesis, and can explain the observed abundance pattern of lead-rich stars. The next section discusses the model parameters of AGB stars. In section 3, we discuss the characteristics of the \(s\)-process at low metallicity and the possibility of lead stars. Finally, in section 4 we summarize the main conclusion that can be drawn from such an analysis.

# 2 MODEL PARAMETERS OF AGB STARS

There are four parameters in the parametric model of Howard et al. (1986) on \(s\)-process nucleosynthesis. They are the neutron irradiation time \(\Delta t\), the neutron number density \(N_n\), the temperature \(T_9\) (in units of \(10^9\) K) at the onset of the \(s\)-process, and the overlap factor \(r\). Combining these quantities, we can obtain the neutron exposure, \(\Delta \tau = N_n v_T \Delta t\), where \(v_T\) is the average thermal velocity of neutrons at \(T_9\). The temperature is fixed at a reasonable value for the \(^{13}\text{C}(\alpha,\text{n})\text{N}\) reaction, \(T_9=0.1\), for these studies.

Using the initial-final mass relations as functions of metallicity presented by Zijlstra (2004), the effects on the parameters can be derived.

## 2.1 The overlap factor

For the AGB model, the overlap factor \(r\) is a fundamental parameter. An analytical formula was given by Iben (1977) as a function of the core mass \(M_c\) in the range \(0.6 \leq M_c \leq 1.36\):

\[
r = 0.43 - 0.795(M_c - 0.96) + 0.346(M_c - 0.96)^2,
\]

We can obtain an initial-final mass relation as a function of metallicity, by fitting results of Zijlstra (2004):

\[
M_c = A(Z) + B(Z)M,
\]

where

\[
A(Z) = 0.46449 + 0.03279\log \frac{Z}{Z_{\odot}} + 0.00044(\log \frac{Z}{Z_{\odot}})^2,
\]

and

\[
B(Z) = 0.08729 - 0.04851\log \frac{Z}{Z_{\odot}} + 0.00468(\log \frac{Z}{Z_{\odot}})^2,
\]

which is valid for \(4 \leq \log \frac{Z}{Z_{\odot}} \leq 0\). Combing the equations (1), (2), (3) and (4), we obtain the overlap factor as a function of the initial mass and metallicity. The overlap factor is shown in Fig. 1.

![Figure 1. The overlap factor of different initial mass AGB stars, as function of metallicity.](image)

which is significantly small at low metallicities, especially for \(3M_{\odot}\) AGB stars. In AGB stars with initial mass in the range \(M = 1.5 \sim 3.0M_{\odot}\), the core mass \(M_c\) lies between 0.6 and 1.4\(M_{\odot}\) at \([\text{Fe/H}] = -2.5\). According to the equation (1), the corresponding values of \(r\) will range between 0.8 and 0.13. Gallino et al. (1998) have found an overlap factor of \(r \approx 0.4 \sim 0.7\) in their standard evolution model of low-mass AGB stars at solar metallicity, which lies in our predicted range of \(r\) [Aoki et al. (2001) have reported an overlap factor of \(r \sim 0.1\), found for the best fit to metal-deficient AGB stars that produced the abundance patterns of LP 625-44 and LP 706-7. In an evolution model of AGB stars, a small \(r\) may be realized if the third dredge-up is deep enough for \(s\)-processed material to be diluted by extensive admixture of unprocessed material. Karakas et al. (2002) have found that the third dredge-up is more efficient for the AGB stars with larger core mass. Taking account of the core-mass dependence, the wide range of \(r\)-values of the lead enhanced stars can be explained naturally by the wide range of core-mass values of AGB stars at low metallicity.

## 2.2 The neutron exposure

Gallino et al. (1998) have pointed out that the neutron density is relatively low, reaching \(\sim 10^7\) cm\(^{-3}\) at solar metallicity. Since the \(^{13}\text{C}\) neutron source is of primary nature, the typical neutron density in the nucleosynthesis zone scales roughly as \(1/Z_{\odot}^{0.9}\), from \(Z_{\odot}\) down to 1/50\(Z_{\odot}\). At lower metallicities, the effect of the primary poison prevails (Gallino et al. 1998; Busso et al. 1999).

There is a possibility for the synthesis of \(s\)-process elements in the AGB stars, i.e., with nucleosynthesis taking place during thermal pulses (Aoki et al. 2001). In this case, the neutron irradiation is derived primarily by the \(^{13}\text{C}(\alpha,\text{n})\text{N}\) reaction, with a minor contribution from the marginal burning of \(^{22}\text{Ne}\).

However, in the \(s\)-process scenario that invokes radiative \(^{13}\text{C}\)-burning, the nucleosynthesis mostly occurs during the relatively long interpulse period, in a thin radiative layer at the top of the He intershell (i.e., the \(^{13}\text{C}\)-pocket model). A second neutron burst giving rise to a small neutron exposure is released by the marginal activation of the \(^{22}\text{Ne}\) neutron source in the convective thermal pulse. The neutron irradiation time \(\Delta t\) should be close to the interpulse period at low metallicity due to the combination of two reasons. The first is that the higher neutron density can lead to
longer neutron irradiation time, and the second is that the shorter interpulse period is expected for larger core-mass of AGB stars (Groenewegen & de Jong 1993). Therefore, adopting the interpulse period as the neutron irradiation time will have a smaller effect on the low-metallicity stars of interest here than that on stars of solar metallicity.

In our calculation, the neutron irradiation time $\Delta t$ is adopted respectively as follows:

Case A: the duration of the thermal pulse, where the core-mass-duration of the convective shell relation is adopted from Iben (1973).

Case B: the interpulse period, where the core-mass-interpulse period relation is adopted from Boothroyd & Sackmann (1988).

We choose respectively $\Delta \tau=0.08\text{mb}^{-1}$ at $[\text{Fe/H}]=-0.3$ in case A, which corresponds to a mean neutron exposure $\tau_0=0.296(T_0/0.348)^{1/2}\text{mb}^{-1}$, and $\Delta \tau=0.2\text{mb}^{-1}$ for $3M_\odot$ AGB stars with solar metallicity in case B (Gallino et al. 1998). Using the initial-final mass relations given by Zijlstra (2004) and the neutron irradiation time $\Delta t$, we can obtain the neutron exposure $\Delta \tau$ as a function of metallicity and initial mass (see Fig.2). The trend shown in Fig.2 (Case A and Case B) can be understood as follows: $\Delta \tau$ is proportional to the neutron number density $N_n$, and the neutron irradiation time $\Delta t$, where $N_n$ is expected to increase with declining metallicity. However, $\Delta \tau$ declines with declining metallicity due to the increasing of stellar core mass, which directly leads to a decline of $\Delta \tau$ at very low metallicity, especially for $3M_\odot$ AGB stars.

Based on the primary nature of the $^{13}$C neutron source, the value of $\Delta \tau$ will reach about $6.3\times10^{-4}\text{mb}^{-1}$ around $[\text{Fe/H}]=-2.5$ for the case of radiative $^{13}$C-burning (Gallino et al. 1995). Our result of case B for the $1.5M_\odot$ AGB stars is close to the above value. Because the neutron irradiation time $\Delta t$ is shorter for the larger AGB stars, the neutron exposure $\Delta \tau$ should be smaller too. Aoki et al. (2001) have reported a neutron exposure, $\Delta \tau \sim 0.7\text{mb}^{-1}$ for metal-deficient stars LP 625-44 and LP 706-7, which is in the range of our calculated results for the both cases. The results shown in Fig. 2 imply that the wide range of $\Delta \tau$ can be obtained naturally by considering the dependence of the irradiation time on the core mass. Since the Pb abundance is very sensitive to the neutron exposure (Gallino et al. 2003; Lugano et al. 2003), large variations of the $[\text{Pb}/\text{hs}]$ ratio could be expected.

3 DISCUSSION

3.1 The Case A

The first model for $^{13}$C-burning in AGB stars assumed that the neutrons were released in convective conditions (Hollowell & Iben 1988; Kappeler et al. 1990). In such calculations, a repeated neutron exposure was achieved thanks to partial overlapping of material cycled through several thermal pulses. The s-process mechanism could be approximated by an exponential distribution of neutron exposures $\propto \exp(-\Delta \tau/\tau_0)$, where the mean neutron exposure is given by $\tau_0=-\Delta \tau/\text{In} r$. The final abundance distributions depend mainly upon $\tau_0$.

In order to investigate the efficiency of the s-process site, $[\text{Pb}/\text{hs}]$ is particularly useful (Straniero et al. 2005). There have been many theoretical studies of s-process nucleosynthesis in low-mass AGB stars (Delaude et al. 2004; Iwamoto et al. 2004; Straniero et al. 2005). Unfortunately, the precise mechanism for chemical mixing of protons from the hydrogen-rich envelope into the $^{13}$C-rich layer to form $^{13}$C-pocket is still unknown (Revni et al. 2004). This makes it even harder to understand the large spread of $[\text{Pb}/\text{hs}]$ found in carbon-rich, metal-deficient stars. It is an interesting exercise to investigate the effect of the parameters presented above upon the s-process efficiency of AGB stars. For this purpose, we have used the simple analytical formulation (Clayton & Rassbach 1963; Clayton & Ward 1974) without depending on any specific stellar model, with many of the neutron-capture rates updated (Bao et al. 2000), to study what physical conditions are possible to reproduce the observed abundance pattern found in the metal-poor stars. The variation of the logarithmic ratio $[\text{Pb}/\text{hs}]$ with metallicity is shown in Fig. 3a, where solid lines represent respectively results of different initial mass of AGB stars. As a comparison, spectroscopic measurements (filled squares) of C and s-rich metal-poor stars are reported. Because of the uncertainties related to the formation mechanism of the $^{13}$C-pocket (Busso et al. 2001), a large spread of $^{13}$C-pocket efficiencies has been proposed by Straniero et al. (2005) in order to explain the spreads of $[\text{Pb}/\text{hs}]$, which has proved to be effective for several purposes (Gallino et al. 1998; Travaglio et al. 1999, Busso et al. 2001). The results (plot lines) predicted by Straniero et al. (2005) for their standard case (hereafter ST), ST$\times$2 and ST/75 case are also presented respectively. The ST case (Gallino et al. 1998) was shown to reproduce

Figure 2. The neutron exposure of different initial mass AGB stars, as function of metallicity.
3.2 The Case B

We use the parametric approach based on the model of low-mass AGB stars computed by Gallino et al. (1998) assuming that all the pulses are identical. In this case, the neutron exposure is not well approximated with the exponential distribution, and the final s-process abundance distributions depend mainly upon the neutron exposure $\Delta r$, the mass fraction of $^{13}$C-pocket in the He intershell $q$ (adopted as 0.05) and overlap factor $r$. The adopted initial abundances of seed nuclei lighter than the iron peak elements were taken to be the solar-system abundances, scaled to the value of [Fe/H]. Because the neutron-capture-element component of the interstellar gas that formed very metal-deficient stars is expected to consist of mostly pure r-process elements, for the other heavier nuclei we use the r-process abundances of the solar system (Arlandini et al. 1999), normalized to the value of [Fe/H]. We carry out s-process nucleosynthesis calculation by means of an extensive reaction network described earlier (Liang et al. 2000). The results are shown in Fig. 4.

It results that for very metal-poor stars, large spreads of [Pb/hs] are predicted for both cases. The agreement of the results with the observations provides a strong support to the validity of the parameters adopted in this work. Here, the logarithmic ratio [Pb/hs] shows a complex trend versus [Fe/H], due to the conjunct effect of the overlap factor and neutron exposure. Although the parameters of the two cases are different in part, the ratios of lead stars obtained in this work are very similar. At [Fe/H] $\simeq -2.0$, the ratios of both cases all reach the maximum value around 0.55. The results obtained in this paper are the evidence that maybe the well established theories of the s-process nucleosynthesis, as it works in solar-like metallicities, may not work well at extremely low metallicity because of greatly changed parameters. In fact, such results could be mainly led to by the new initial-final mass relations (Zijlstra 2004), i.e. the inefficient mass loss of the AGB stars at low metallicity.
4 CONCLUSION

Theoretically, a s-process pattern should be obtained from an AGB star with fixed metallicity and initial mass. Taking account of the core-mass dependence, the large intrinsic spread of integrated neutron irradiations for the AGB stars at low metallicities is obtained, then the scatter of [Pb/hs] such as found in low metallicities can therefore be explained naturally when varying the initial mass of the AGB stars. Based on the relation of the overlap factor with the initial mass of the AGB stars, we can speculate that the Pb stars are polluted by low mass AGB stars (e.g. 1.5-2.5M⊙) and the non-Pb stars ([Pb/hs]<1) are polluted by larger mass AGB stars. We remind the reader that though the parametric approach is still useful to interpret observation data, it does not refer to detailed stellar evolution models. Obviously, a more precise overlap factor-core mass law and a more precise neutron irradiation time-core mass relation still have to wait for new models of nucleosynthesis in AGB stars.

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