Nucleosynthesis and Mixing on the Asymptotic Giant Branch. III. Predicted and Observed s-Process Abundances

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Abstract

We present the results of s-process nucleosynthesis calculations for asymptotic giant branch (AGB) stars of different metallicities and different initial stellar masses (1.5 and 3 \( M_\odot \)), and we present comparisons of them with observational constraints from high-resolution spectroscopy of evolved stars over a wide metallicity range. The computations were based on previously published stellar evolutionary models that account for the third dredge-up phenomenon occurring late on the AGB. Neutron production is driven by the \( ^{13}\text{C}(n,\gamma)\) reaction during the interpulse periods in a tiny layer in radiative equilibrium at the top of the He- and C-rich shell. The neutron source \(^{13}\text{C}\) is manufactured locally by proton captures on the abundant \(^{12}\text{C}\); a few protons are assumed to penetrate from the convective envelope into the radiative layer at any third dredge-up episode, when a chemical discontinuity is established between the convective envelope and the He- and C-rich zones. A weaker neutron release is also guaranteed by the marginal activation of the reaction \(^{22}\text{Ne}(n,\gamma)\) during the convective thermal pulses. Owing to the lack of a consistent model for \(^{13}\text{C}\) formation, the abundance of \(^{13}\text{C}\) burnt per cycle is allowed to vary as a free parameter over a wide interval (a factor of 50). The s-enriched material is subsequently mixed with the envelope by the third dredge-up, and the envelope composition is computed after each thermal pulse. We follow the changes in the photospheric abundance of the Ba-peak elements (heavy s elements) and that of the Zr-peak ones (light s elements), whose logarithmic ratio \( \text{[hs/ls]} \) has often been adopted as an indicator of the s-process efficiency (e.g., of the neutron exposure). Our model predictions for this parameter show a complex trend versus metallicity. Especially noteworthy is the prediction that the flow along the s-path at low metallicities drains the Zr and Ba peaks and builds an excess at the doubly magic \(^{208}\text{Pb}\), which is at the termination of the s-path. We then discuss the effects on the models of variations in the crucial parameters of the \(^{13}\text{C}\) pocket, finding that they are not critical for interpreting the results. The theoretical predictions are compared with published abundances of s-elements for AGB giants of classes MS, S, SC, post-AGB supergiants, and for various classes of binary stars, which supposedly derive their composition by mass transfer from an AGB companion. This is done for objects belonging both to the Galactic disk and to the halo. The observations in general confirm the complex dependence of neutron captures on metallicity. They suggest that a moderate spread exists in the abundance of \(^{13}\text{C}\) that is burnt in different stars. Although additional observations are needed, it seems that a good understanding has been achieved of s-process operation in AGB stars. Finally, the detailed abundance distribution including the light elements (CNO) of a few s-enriched stars at different metallicities are examined and satisfactorily reproduced by model envelope compositions.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: AGB and post-AGB — stars: evolution — stars: low-mass, brown dwarfs

1. Introduction

In this paper we present an interpretation of the observed s-element abundances in evolved red giants in light of current models for the nucleosynthesis occurring in low-mass stars (LMSs). The red giants studied here are primarily those powered by hydrogen and helium burning in two shells located above a degenerate CO core and are called asymptotic giant branch (AGB) stars (see, e.g., Iben \\& Renzini 1983). Late on the AGB, they undergo recurrent thermal instabilities of the He shell (thermal pulses [TPs]), in which partial He burning occurs convectively over short periods of time, sweeping the whole region that lies between the H and the He shells (hereafter, the He intershell). The stars undergoing such processes are semiregular or Mira variables showing the short-lived Tc in their spectra (Merrill 1952). They belong to the spectral types MS, S, SC, or C(N) and are called intrinsic TP-AGB stars (Lambert 1985; Smith \\& Lambert 1990, hereafter SL90; Plez, Smith, \\& Lambert 1993). Strong and variable stellar winds, with mass-loss rates \( \dot{M}/dt \) from \( 10^{-7} \) to \( 10^{-5} \ M_\odot \text{ yr}^{-1} \), progressively reduce their envelopes, leaving behind a degenerate CO core, which will eventually become a white dwarf. During the TP-AGB phase, material from the He intershell, enriched in \(^{12}\text{C}, ^{22}\text{Ne}, \) and s-process elements, appears at the surface, thanks to repeated downward extensions of the envelope convection (third dredge-up [TDU]). In other cases, the star that was the site of the s-element synthesis appears to have left the TP-AGB phase, ejecting most of its envelope and exposing the hot layers immediately above the H shell. Such a star appears as a post-AGB, carbon-rich and s-element–rich supergiant of classes A, F, or G (Van Winckel \\& Reyniers 2000).
Further constraints on neutron capture nucleosynthesis in the Galaxy come from binary systems, in which the more massive component, while on the TP-AGB phase, has transferred part of its envelope onto a lower mass companion, now seen to be enriched in $s$-elements. It is therefore this companion (extrinsic AGB) that becomes the object of our study (see Jorissen & Mayor 1988, Han et al. 1995, and Jorissen et al. 1998 for a treatment of mass transfer and Ba star masses and Smith 1984, Luck & Bond 1981, 1991, and Luck, Bond, & Lambert 1990 for details on the resulting abundances). In this group of stars, we find the classical Ba II giants and other sources in which the secondary component has in its turn evolved into the early AGB phases, so that it can be distinguished from "normal" MS, S, SC, and C(N) stars only by the absence of Tc. The group of extrinsic AGBs also contains several classes of CH-strong dwarfs, subgiants, and giants at various metallicities. These are low-luminosity stars with $s$-process enrichments that are most probably not spectroscopic binaries, e.g., the N-rich subdwarf HD 25329 (Beveridge & Sneden 1994), and HD 23439A and 23439B (Tomkin & Lambert 1999). In these cases, it is presumed that their natal clouds were contaminated by ejecta from AGB stars. This is, e.g., the case of the $s$-enrichment in red giants belonging to the globular cluster ω Centauri (Smith et al. 2000).

As far as nucleosynthesis is concerned, current studies ascribe neutron captures to the activation of the reactions $^{13}$C($^3$He,$n$)$^{16}$O and $^{22}$Ne($^3$He,$n$)$^{25}$Mg (Iben & Renzini 1982; Hollowell & Iben 1988; Gallino et al. 1988; Käppeler et al. 1990; Busso, Gallino, & Wasserburg 1999, hereafter BGW99). The same reactions may also affect the nucleosynthesis of lighter nuclei, like fluorine, sodium, and the unstable $^{26}$Al (Mowlavi & Meynet 2000; Goriely & Mowlavi 2000; Mowlavi 1999).

The principal goal of this paper is to verify the ability of the current forms of AGB models to account for the observed abundance distributions in evolved stars. In § 2 we discuss the general features of our models and the choices made for the parameterization of the neutron source $^{13}$C. We also comment on the major effects on $s$-process nucleosynthesis introduced by varying the initial metallicity. A comparison of observed heavy-element abundances of intrinsic and extrinsic $s$-enriched stars with model predictions follows in § 3. Detailed fits to the observed compositions including the light elements of three selected stars are sketched in § 4. Finally, in § 5 we summarize the main conclusions that can be drawn from such an analysis.

2. THE ADOPTED MODELS FOR STELLAR EVOLUTION AND NUCLEOSYNTHESIS

2.1. Indices of $s$-Processing

Abundance analyses of stars enriched by $s$-processing may often provide quantitative information for only a few neutron-rich elements. This has led to simple characterizations of the overabundances. Following Luck & Bond (1981, 1991), it is common to monitor the $s$-process efficiency through the relative abundances of the $s$-elements at the Ba peak (collectively indicated as "heavy $s$" [hs]) with respect to those at the Zr peak (indicated as "light $s$" [ls]). Indeed, those nuclei are placed at neutron magic numbers $N = 82$ and 50, are mainly of $s$-process origin, and act as bottlenecks for the $s$-process path because of their low neutron capture cross sections. Consequently, for relatively low $s$-process efficiencies, the neutron flux mainly feeds the nuclei at the Zr peak, while for higher exposures, the Ba-peak species are favored (see § 3.1 for a deeper analysis).

The average logarithmic ratio normalized to solar [hs/ls], defined as $\log_{10}(\text{hs}/\text{ls}) - \log_{10}(\text{hs}/\text{ls}_{\odot})$, has been extensively used as a measure of the neutron capture efficiency in building up the $s$ elements and proved useful for the interpretation of the Galactic disk stars (Busso et al. 1992, 1995, hereafter Papers I and II, respectively). The choice of the specific elements to consider in the average hs and ls abundances varies from author to author and depends on the quality of the spectra available. The definition adopted by Luck & Bond (1981, 1991) included Sr, Y, and Zr in the ls group and Ba, La, Nd, and Sm in the hs group. In presenting the model results, we instead consider Y and Zr as ls. We generally exclude Sr, despite the fact that it is mainly of $s$-process origin, because it has been measured precisely only in a minority of the sample stars. For the hs group, we include La and Nd, which are present with several lines in most sample stars. The results would not be significantly changed if we adopted the same choice as Luck & Bond (1981, 1991). Whenever possible, we follow the same rules in selecting the observations. There are, however, cases in which this is not possible. One is represented by the star CS 22898−027 (McWilliam et al. 1995), in which ls can be defined only through Sr (Y and Zr were not measured). For hs, the situation is more complex. There are cases in which only one element of the couple La and Nd was measured, in other cases only estimates of the Ba abundance exist, etc. The stars affected by such problems are explicitly commented on later in order to make clear which choices were made (see discussion of Table 2). These limitations increase slightly the uncertainties in the constraints.

In addition, the degree of $s$-process enrichment is of interest. We consider the logarithmic ratios, normalized to solar, [ls/Fe] and [hs/Fe] as measures of the enrichment. For the intrinsic stars, both indices increase with the number of TDU, but the [hs/ls] ratio after a relatively few TDU approaches an asymptotic value. In the case of the extrinsic stars, [ls/Fe] and [hs/Fe] are dependent on the values of these indices in the AGB envelope during mass transfer and on the degree of dilution occurring in the extrinsic star on receipt of the mass or subsequently.

For a few stars, a quite extensive array of heavy elements has been measured, and, in these cases, theoretical models may be tested for their ability to reproduce the suite of elemental abundances, which is a finer test than that possible using indices ls and hs.

2.2. General Characteristics of $s$-Processing in AGB Stars

As mentioned, the main neutron source allowing $s$-processing to take place in AGB stars is the reaction $^{13}$C($^3$He,$n$)$^{16}$O. Its activation requires the penetration of a small amount of protons from the envelope into the He intershell, i.e., the region between the H and He shells, most likely occurring during the postflash luminosity dip, when the H shell is extinguished and TDU can occur (Iben & Renzini 1983). Studies on the required mixing mechanisms have made use of diffusive or hydrodynamical simulations (Iben & Renzini 1982; Hollowell & Iben 1988; Herwig et al. 1997; Herwig 2000; Cristallo et al. 2001). They are still a matter of debate, although a consensus is emerging that partial mixing must indeed occur. At least in some cases, it may also be affected by rotational shears (Langer et al. 1999), but
a self-consistent model is still not possible in stellar codes. Because of these uncertainties, the amount of \(^{13}\text{C}\) that forms in a pocket at the top of the He intershell and its profile in mass must be represented by free parameters. Introducing a range of \(^{13}\text{C}\) abundances at a given metallicity proved to be effective for several purposes (see, e.g., Gallino et al. 1998, hereafter G98; Travaglio et al. 1999, hereafter T99, Goriely & Mowlavi 2000).

The alternative to the \(^{13}\text{C}\) neutron source is the \(^{22}\text{Ne}(\alpha, n)\) \(^{25}\text{Mg}\) reaction, which is triggered when the temperature \(T\) exceeds \(3 \times 10^8\) K, but this reaction does not play a dominant role in AGB stars of \(M \leq 3 - 4\ M_\odot\) (hereafter LMSs). In fact, in LMSs the maximum temperature at the bottom of TPs, although gradually increasing with the pulse number, barely reaches the above mentioned value. Despite the very low neutron exposure associated with its activation in LMSs, the peak neutron density generated by the \(^{22}\text{Ne}\) source is rather high (up to \(n_\text{n} = 10^{10}\) cm\(^{-3}\)) and affects many branchings along the \(s\)-path that are sensitive to the neutron density and/or temperature (Käppeler et al. 1990; Arlandini et al. 1999). Notice that the final modifications on branching-dependent isotopes are important since the \(s\)-processed and partially diluted matter is irradiated repeatedly and therefore keeps a partial memory of all the previous high-temperature phases.

In more massive AGB stars (5 \(M_\odot < M < 8\ M_\odot\)) hereafter intermediate-mass stars [IMSs]), \(^{22}\text{Ne}\) burns efficiently through the \(^{22}\text{Ne}(\alpha, n)\) \(^{25}\text{Mg}\) and \(^{22}\text{Ne}(\alpha, \gamma)\) \(^{26}\text{Mg}\) reactions in roughly equal proportion since the maximum bottom temperature in TPs is \(T \geq 3.5 \times 10^8\) K (Iben 1975; Truran & Iben 1977). As a consequence, a significant neutron exposure is made available. The simultaneous production of \(^{25}\text{Mg}\) and \(^{26}\text{Mg}\) occurs since these isotopes are expected to be enhanced in the photospheres of AGB stars of intermediate mass. Moreover, the high peak neutron density (\(n_\text{n} > 10^{11}\) cm\(^{-3}\)) induces a considerable production of the few neutron-rich nuclei involved in those \(s\)-process branchings that are sensitive to the neutron density, such as \(^{46}\text{Kr}, \ 81\text{Rb},\) and \(^{96}\text{Zr}\). Their abundances can be enhanced even more than for the \(s\)-only species. Moreover, IMSs may suffer from the so-called hot bottom-burning (HBB) process in the deep convective envelope, which would decrease the photospheric \(^{13}\text{C}/^{12}\text{C}\) ratio and enhance the abundance of Li. It would also reduce the C/O ratio, thus preventing the star from becoming C-rich for most of its AGB phase (see, e.g., Lattanzio & Forestini 1999).

The observational evidence so far available points toward a relatively low peak neutron density in AGB stars (\(n_\text{n} < 10^8\) cm\(^{-3}\)), as derived from the Sr/Rb abundance ratio and, in a few cases from the Zr isotopic mix (Lambert et al. 1995). This can be interpreted as an indication that most intrinsic, and extrinsic AGB stars are of rather low mass (Busso et al. 1988). The fact that AGB stars of intermediate mass are rather rare is then confirmed by the roughly solar isotopic ratio measured for Mg in MS and S giants (see, e.g., Clegg, Lambert, & Bell 1979; Blanco, McCarthy, & Blanco 1980; McWilliam & Lambert 1988).

2.3. The Updated Reference Models

Stellar models were computed using the FRANEC code (Straniero et al. 1997; G98) and spanned the metallicity range from solar down to 1/20 solar (1.5 \(M_\odot\)) and from solar down to \(\frac{3}{2}\) solar (3 \(M_\odot\)).

Our nucleosynthesis predictions, covering the metallicity interval from \([\text{Fe/H}] = 0.3\) down to \([\text{Fe/H}] = -3.6\), were calculated as postprocess runs, extrapolating the stellar parameters from the mentioned coarser grid of full evolutionary models. The differences in the physical structure of the He intershell are found to be small, even for models with large differences in the initial metallicities (see also Boothroyd & Sackmann 1988, 1999). The parameter most heavily affected by the metal content is the TDU, which is found to increase in efficiency for decreasing \([\text{Fe/H}]\)-values. For these reasons, the amount of dredge-up at very low metallicities may be somewhat underestimated in our extrapolations, and TDU can also occur for masses lower than actually found. Mass loss was considered through the Reimers (1975) formula, varying its free parameter to obtain a wide range of parameterizations. The values considered in this paper are \(\eta = 0.3\) (1.5 \(M_\odot\)) and \(\eta = 1.5\) (3 \(M_\odot\)). With the FRANEC code and its assumptions for convective mixing, TDU is found to cease when the residual envelope mass becomes smaller than about 0.5 \(M_\odot\) while TPs are still going on. Given the uncertainties of the mixing procedure in stellar models, and of the mass-loss rates, we cannot claim that this last finding is a common property of real AGB stars. However, on this point the different stellar codes tend to agree (see also Lattanzio & Karakas 2001). Should this correspond to a real physical property, then it would also imply that stars with too small envelope masses (hence, also with too small initial masses) cannot undergo TDU and cannot contribute to the chemical enrichment of the Galaxy (T99). The minimum initial mass at which TDU is found with the FRANEC code is 1.5 \(M_\odot\) for a solar composition, and it decreases slightly for decreasing metallicity; however, the uncertainty is high, and the actual values should be tuned through comparisons with observations (see also § 3.2 and the discussion of Fig. 7). Exceptional conditions probably have to be invoked to explain objects with unusual \(s\)-enrichments, up to 1 order of magnitude higher than the maximum defined by common AGB stars; see, e.g., the cases of F Sagittae (Gonzalez et al. 1998), Sakurai's object (Asplund et al. 1999), and, in general, the class of R CrB stars (Asplund et al. 2000). We also recall that in Paper I we analyzed what would be the consequences of a prolonged interruption in the TDU process. We showed that, in this case, some MS or S stars without Tc might actually be intrinsic, Tc having decayed because of a lack of refurbishing from the He intershell.

The first published models for \(^{13}\text{C}\) burning in AGB stars assumed that the neutrons were released from the \(^{13}\text{C}(\alpha, n)\) \(^{16}\text{O}\) reaction in convective conditions, after the \(^{13}\text{C}\) pocket was ingested by the next TP (Hollowell & Iben 1988; Käppeler et al. 1990). The resulting \(s\)-process nucleosynthesis was analyzed to understand abundances in AGB stars of the Galactic disk (Papers I and II). In such calculations, a repeated neutron exposure was achieved thanks to partial overlapping of material cycled through several TPs. Although more complex than in the simple original sketch by Ulrich (1973), the \(s\)-process mechanism could still be approximated by an exponential distribution of neutron exposures. We recall that the classical analysis of the main component represented by the solar system \(s\)-process abundances in the atomic mass range \(A = 85 - 208\) (see, e.g., Käppeler, Beer, & Wisshak 1989) assumed a distribution function of neutron exposures \(\rho(\tau) \sim \exp (-\tau/\tau_\text{th})\), where \(\tau\) is the time-integrated neutron flux \(\tau = \int n_\text{n} v_\text{th} dt\), with \(v_\text{th}\)
being the thermal velocity and \( n_n \) the neutron density (Seeger, Fowler, & Clayton 1965). The parameter \( \tau_0 \) is called the mean neutron exposure. According to Arlandini et al. (1999), the main component is best reproduced with \( \tau_0 = (0.296 \pm 0.003)(kT/30 \text{ keV})^{1/2} \). As a matter of fact, previous AGB stellar models already showed that different \( s \)-element distributions were obtained by varying the amount of \(^{13}\text{C}\) in the pocket and/or the initial metallicity. In this respect, the observed spread of [hs/ls]-values in Galactic disk MS and S stars was explained quantitatively by saying that they imply values of the mean neutron exposure \( \tau_0 \) expressed at 30 keV in the range 0.2–0.4 mbarn\(^{-1}\). CH and Ba stars were found to extend the range of mean neutron exposures further, up to \( \tau_0(30 \text{ keV}) \sim 0.8–1.0 \text{ mbarn}\(^{-1}\) (Paper II).

A reanalysis of AGB evolution was recently pursued by various authors (e.g., Herwig et al. 1997; Herwig, Schönberner, & Blöcker 1998; Frost et al. 1998; Frost, Lattanzio, & Wood 1998). We shall follow here the work by Straniero et al. (1997). They showed that all \(^{13}\text{C}\) nuclei present in the pocket are consumed locally in radiative conditions (over a time interval of a few times \( 10^4 \) yr) when these layers are heated up to \( 10^8 \) K before the next convective instability sets in. The rate of the \(^{13}\text{C}(a,n)^{16}\text{O}\) reaction (Denker et al. 1995) is rather uncertain at the relevant temperatures (\( T \sim 0.9 \times 10^8 \) K), but we expect the complete exhaustion of \(^{13}\text{C}\) in the radiative interpulse phase for all reasonable values of the rate (Arlandini et al. 1999). In such conditions, the neutron fluxes are characterized by a rather low neutron density (\( n_n \leq 1 \times 10^7 \text{ n cm}^{-3} \)) as a consequence of the relatively low temperature at which \(^{13}\text{C}\) burns. The effect of the recurrent convective instabilities is nevertheless of the highest importance since they dilute the \( s \)-enriched material of the \(^{13}\text{C}\) pocket over the whole He intershell, allowing subsequent neutron capture episodes to occur over a mixture containing fresh iron seed nuclei and material already \( s \)-processed in the previous cycles. The ensuing chemical homogenization of the He intershell also allows the neutron-rich nuclei to be mixed with the envelope by TDU.

The fact that \(^{13}\text{C}\) burns radiatively in the interpulse period makes the \( s \)-process more complex than previously assumed. Further complications are due to the fact that the mass involved in each TP decreases with time, as the core mass increases, while the overlapping factor \( r \) between adjacent pulses decreases with pulse number. The ensuing neutron exposure is much closer to a superposition of few single irradiations than to an exponential distribution of neutron exposures (see G98 for further details).

For the sake of our comparisons with observed stars, we adopt a wide range of \(^{13}\text{C}\) abundances in the pocket. We include the case indicated as standard (ST) by G98, corresponding to \( 4 \times 10^{-6} M_\odot \) of \(^{13}\text{C}\), and values scaled upward by a factor of 2 and downward by factors of 1.5, 3, 6, 12, and 24 with respect to that choice. The ST case was so named because this amount of \(^{13}\text{C}\) for AGB stars in the 1.5–3 \( M_\odot \) mass range at \([\text{Fe/H}]=−0.3\) appears to explain the main solar component of the \( s \)-process (Arlandini et al. 1999). Notice that the same result can be obtained by varying simultaneously the metallicity and the amount of \(^{13}\text{C}\) in the pocket provided that the \(^{13}\text{C}/\text{Fe}\) ratio remains constant; this ratio essentially fixes the number of neutrons available per heavy seed. It is, however, clear that both the particular \( s \)-element distribution achieved in the Sun and the spread of \( s \)-process abundances observed in chemically unevolved stars at each metallicity (i.e., stars that have maintained their initial composition) should be considered as the result of a complex chemical evolution of the Galaxy through the astration mechanism over various generations of AGB stars of different masses, metallicities, and \( s \)-process efficiencies.

2.4. Metallicity Effects in the Models

For each choice of the \(^{13}\text{C}\) pocket and stellar mass, the \( s \)-process efficiency in the He intershell varies according to the initial metallicity. Figures 1 and 2 show the overproduction factors of stable elements from Cu to Bi in the material cumulatively mixed from the He intershell to the envelope. The results refer to the ST choice for the \(^{13}\text{C}\) pocket for AGB models of 1.5 \( M_\odot \) and metallicity varying from \([\text{Fe/H}]=0.3\) down to \([\text{Fe/H}]=−0.6\) (Fig. 1) and from \([\text{Fe/H}]=−1\) down to \([\text{Fe/H}]=−3\) (Fig. 2). In these figures, the elements represented by filled symbols owe more than 50% of their solar abundance to the \( s \)-process according to the analysis by Arlandini et al. (1999). The remaining elements are indicated as crosses. The elements used here to build the hs and ls integrated abundances are indicated explicitly in the third panel of Figure 1. In the \( s \)-processed material mixed with the envelope, the unstable nuclei with a half-life longer than an interpulse period (typically between \( 10^4 \) and \( 10^5 \) yr in LMs) but shorter than \( 10^9 \) yr, have been allowed to decay, as expected for extrinsic AGB stars. For comparison, the abundances before such decays are shown as open symbols (squares for the main \( s \)-elements). The isotopes involved are the pairs \(^{93}\text{Zr}−^{93}\text{Nb}, ^{99}\text{Tc}−^{99}\text{Ru},...

![Fig. 1.—Distribution of the elements from Cu to Bi in the He intershell as a function of the initial metallicity. The elements mainly produced by the main component of the \( s \)-process (by at least 50% according to Arlandini et al. 1999) are shown as filled squares. Pb has a special symbol (filled diamond) because it is mainly attributed to the strong \( s \)-process component deriving from AGB stars of low metallicity (Travaglio et al. 2001). The models refer to a 1.5 \( M_\odot \) star, with the choice ST for the \(^{13}\text{C}\) pocket discussed in the text, and with metallicities from \([\text{Fe/H}]=0.3\) down to −0.6. For elements affected by the decay of unstable isotopes whose half-life is longer than a typical interpulse period but shorter than \( 10^9 \) yr, open symbols refer to abundances before decay.](image)
At nearly solar metallicities. At lower metallicities, like those dent on the initial composition. They show how the ls ele-
ments (initial mass of the parent star, abundance of \(^{13}\text{C}\) in the pocket, and metallicity).

In Figures 3a, 3b, and 3c and Figures 4a, 4b, and 4c, we show predicted values of \([\text{hs}/\text{ls}], [\text{ls}/\text{Fe}], \) and \([\text{hs}/\text{Fe}]\) in the photosphere at the last TDU episode for the 1.5 and 3 \(M_\odot\) stellar models. The nonlinear trends displayed by the plots reveal the complex dependence on metallicity of the integrated abundances ls and hs. This is due to the neutron exposure, which increases with decreasing abundance of the iron seed nuclei. To illustrate this, let us follow the ST case. Starting at metallicities higher than solar and moving toward lower \([\text{Fe}/\text{H}]\)-values, a minimum with \([\text{hs}/\text{ls}] = -0.54\) is first reached at \([\text{Fe}/\text{H}] = 0.2\) (the Zr-peak elements are more abundantly produced for moderate exposures, hence for relatively high metallicities). Then a maximum with \([\text{hs}/\text{ls}] = 1.2\) follows at \([\text{Fe}/\text{H}] = -1\). Finally, for even lower metallicities, the s-process flow extends beyond the Zr-peak and Ba-peak nuclei to cause an accumulation at \(^{208}\text{Pb}\), and \([\text{hs}/\text{ls}]\) declines again. Reducing the amount of \(^{13}\text{C}\) burnt has the effect of displacing the maximum and the minimum of the curve toward lower metallicities. Note that the maxima reach values in \([\text{hs}/\text{ls}]\) up to 1.2, consistently higher than in all previous expectations. The minima reach down to \(-0.7\) at an \([\text{Fe}/\text{H}]-\)value depending on the \(^{13}\text{C}\) choice.

At extremely low \([\text{Fe}/\text{H}]-\)values, the scarcity of Fe nuclei becomes important. Here their role as seeds for the s-process is replaced partly by lighter (intermediate atomic mass) nuclei, whose abundances remain high because of both the known enhancement of \(\alpha\)-rich elements in halo stars and the fact that they are synthesized from primary \(^{13}\text{C}\) generated in the He intershell and mixed with the envelope by TDU. When this \(^{13}\text{C}\) is transformed into \(^{14}\text{N}\) by the H-burning shell, it provides more fuel for the chain \(^{14}\text{N}(\alpha, \gamma)^{18}\text{F}(\beta^- \nu)^{18}\text{O}(\alpha, \gamma)^{22}\text{Ne}\) early in the TP. The nuclei that are the progeny of \(^{22}\text{Ne}\), usually considered merely as neutron filters (or “poisons”) at higher metallicities, now assume a more complex role. Neutron captures on them generate a small leakage that crosses the iron peak, thus allowing the s-processing on heavy isotopes to continue.

Because of the above phenomena, the s-nuclei cannot be considered as being simply of “secondary” nature. It is true that they require previously built seeds to be formed, but at moderately low metallicities their secondary behavior is masked by the increase in the neutron exposure, on which the resulting s-process abundances strongly depend (Clayton 1988). At very low \([\text{Fe}/\text{H}]-\)values, part of the seeds feeding them are primary, so that they achieve a trend that only slightly decreases for decreasing \([\text{Fe}/\text{H}]\).

2.6. Sensitivity of the Results to Model Parameters

Neutrons released by the \(^{13}\text{C}\) neutron source are captured locally in the \(^{13}\text{C}\) pocket. Only after their ingestion in the next TP are the s-enriched layers of the \(^{13}\text{C}\) pocket mixed together and spread over the (now convective) He intershell. To better understand how this complex mechanism occurs, and to study its sensitivity to input parameters, we consider in some detail the behavior of s-processing in the various layers of the \(^{13}\text{C}\) pocket together with the effects of mixing and dilution operated by TPs. For any \(^{13}\text{C}\) neutron burst, the starting composition of Fe seeds and heavy elements in the pocket is not the initial one but rather the composition left behind by the operation of previous
TPs (see Fig. 5), which are already highly enriched in heavy elements.

This is illustrated schematically in Table 1, in which the evolution of three representative isotopes of the Zr, Ba, and Pb peaks are followed for the model of an AGB star of 1.5 $M_\odot$ and solar metallicity, adopting the ST choice for the $^{13}$C pocket. The relevant zones of the stellar structure are shown in Figure 5. For illustration, let us consider the layers in the pocket of initial abundance $X(^{13}\text{C}) = 0.003$ and 0.004. Column (1) gives the TP number (with TDU) that precedes the corresponding $^{13}$C formation episode, and column (2) indicates the zone to which the abundances refer—layer 1 and layer 2, as indicated in the figure—the average in the $^{13}$C pocket at the end of the interpulse phase (zone 3 in the figure), and finally the average at the end of the next TP (labeled as "4" in the figure). The composition of this last region includes the effects of dilution over the extension of the convective He intershell, with material from upper layers containing ashes of H-shell burning and material from lower layers already $s$-processed in the previous TP cycles. During each TP, one also has to take into account the small neutron burst by the $^{22}$Ne source, but this affects only marginally the production of $^{94}$Zr, $^{138}$Ba, and $^{208}$Pb. Column (3) gives the mass (in solar units) affected by

Fig. 3.—Predicted ratios (a) [hs/ls], (b) [ls/Fe], and (c) [hs/Fe] from AGB stellar models of 1.5 $M_\odot$. Each curve refers to a different choice of the $^{13}$C pocket, as shown by the labels and discussed in the text.
the next convective TP and column (4) gives the neutron exposure $\delta(t)$ (in units of mbarn$^{-1}$), where $\delta(t) = \int n_n v_n \, dt$ is integrated over the interpulse period. Typical thermal conditions during $^{13}$C consumption correspond to $kT = 8$ keV. Columns (5), (6), and (7) give the production factors of $^{94}$Zr, $^{138}$Ba, and $^{208}$Pb, respectively, relative to solar (Anders & Grevesse 1989). Although the three selected isotopes are not of purely $s$-origin, they owe most of their production to the $s$-process. Following their synthesis as a function of pulse number in the two selected zones, we note how in the first cycle a small difference in $\delta(t)$ in the two regions gives rise to a huge difference in their production factors. This lets the highly nonlinear trend of the $s$-process efficiency to show up. However, the ratio of the production factors between the two zones is progressively smoothed in the subsequent TPs. For $^{94}$Zr/$^{94}$Zr$_\odot$, it goes from 0.21 in the first $^{13}$C-burning episode to 0.66 in the fifth and to 0.73 in the 20th. For $^{138}$Ba/$^{138}$Ba$_\odot$, the range is from 0.47 to 0.55 and to 0.64, respectively. (See G98 for a discussion of asymptotic conditions reached in advanced TPs.) Concerning $^{208}$Pb, the production of this isotope at the termination of the $s$-process path grows with the pulse number more slowly than the nuclei at the other two $s$-process peaks.

The neutron exposures listed in column (4) show a slight decline with increasing pulse number in both selected layers. This smoothing effect is due to the repeated averag-
The zones relevant for understanding the results listed in Table 1 are indicated.

ing of the s-process products operated by the TPs, which dilute the s-enriched layers in the way described above 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-elements, as our calculations demonstrate. In fact, we repeated the whole series of nucleosynthesis computations for different metallicities just assuming, for each choice of the total 13C concentration, the simplest possible profile, i.e., a constant abundance throughout the pocket. In this exercise a mass fraction \( X_{13} = 0.004 \) represents the "smoothed" ST case. The resulting [hs/ls] trend versus metallicity is shown in Figure 6.

### Table 1

**Evolution of Three Representative Isotopes of the Zr, Ba, and Pb Peaks in the s-Process Pocket**

| Thermal Pulse | Zone | \( M(\text{TP}) \) (\( M_\odot \)) | \( \delta(\tau) \) (mbar-1) | \( ^{94}\text{Zr}/^{94}\text{Zr}_0 \) | \( ^{138}\text{Ba}/^{138}\text{Ba}_0 \) | \( ^{208}\text{Pb}/^{208}\text{Pb}_0 \) |
|---------------|------|----------------|-----------------|----------------|----------------|-----------------|
| 1             | Layer 1 | ... | 0.194 | 266 | 7.5 | 3.8 |
|               | Layer 2 | ... | 0.233 | 1240 | 15.9 | 4.7 |
|               | 13C pocket | ... | ... | 973 | 13.6 | 4.4 |
|               | End of second TP | 0.019 | ... | 39 | 1.5 | 1.1 |
| 2             | Layer 1 | ... | 0.189 | 1020 | 329 | 4.1 |
|               | Layer 2 | ... | 0.229 | 1920 | 684 | 5.4 |
|               | 13C pocket | ... | ... | 1670 | 587 | 5.0 |
|               | End of third TP | 0.018 | ... | 91 | 25 | 1.2 |
| 5             | Layer 1 | ... | 0.183 | 1680 | 730 | 19 |
|               | Layer 2 | ... | 0.222 | 2540 | 1330 | 34 |
|               | 13C pocket | ... | ... | 2300 | 1170 | 30 |
|               | End of sixth TP | 0.016 | ... | 175 | 82 | 2.7 |
| 10            | Layer 1 | ... | 0.177 | 1880 | 986 | 68 |
|               | Layer 2 | ... | 0.216 | 2720 | 1630 | 107 |
|               | 13C pocket | ... | ... | 2490 | 1450 | 96 |
|               | End of 11th TP | 0.013 | ... | 236 | 145 | 10 |
| 15            | Layer 1 | ... | 0.168 | 1960 | 1030 | 81 |
|               | Layer 2 | ... | 0.207 | 2770 | 1670 | 123 |
|               | 13C pocket | ... | ... | 2550 | 1490 | 112 |
|               | End of 16th TP | 0.011 | ... | 273 | 174 | 14 |
| 20            | Layer 1 | ... | 0.161 | 2160 | 1170 | 99 |
|               | Layer 2 | ... | 0.199 | 2960 | 1830 | 149 |
|               | 13C pocket | ... | ... | 2740 | 1650 | 136 |
|               | End of 21st TP | 0.0093 | ... | 351 | 231 | 20 |
6. When comparing it with the previous behavior (Fig. 3a), it immediately appears that the two sets of results are almost indistinguishable. This gives us confidence in the results, even in the absence of a self-consistent model for the formation of the \(^{12}\)C pocket.

3. OBSERVATIONS OF \(s\)-PROCESS ENRICHMENT IN DISK AND HALO STARS

3.1. Un-evolved Stars

In our comparisons with compositions of \(s\)-enriched stars, we involve both intrinsic and extrinsic AGBs. The use of indices such as \([ls/Fe]\), \([hs/Fe]\), and \([hs/ls]\) calls for an assumption about the initial values of them. It is common to assume that the star, while on the main sequence, had \([ls/Fe] = [hs/ls] = 0\). These initial conditions are also adopted in the theoretical calculations. Given the increasing quality of the observational data and the sophistication of the models, it is worthwhile to review the evidence on heavy-element abundances in disk and halo stars.

Intrinsic, that is single AGB and post-AGB, stars build up their \(s\)-enrichments as they experience successive TDUs. One predicts the enrichment and \([hs/ls]\) to evolve as the AGB evolves. This evolution should be observable through abundance analyses of a large sample of intrinsic stars. Extrinsic stars gain their \(s\)-enrichments by mass transfer from an AGB companion. Then, the measured \([s/Fe]\) refers to the average \(s\)-processed material of the AGB star after dilution by mixing with the envelope of the presumed unevolved companion that is now the extrinsic, \(s\)-enriched star. If, as is often the case, considerable \(s\)-processed material is transferred, the initial composition of the star is effectively irrelevant, and the observed \([hs/ls]\) is the one of the material transferred to the secondary component. Again, predictions for \([s/Fe]\) and \([hs/ls]\) are testable using compositions of extrinsic stars.

Enrichments are quoted relative to the solar composition scaled to the metallicity of the star. Hence, \([ls/Fe]\) denotes the enrichment, provided that \([ls/Fe] = 0\) for an unevolved star of that metallicity \([Fe/H]\). This certainly appears to be the case for stars with \([Fe/H] \geq -1\), but more metal-poor stars present an interesting issue, especially those with \([Fe/H] < \leq -2.5\).

Edvardsson et al. (1993) showed that in their sample of disk stars \([Fe/H] > -0.8\) relative abundances (\([s/Fe]\)) were solar to within about 0.1 dex. Studies of more metal-poor stars were reported by Zhao & Magain (1991) for Y and Zr and by Gratton & Sneden (1994) for a sample of \(ls\) and \(hs\) elements. In the range \([Fe/H] \geq -1\) to \(-2\), there do appear to be slight departures from \([s/Fe] = 0\). Gratton & Sneden report mean values from a combination of their data with that of Zhao & Magain's measurements: \(<[s/Fe]> = 0.07\) (Sr), \(-0.17\) (Y), and \(0.20\) (Zr) for the light-\(\alpha\)-elements, with uncertainties \(\sigma\) of individual values of about 0.1 dex. For heavy-\(\alpha\)-elements, Gratton & Sneden from their own results give \(<[s/Fe]> = -0.08\) (Ba), \(-0.11\) (La), \(0.04\) (Nd), and \(0.14\) (Sm), also with an uncertainty of about 0.1 dex. Standard errors of these means are about 0.04 dex. These uncertainties are so much smaller than those associated with the measurement of abundances in intrinsic and extrinsic \(s\)-enriched stars that we ignore the small corrections that might be applied to the measured \([s/Fe]\) to account for departures from \([s/Fe] = 0\) in the star's original material. One exception to this is made when attempting to reproduce the detailed distribution of abundances, including several elements, as in the three cases discussed in \(\S\ 4\).

Metal-poor stars with \([Fe/H] < -2.5\) show an extraordinary range in heavy-element abundances (McWilliam et al. 1995, 1996; Ryan, Norris, & Beers 1996; McWilliam 1997, 1998). At a given \([Fe/H]\), ratios such as \([Sr/Fe]\) and \([Ba/Fe]\) range over 2 dex or more, from almost \(-2\) to 1. McWilliam (1998) showed that \([Ba/Eu]\) has essentially a unique value despite the enormous range in their abundances (relative to Fe), with that value being the solar \(r\)-process value. Most of the stars have a solar \(r\)-process mix of heavy elements, a mix inherited from their natal clouds that were contaminated by ejecta from perhaps one or two Type II supernovae. In light of the large range in the heavy-element to iron abundances, a signature of severe \(s\)-processing may not always be evident; for example, the addition of substantial amounts of \(s\)-processed material to a star having an initial \([Ba/Fe] \sim -2\) could still leave the star with a \([Ba/Fe]\) less than the maximum shown by unevolved stars. With certain assumptions (i.e., Eu is purely an \(r\)-process product, and the \(r\)-process nuclides are present in solar proportions), it is possible to attempt a resolution of the elemental abundances into \(s\)- and \(r\)-process contributions (Burris et al. 2000). These attempts may, however, be hampered by the recognized bimodal distribution of \(r\)-elements, the lighter species with atomic mass weight below 130–140 being produced by a different and rarer subclass of Type II supernovae than the heavier nuclei (Wasserburg & Qian 2000). In this paper, we restrict discussion to stars with a \([Ba/Fe]\) well outside the range spanned by the majority of the very metal-poor stars. We further eliminate stars for which severe enrichment by the \(r\)-process is the more plausible explanation. A few stars do appear to be highly enriched in \(s\)-process products. These are either stars on the main sequence or low-luminosity red giants; i.e., they are either binary (e.g., metal-deficient Ba stars) or were born out of gas enriched with ejecta from AGB stars. In the latter case, the meaning of “extrinsic” must be extended and should not be assumed to be always synonymous with a mass transfer binary. The only possibility that such stars are intrinsically \(s\)-enriched is that a neutron source is tapped prior to the AGB phase. The He-core flash is a conceivable suspect, but models so far have not confirmed this idea. The enormous range in \([s/Fe]\) at a given \([Fe/H]\) is a complicating factor in the identification and interpretation of \(s\)-enriched stars, whether intrinsic or extrinsic.

3.2. The \(s\)-Enriched Stars of the Galactic Disk and Halo

Galactic disk \(s\)-enriched stars, here \([Fe/H] > -1\), were considered in Paper II. They include the intrinsic MS and S stars with technetium and the cool carbon stars. Extrinsic stars include MS/S stars with no Tc, the Ba II giants, and the CH subgiants. Here we collate the observational results of the highest quality. With two exceptions, we limit discussion to analyses based on spectra recorded on Reticons or CCDs. The two exceptions are the survey of Smith (1984) and the use of the results of Tech (1971) for Capricorni by Smith & Lambert (1984). Among the now excluded stars are the cool carbon stars for which heavy-element abundances are uncertain owing to severe molecular line blanketing. For halo stars, here \([Fe/H] < -1\), we gather results from the literature. The observed values for the parameters \([ls/Fe]\), \([hs/Fe]\), and \([hs/ls]\) are listed in Table 2 together with references to the original observations. This table forms the
| Star          | Alias       | [Fe/H] | [ls/Fe] | [hs/Fe] | [hs/ls] | Type       | Reference |
|--------------|-------------|--------|---------|---------|---------|------------|-----------|
| HD 30959     |             | −0.11  | 0.9     | 0.4     | −0.5    | MS/S (Tc)  | 1         |
| HD 58521     |             | −0.18  | 0.7     | 0.5     | −0.2    | Idem       | 2         |
| HD 64352     |             | −0.25  | 0.6     | 0.4     | −0.2    | Idem       | 2         |
| HD 65712     |             | −0.17  | 0.8     | 0.6     | −0.2    | Idem       | 3         |
| HD 106198    |             | −0.04  | 0.2     | 0.1     | −0.1    | Idem       | 2         |
| HD 163990    |             | 0.09   | 0.7     | 0.1     | 0.6     | Idem       | 1         |
| HD 172804    |             | −0.06  | 1.0     | 0.9     | −0.1    | Idem       | 2         |
| HD 199799    |             | 0.17   | 0.6     | 0.3     | −0.3    | Idem       | 2         |
| HD 200527    |             | 0.06   | 0.3     | 0.2     | −0.1    | Idem       | 3         |
| HD 216672    |             | −0.07  | 0.5     | 0.4     | −0.1    | Idem       | 3         |
| BD +48°1187  |             | 0.07   | 1.4     | 1.0     | −0.4    | Idem       | 2         |
| HD 144578    |             | 0.20   | 1.0     | 1.5     | 0.5     | SC         | 4         |
| HD 198164    |             | 0.20   | 0.8     | 0.7     | −0.1    | Idem       | 4         |
| HD 286340    |             | 0.00   | 1.4     | 1.2     | −0.2    | Idem       | 4         |
| CD −52°5798  |             | 0.30   | 0.9     | 1.0     | 0.1     | Idem       | 4         |
| Average SC (see text) |        | 0.18   | 1.0     | 1.1     | 0.1     | ...        | ...       |
| HD 56126     |             | 1.00   | 1.5     | 1.4     | −0.1    | post-AGB   | 5         |
| HD 187868    |             | −0.60  | 1.4     | 0.9     | −0.5    | Idem       | 6         |
| HD 235885    |             | −0.49  | 2.4     | 2.5     | −0.1    | Idem       | 6         |
| IRAS 04296+3429 | IRAS 22272+5435 | −0.60 | 1.7 | 1.4 | −0.3 | Idem | 5 |
| IRAS 05341+0852 | GLMP 74 | −0.80 | 1.9 | 2.5 | 0.6 | Idem | 5 |
| IRAS 07430+1115 | GLMP 192 | −0.46 | 1.7 | 1.2 | −0.5 | Idem | 5 |
| IRAS 22233+4327 | GLMP 1058 | −0.30 | 1.3 | 0.9 | −0.4 | Idem | 5 |
| IRAS 23304+6147 | GLMP 1078 | −0.80 | 1.6 | 1.8 | 0.2 | Idem | 5 |
| IRAS Z02229+6208 |         | −0.45 | 1.6 | 0.8 | −0.8 | Idem | 7 |

| Star          | Alias       | [Fe/H] | [ls/Fe] | [hs/Fe] | [hs/ls] | Type       | Reference |
|--------------|-------------|--------|---------|---------|---------|------------|-----------|
| HD 25408     |             | −0.82  | 0.7     | 1.1     | 0.4     | Halo C star | 8         |
| HD 59643     |             | −0.70  | 1.4     | 2.1     | 0.7     | Idem       | 8         |
| HD 187216    |             | −2.50  | 1.4     | 2.8     | 1.4     | Idem       | 9         |
| HD 189711    |             | −1.15  | 1.4     | 2.1     | 0.7     | Idem       | 8         |
| HD 197604    |             | −0.90  | 0.4     | 1.5     | 1.1     | Idem       | 8         |

| Star          | Alias       | [Fe/H] | [ls/Fe] | [hs/Fe] | [hs/ls] | Type       | Reference |
|--------------|-------------|--------|---------|---------|---------|------------|-----------|
| HD 7531      |             | −0.13  | 0.8     | 0.7     | −0.1    | MS-S (no Tc) | 1         |
| HD 22649     |             | −0.07  | 0.8     | 0.7     | −0.1    | Idem       | 3         |
| HD 35155     |             | −0.53  | 0.7     | 1.7     | 1.0     | Idem       | 2         |
| HD 59872     |             | −0.21  | 0.7     | 0.7     | 0.9     | Idem       | 2         |
| HD 11667     |             | −0.17  | 0.6     | 0.5     | −0.1    | Idem       | 2         |
| HD 147923    |             | −0.01  | 0.4     | 0.2     | −0.2    | Idem       | 2         |
| HD 151011    |             | 0.04   | 0.6     | 0.4     | −0.2    | Idem       | 2         |
| HD 16458     |             | 0.43   | 1.3     | 0.9     | −0.4    | Ba II giant | 10        |
| HD 44896     |             | −0.25  | 1.0     | 0.9     | −0.1    | Idem       | 11        |
| HD 46407     |             | −0.42  | 1.2     | 1.1     | −0.1    | Idem       | 12        |
| HD 60197     |             | −0.05  | 0.7     | 0.7     | 0.0     | Idem       | 11        |
| HD 104979    |             | −0.47  | 0.6     | 1.0     | 0.4     | Idem       | 13        |
| HD 116713    |             | −0.29  | 1.1     | 1.1     | 0.0     | Idem       | 12        |
| HD 121447    |             | 0.05   | 0.7     | 0.7     | 0.0     | Idem       | 11        |
| HD 139195    |             | −0.24  | 0.7     | 0.5     | −0.2    | Idem       | 13        |
| HD 178717    |             | −0.18  | 0.9     | 0.9     | 0.0     | Idem       | 11        |
| HD 204075    |             | −0.11  | 1.0     | 0.9     | −0.1    | Idem       | 14, 15    |
| DM −64°4333  |             | 0.05   | 0.8     | 0.6     | −0.2    | Idem       | 11        |
| NGC 2420-D   |             | −0.45  | 0.2     | 0.5     | 0.3     | Idem       | 16        |
| NGC 2420-X   |             | −0.58  | 1.3     | 1.2     | −0.1    | Idem       | 16        |
| HD 4395      |             | 0.33   | 0.7     | 0.5     | −0.2    | CH subgiant | 17        |
| HD 11377     |             | −0.05  | 0.4     | 0.2     | −0.2    | Idem       | 17        |
| HD 88446     |             | −0.36  | 0.9     | 0.8     | −0.1    | Idem       | 17        |
| HD 89944     |             | −0.27  | 1.0     | 0.7     | −0.3    | Idem       | 17        |
| HD 125079    |             | −0.16  | 1.0     | 0.8     | −0.2    | Idem       | 17        |
| HD 182274    |             | −0.18  | 0.8     | 0.7     | −0.1    | Idem       | 17        |
| HD 204613    |             | −0.35  | 1.0     | 0.6     | −0.4    | Idem       | 17        |
set of observational constraints to theoretical predictions, extending over the whole metallicity range in the Galaxy. We have attempted to separate the stars into the categories extrinsic and intrinsic.

Brief remarks on the stars in Table 2 follow; the sample is certainly not complete, but we hope it is at least as homogeneous as possible and takes into account the most representative $s$-enhanced sources in the Galaxy. In our comments below, we begin with several classes of what are considered to be intrinsic stars:

**$MS/S$ stars with Tc.—**For a sample of intrinsic stars of disk metallicity, we select the MS and S stars that exhibit Tc lines in their spectra. The presence of Tc implies that these stars are experiencing TDU's; i.e., they are intrinsically $s$-enriched. Smith & Lambert (1985, 1986, hereafter SL85 and SL86, respectively) and SL90 analyzed 11 MS/S stars and a sample of normal M stars differentially with respect to the late-K giant LP 706, respectively (and SL90) and SL91 analyzed 11 MS/S stars and a sample of normal M stars differentially with respect to the late-K giant LP 706, respectively (and SL90). These span the metallicity range from SL85 and SL86, respectively) and SL90 analyzed 11 MS/S stars and a sample of normal M stars differentially with respect to the late-K giant LP 706, respectively (and SL90). These span the metallicity range from $-1.2$ to $0.2$. The fact that the reference stars—mainly K5 III stars—are not severely impacted by molecular line blanketing. A recent analysis of C(N) stars by Abia et al. (2001) further discusses the uncertainties in measuring C-rich spectra and partially reconsiders the SC data, suggesting the possibility of unidentified blends affecting the quantitative results. Because of this, we give lower weight to the results for these SC/S stars and represent them collectively through their mean abundances (see Table 2 and Figs. 7, 8, and 9).

**Post-AGB C-rich stars.—**The label “post-AGB” is applied to a variety of luminous warm stars. Here we pick out those that are rich in carbon, with most identified from IRAS surveys as showing a 21 μm broad emission feature. Six stars were analyzed by Van Winckel & Reyniers (2000), two by Reddy, Bakker, & Hrivnak (1999), and one by Zač, Klochkova, & Panchuk (1995). These span the metallicity

| Star | Alias | [Fe/H] | [ls/Fe] | [hs/Fe] | [hs/ls] | Type | Reference |
|------|-------|--------|---------|---------|---------|------|-----------|
| HD 216219 .......... | SAO 108214 | -0.32 | 1.0 | 0.9 | -0.1 | Idem 17 |          |
| HD 219116 .......... | SAO 165564 | -0.34 | 0.9 | 1.2 | 0.3 | Idem 17 |          |
| HD 26 .......... | SAO 109003 | -0.40 | 1.0 | 1.5 | 0.5 | CH giant 18 |          |
| BD +75°348 .......... | SAO 6630 | -0.80 | 1.4 | 1.7 | 0.3 | Extr. C giant 19 |          |

**Extrinsic Galactic Halo AGB Stars**

| Star | Alias | [Fe/H] | [ls/Fe] | [hs/Fe] | [hs/ls] | Type | Reference |
|------|-------|--------|---------|---------|---------|------|-----------|
| HD 187861 .......... | CGCS 4524 | -1.65 | 1.0 | 1.9 | 0.9 | CH giant 18, 20 |          |
| HD 198269 .......... | SAO 106516 | -1.40 | 0.8 | 1.2 | 0.4 | Idem 18 |          |
| HD 201626 .......... | SAO 89499 | -1.30 | 1.1 | 1.6 | 0.5 | Idem 18 |          |
| HD 209621 .......... | HP Peg | -0.90 | 1.1 | 2.4 | 1.3 | Idem 18 |          |
| HD 224989 .......... | BD -03°5751 | -1.60 | 0.8 | 1.9 | 1.1 | Idem 18 |          |
| CD -38°2151 .......... | SAO 196068 | -1.40 | 0.6 | 1.1 | 0.5 | Idem 18 |          |
| BD +67°922 .......... | AG Dra | -1.30 | 0.5 | 1.0 | 0.5 | Yellow symb. 21 |          |
| BD -21°3873 .......... | IV Vir | -1.32 | 0.4 | 0.5 | 0.1 | Idem 22 |          |
| He 2467 .......... | ... | -1.11 | 1.0 | 1.1 | 0.1 | Idem 23 |          |
| HD 196944 .......... | SAO 144688 | -2.45 | 0.6 | 1.3 | 0.7 | C-rich giant 24 |          |
| LP 625 -44 .......... | ... | -2.71 | 1.1 | 2.4 | 1.3 | C-rich subgiant 25 |          |
| CS 22898 -027 .......... | ... | -2.35 | 1.0 | 2.4 | 1.4 | Idem 26, 27 |          |
| LP 706 -7 .......... | ... | -2.74 | 0.3 | 1.9 | 1.6 | Idem 28 |          |
| HD 74000 .......... | SAO 154538 | -2.08 | 0.3 | 0.3 | 0.0 | N-rich dwarf 28 |          |
| HD 25329 .......... | SAO 56928 | -1.84 | 0.4 | 0.5 | 0.1 | Idem 29 |          |

### REFERENCES

(1) Smith & Lambert 1985; (2) Smith & Lambert 1990; (3) Smith & Lambert 1986; (4) Abia & Wallerstein 1998; (5) Van Winckel & Reyniers 2000; (6) Zač et al. 1995; (7) Reddy et al. 1999; (8) Kipper et al. 1996; (9) Kipper & Jørgensen 1994; (10) Tomkin & Lambert 1983; (11) Smith 1984; (12) Kovács 1985; (13) Tomkin & Lambert 1986; (14) Smith & Lambert 1984; (15) Tech 1971; (16) Smith & Sunzef 1971; (17) Smith et al. 1993; (18) Vanture 1992; (19) Zač et al. 2000; (20) A. D. Vanture 2000, private communication; (21) Smith et al. 1996; (22) Smith et al. 1997; (23) Pereira et al. 1998; (24) Zač et al. 1998; (25) Aoki et al. 2000; (26) McWilliam et al. 1995; (27) McWilliam 1998; (28) Norris et al. 1997; (29) Beveridge & Sneden 1994.
Observed abundance ratios \([\text{hs/ls}]\) in the chosen set of intrinsic and extrinsic AGB stars at all metallicities. The filled and unfilled symbols refer to intrinsic and extrinsic stars, respectively. The typical value of the observational uncertainty is shown. SC stars have been represented by their average (see Table 2). The small symbols refer to stars that have lower weight in our analysis, as explained in the text. The curves represent the predictions from the models specified on the figure itself.

Intrinsic metal-poor carbon stars.—A series of analyses on such stars have been reported by Kipper and colleagues. Kipper et al. (1996) discuss five stars with \([\text{Fe/H}]\) between \([-0.7\) and \(-1.15\). Kipper & Jørgensen (1994) analyzed a much more metal-poor star \((\text{Fe/H}) = -2.5\). Two earlier analyses (Kipper & Kipper 1990; Kipper 1992), not included in our tables because they were based on photographic spectra, were also of very metal-poor stars, \([\text{Fe/H}] = 2.8\) for HD 13826 (V Arietis) and \([\text{Fe/H}] = 2.9\) for HD 112869 (TT Cam). Interpretation of these results must bear in mind that molecular line blanketing in the spectra of these cool giants is severe and, even in the case of the most metal-poor stars, limits the accuracy of the elemental abundances: “metal abundances have quite large errors amounting to 0.5 dex due to extremely heavy blending of most metal lines by molecular lines” (Kipper & Jørgensen 1994) but in some cases (say Fe) may be 0.2 dex. The nature of blending-based errors is such that they cannot always be expected to be reduced in forming ratios such as \([\text{hs/ls}]\). As in the case of SC stars, we therefore assign lower weight to such results. The status of these stars is a little uncertain. Despite their temperatures, somewhat in excess of those for typical AGB stars, “possibly all cool halo carbon stars may have formed as intrinsic carbon stars” (Kipper et al. 1996). We therefore suppose them to be intrinsic, although this assumption should be better checked in the future. Being old objects, they should be of rather low mass, but TDU becomes more efficient for low metallicities, so that the C-star phenomenon might extend to lower masses for halo stars. Indeed, it is known that the number ratio between C stars and M giants increases at low metallicity. They are rich in \(^{13}\text{C}\), like the rather common CJ
Extrinsic stars in the Galactic disk.—We include here MS and S stars without Tc in their spectra, which are supposed to be evolved versions of barium stars. Indeed, abundance analyses by SL85, SL86, and SL90 show that they have s-enrichments like those of Ba II K-type giants. The same rules discussed for MS/S stars with Tc on the selection of ls and hs abundances apply here. We also consider the CH subgiants analyzed by Smith, Coleman, & Lambert (1993) and Ba II giants from several sources (Smith 1984; Smith & Lambert 1984; Tomkin & Lambert 1983, 1986; Kovács 1985; Smith & Suntzeff 1987). For CH subgiants, we include Ba and Nd in the hs index, as was done by Smith et al. (1993). Because of our already mentioned choices on the type of observations to include, we omit extrinsic stars from Luck & Bond (1981, 1984, 1985, 1991) because abundances were derived from photographic spectra. As shown elsewhere (e.g., Busso & Gallino 1997), those abundances can be, in general, well explained by AGB models; however, they give constraints qualitatively similar to those already provided by our more homogeneous set of data. In the class of extrinsic Galactic disk stars, we may include also the K giant BD +75°348 (Začs, Schmidt, & Schuster 2000), which has [Fe/H] = −0.8 and s-enrichment similar to those of an extreme Ba II star. One supposes it is a spectroscopic binary, but radial velocity measurements are presently lacking.

Extrinsic Galactic halo AGB stars.—In the group of Galactic halo extrinsic stars we include the objects described below:

**CH giant stars.**—A sample of these stars, the metal-poor or halo counterpart of the classical Ba II giants, were analyzed by Vanture (1992). Abundances of heavy elements were reported for seven stars with [Fe/H] from −0.9 to −1.7. A revision for HD 187861 was also suggested by A. D. Vanture (2000, private communication). Their status as extrinsic is confirmed by their designation as spectroscopic binaries (McClure 1983, 1984). Owing to the larger uncertainty in abundance determinations in these stars (in particular, HD 209621 and HD 221959), we assign lower weight to these results.

**Yellow symbiotic stars.**—Three such stars have been analyzed recently: AG Draconis (Smith et al. 1996), BD−21°3873 (Smith et al. 1997), and He 2−467 (Pereira, Smith, & Cunha 1998). “Yellow” denotes that the giant has a spectral type of G-K and, hence, its spectrum is not cluttered with the TiO lines found in redder symbiotic stars. It is fair to presume that the giant has accreted material from its companion, which is now a white dwarf but earlier was a mass-losing AGB star.

**HD 196944.**—Začs, Nissen, & Schuster (1998), who analyzed this star, considered it unlikely that it is a post-AGB star and place it as a peculiar AGB star or a CH star (i.e., extrinsic).

LP 625−44, LP 706−7, and CS 22898−027.—The first is a C-rich star with [Fe/H] = −2.7, analyzed by Norris, Ryan, & Beers (1997) and Aoki et al. (2000). With [Ba/Fe] = 2.7, it is about 2 dex more Ba-rich than the most Ba-rich normal metal-poor stars (McWilliam et al. 1995), and the ratio [Ba/Eu] = 0.8 implies s-process enrichment rather than r-process contamination (for which [Ba/Eu] = −0.8 in the solar case, which seems to be representative of the heaviest elements in metal-poor r-process–dominated stars). Aoki et al. consider, partly on the grounds of radial velocity variations, the star to be the “result of mass transfer in a binary system from a previous AGB companion” (i.e., LP 625−44 is an extrinsic star). Abundances are taken from Aoki et al. It is clear that abundances from Ba to Pb follow the pattern expected of s-processing in a metal-poor AGB star of low mass. The low abundance of Europium, a traditional tracer of the r-process, is well-fitted by the predictions of the marginal s-process contribution, which amounts to only 5% of solar Eu. The C-rich star LP 706−7 (Norris et al. 1997), with [Ba/Fe] = 2.0, is similar to LP 625−44 but slightly less evolved. It might be considered extrinsic, but proof in the form of radial velocity variations is presently lacking. CS 22898−027 (McWilliam et al. 1995; McWilliam 1998) is similarly C-rich and s-process enriched.

In contrast to this trio, there are stars, even C-rich stars, whose pattern of heavy-element overabundances is that of the r-process. The best known examples are CS 22892−052 (Sneden et al. 1996), HD 115444 (Westin et al. 2000), and CS 31082−001 (Cayrel et al. 2001), but other similar objects exist (see, e.g., Hill et al. 2000; Barbuy et al. 1997). Relative abundances of the heavy elements Ba to Pb match well the solar r-process abundances; the low [Ba/Eu] ratio is that expected of a solar-like r-process. Any possible s-process contribution to the abundances is swamped by the dominant r-process contribution. It should be noted that in very metal-poor stars, while the relative abundances of heavy elements are remarkably similar to those in the solar r-process, the ratio of the heavy- to light- elements is variable from star to star (Qian, Vogel, & Wasserburg 1998; Burris et al. 2000; Qian & Wasserburg 2001). As mentioned, this has been interpreted in the framework of a bimodal r-process coming from supernovae of different frequency (Wasserburg & Qian 2000; Sneden et al. 2000).

A pair of stars showing evidence of carbon (and nitrogen) enrichment with heavy-element abundances intermediate between pure solar r-process and an s-process was analyzed by Hill et al. (2000). That the ratio [Ba/Eu] ≈ 0.0 is intermediate between that of the r-process–dominated CS 22892−052 (≈ 0.8) and that of the s-process–dominated LP 624−44 (≈ 0.8) implies that the atmospheres of the pair are a blend of r- and s-processed material. Unfortunately, the mentioned fact that there is not a unique set of r-process abundances for light and heavy elements bedevils attempts to resolve the abundances of the Hill et al. stars into their r- and s-process components. In particular, the star-to-star variation in the ratio of the light r- to heavy r-elements necessarily compromises the extracted ratio of the ls to hs elements. Until the star-to-star variation is better understood, selection of s-process–enriched, very metal-poor stars is limited to those stars where the s-process is obviously dominant. Although the present sample is extremely small,
there is a tantalizing hint that the r-process−enriched stars like CS 22895−052 are giants and that the s-process−enriched stars like LP 625−44 are dwarfs or subgiants.

N-rich subdwarfs: HD 25329 and HD 74000.—The rare class of N-rich subdwarfs was discovered by Bessell & Norris (1982). Beveridge & Sneden (1994) analyzed two of these stars. For HD 25329, they determined the abundances of nine heavy elements, but for HD 74000, just three heavy elements were measured. These stars have metallicities of −1.8 and −2.1, respectively. An s-process enrichment is indicated for HD 25329; too few elemental abundances were given for HD 74000 to make a similar assertion. The heavy elements, as well as the N, Na, and Al enrichments, were attributed to synthesis in an AGB star, but lacking direct evidence for a companion, the possibility of contamination of the natal clouds was left open.

3.3. Observation and Theory

Estimates of [ls/Fe], [hs/Fe], and [hs/ls] were made for the stars in the previous section. Our estimates may differ from published values because we elect to consider a different mix of elements. The differences are slight, and the overall conclusions drawn from the assembled data are unaffected by whether the original or our choices of heavy elements is adopted. We adopt, in general, the published estimates of [Fe/H]; exceptions are MS/S giants, where we make use of the more reliable [M/H]-values, “M” indicating an average from Ti to Fe. Using this average changes only slightly the values of [ls/Fe] and [hs/Fe]. Here we compare the s-process indices against theoretical predictions.

The run of [hs/ls] versus [Fe/H] is shown in Figure 7, where filled and unfilled symbols refer to intrinsic and extrinsic stars, respectively. The two N-rich subdwarfs are shown as asterisks. Theoretical predictions for ST/1.5 (solid line) provide an approximate average fit to the data. For a comparison, two more lines, representing the envelope of our maximal and minimal predictions for [hs/ls] (as deduced from Fig. 3a) are shown as dashed lines. This makes clear that most observed data are explained, within the errors, by model curves. The most remarkable outliers in Figure 7 are four C-rich objects with [Fe/H] ≤ −2 (one probably intrinsic, three probably extrinsic). They are CS 22898−027, LP 625−44, LP 706−7, and HD 187216. The first has been already commented on: the absence of Y and Zr makes its data rather uncertain in our picture. The last was already recognized as a puzzle difficult to accommodate in any explanation based on LMS evolution/nucleosynthesis by Kipper & Jørgensen (1994), but it has a complex spectrum and larger than average error bars that should be attributed to its abundances. LP 625−44 was recently analyzed by Ryan et al. (2001), who found the distribution of s-elements from Ba to Pb in remarkable agreement with nucleosynthesis predictions from very low mass stars (M ≤ 1.3 M⊙). The same may hold for LP 706−9, but spectra of higher resolution are needed. A very low initial mass, in connection with possible large inhomogeneities in the parent interstellar medium at low metallicities, might be invoked for explaining the whole set of abundances in these extreme halo C-rich objects. We have problems in the fits also with IRAS 22272+5435, a post-AGB supergiant from Zącś et al. (1995). However, this star has a large uncertainty in its metal abundances (e.g., Fe is deficient, the other elements of the Fe group are overabundant, and the s-element abundances have uncertainties up to 0.5 dex) so that we must attribute a lower weight to it.

Conversion of a normal star to an extrinsic star by mass transfer from an AGB companion is not expected to change the [hs/ls] index. This expectation assumes that there is no differentiation/fractionation during the transfer of mass. Certainly, if dust and gas in the stellar wind are transferred and accreted differently, one might expect a difference owing to the selective condensation of elements into and onto grains. A cautious interpretation of Figure 7 is that intrinsic and extrinsic stars follow similar trends of [hs/ls] versus [Fe/H]. There is a suspicion voiced first by Reddy et al. (1999) and Van Winckel & Reyniers (2000) that the intrinsic post-AGB C-rich stars have a lower [hs/ls] than the Ba II stars and the CH giants. The two N-rich subdwarfs stand apart from the remainder of the sample and are also distinguished by quite mild s-enrichments, explained only by models with the lowest 13C concentration in the pocket. In what follows, we consider them separately from the majority of the sample.

The indices [ls/Fe] and [hs/Fe] are expected to be different for intrinsic and extrinsic stars with a likelihood that, if the mass transfer is not selective, extrinsic stars could show lower values than intrinsic stars of the same metallicity. Remarkably, the run (Fig. 8) of [ls/Fe] versus [Fe/H] follows the theoretical prediction for ST/1.5 for intrinsic AGBs, while extrinsic ones lie, on average, below the curves, as expected. If the predictions were reduced by only about 0.2 dex, the fit would be even more satisfactory, especially for Galactic disk stars. This can easily be achieved when one considers that model curves refer to the final AGB situation, while several intrinsic AGBs (MS and S stars) are certainly in a previous stage and therefore have not yet reached the terminal values of their s-enhancements (see § 3.4 and also Abia et al. 2001). In light of Figure 3, a better average trend can alternatively be obtained by choosing a prediction between the ST/1.5- and ST/3-values. This possibility of accounting for the observed data by varying either the efficiency of nucleosynthesis or that of mixing was already encountered in Paper I, where we showed that sometimes only the consideration of the whole distribution of s-elements (if available) can solve this ambiguity. Observed and predicted [hs/ls] indices are shown in Figure 9. Disk stars, especially for [Fe/H] > −0.5, fit the prediction for ST/1.5 reasonably well, as above. There is a hint that observations for the intrinsic stars fall below the ST/1.5 model curve around [Fe/H] ≈ −1, and the same duplicity of solutions mentioned for the ls abundances applies.

In short, the collated observations of s-enrichment in intrinsic and extrinsic stars are, as a whole, rather well accounted for by the models of s-processing and TDUs in AGB stars. In particular, predictions for the ST/1.5 case provide, at all metallicities, a sort of average trend that nicely compares with observations when the effects of mixing are taken into account. Our analysis considered a mass of 1.5 M⊙ for the AGB star. In general, this is not a critical choice; Figures 3 and 4 show a weak dependence of the predictions on initial stellar mass as long as we consider low-mass AGB stars. However, some exceptions exist. Four examples in Figure 7 have been mentioned. Three additional cases are HR 774, BD +75°348, and IRAS 07134+1005. We find a solution with 3 M⊙ models in the first two cases, and we need a mass lower than 1.5 M⊙ in the last one (also see § 4 for the peculiar case of HD 25329).
Information on the initial mass of the AGB star is provided by detailed comparisons of observed abundances with theoretical predictions for \([\text{hs}/\text{ls}], [\text{ls}/\text{Fe}], \) and \([\text{hs}/\text{Fe}],\) as deduced by Figures 3a, 3b, and 3c for \(M = 1.5 M_\odot\) and by Figures 4a, 4b, and 4c for \(M = 3 M_\odot,\) respectively. Indeed, the values of these parameters provided by the models are rather sensitive to the initial mass and to the metallicity of the model star adopted.

3.4. A Closer Look at the Role of Mixing.

Concerning the two parameters (efficiency of mixing and of nucleosynthesis) that affect the \(s\)-process distributions of Figures 7, 8, and 9, we actually have tools to discriminate their relative role thanks to the fact that models of the envelope abundances were computed pulse after pulse. An example of this is shown in Figure 10, which is the equivalent of Figure 2 of Paper I and Figure 6 of Paper II, but is computed with the new models: it is built for Galactic disk metallicity models of \(1.5 M_\odot\) and contains only data points for Galactic disk stars. The continuous lines show model envelope enrichments up to our last TDU episode for different \(s\)-process efficiencies as measured by the value of the number ratio between \(^{13}\text{C}\) and iron in the pocket. In order to understand the importance of gradual mixing, the dashed lines connect the points representing the fourth and eighth TDU episodes. The figure shows clearly how many stars have abundances that are best explained by situations less extreme than those of Figures 3 and 4, which represent the termination points in the distributions of Figure 10. In particular, several MS/S stars with technetium in their spectra find a solution only with a limited number of TDU episodes, as expected by their belonging to a class that is intermediate between unprocessed M giants and C stars. A complementary view is provided by Figures 11 and 12, where the curves (again from the \(1.5 M_\odot\) case) show model envelope compositions at different metallicities (similar to Fig. 3) in the plane \([s/\text{Fe}]\) versus \([\text{ls}/\text{ls}]\). Here \(s\) means the average of both \(hs\) and \(ls\) abundances and therefore gives integrated information on the \(s\)-element enrichment. The high nonlinearity of the models as a function of the iron content of the star can be inferred by the indication on the plot of where the high and low metallicities lie. The loops correspond to the maxima in Figure 3. While Figure 11...

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![Figure 10](image1.png)

**Fig. 10.**—Observed trend of the ls element abundances \([\text{ls}/\text{Fe}]\) vs. \([\text{ls}/\text{ls}]\) for Galactic disk intrinsic and extrinsic AGB stars. The solid curves refer to envelope models with different \(s\)-process efficiency, as monitored by the \(N^{(13)}\text{C}/N^{(56)}\text{Fe}\) ratio (here normalized to the case that fits the main component in the solar system). The dashed lines connect the points corresponding to the fourth and eighth dredge-up episode to make clear how the stars distribute along the TP-AGB evolutionary sequence.

![Figure 11](image2.png)

**Fig. 11.**—Average \(s\)-process enrichment \([s/\text{Fe}]\) as a function of the \([\text{ls}/\text{ls}]\) abundance ratio for the various classes of stars studied. The post-AGB supergiants lie in the region of the maximum \(s\)-enrichment, as expected. The curves refer to \(1.5 M_\odot\) AGB model stars. They reflect the enrichment of \(s\)-elements for different metallicities at the very end of the TP-AGB phase. The regions where the highest and lowest metallicities explored lie are indicated.

![Figure 12](image3.png)

**Fig. 12.**—Same as Fig. 11, but for a much larger dilution with an unprocessed envelope, as obtained at an initial phase of TP-AGB evolution after only four TDU episodes.
represents the situation at the end of the AGB phase, Figure 12 is constructed with the predictions after only four pulses. This last case shows the composition of a material that is highly diluted; i.e., it contains a small s-process enrichment from the He intershell. Most data points are bracketed by the predictions of the two plots, showing again that observations present to us a variety of mixing efficiencies. In these plots model curves allow one to appreciate only the total dilution; hence, one cannot discriminate between, for example, intrinsic MS stars and extrinsic Ba stars, although only the former class owes its dilution to an incomplete dredge-up of He intershell material, while the second includes mass transfer in a binary system.

There are particular and intriguing issues in the plots from Figure 7 to Figure 12. Two will be mentioned: the case of the post-AGB stars and the Ba II stars and the N-rich subdwarfs. As noted earlier (Reddy et al. 1999; Van Winckel & Reyniers 2000), there is a suggestion that the post-AGB intrinsic C-rich stars have a lower [ls/ls] than the Ba II giants. This difference of about 0.3 dex arises because of roughly equal and opposite offsets of the two groups in the indices [ls/Fe] and [hs/Fe]. Given that the atmospheres of the two groups of stars differ in temperature and surface gravity, the possibility exists that these small differences in [ls/Fe] and [hs/Fe] reflect systematic errors in the LTE analyses of either or both sets of stars. It is certainly premature to consider other explanations, among them the selective accretion of elements by the extrinsic star in a mass transfer process. Detailed comparisons of observed and predicted abundances of Ba II giants could reveal clues to the possible difference with post-AGB stars; we discuss one such case in the next section. A further remarkable point to be mentioned for post-AGB stars is that our envelope compositions at the last TP found with the stellar code can fit them quite well despite the noticeable envelope mass remaining in the models when TDU ceases. This may support the finding that TDU disappears well before the envelope is completely eroded by mass loss. The physical reason has been suggested to lay in a sudden instability of the whole envelope, driven by a sharp reduction of the gas pressure and by the establishment of a super-Eddington luminosity (Lattanzio, Forestini, & Charbonnel 2000; Swei- gart 1998; Wood & Faulkner 1986). A closer look at the N-rich subdwarf HD 25329 is given in the next section.

4. DETAILED PHOTOSPECTRAL COMPOSITIONS: A FEW EXAMPLES

As mentioned in the previous subsection, consideration of just the hs and ls enhancements may leave unclear the relative importance of the two main processes controlling the abundances, i.e., the efficiency of neutron captures and the dilution mechanisms (first through TDU and subsequently through mass transfer for the binary sources).

Disentangling the two effects is made easier when the detailed set of observations for individual elements is available, including the CNO group and other light nuclei. Indeed, the synthesis of this last group by the red giant is almost entirely unrelated to the efficiency of the neutron source. In particular, because of the rather fixed abundance of $^{12}\text{C}$ in the He intershell at the occurrence of TDU [$X(^{12}\text{C}) \approx 0.20-0.23$], the photospheric abundance ratio between carbon and s-elements helps to set independent constraints on the dilution with the envelope. One must, however, take into account the complications introduced by the possible activation of H-burning processes in the envelope, which can burn $^{12}\text{C}$ and produce $^{13}\text{C}$ and $^{14}\text{N}$. These are HBB processes, occurring in stars of intermediate mass (Lattanzio & Forestini 1999; Lattanzio et al. 2000) and CBPs in stars of mass $M \leq 2.3 \, M_{\odot}$ (Gilroy 1989; Gilroy & Brown 1991; Charbonnel 1995; Wasserburg et al. 1995; Charbonnel, Brown, & Wallerstein 1998; see also discussion in BGW99). In IMSs, when HBB is at play, the $^{12}\text{C}/^{13}\text{C}$ ratio decreases to its CNO equilibrium value of $\sim 3.5$ and remains rather low even during the TP-AGB phase. Concerning CBP in LMSs, it already reduces the $^{12}\text{C}/^{13}\text{C}$ ratio during the red giant phase, and its effects depend on the initial mass. According to observations of giant stars in Galactic clusters, this ratio is $\sim 12$ for $M = 1.5 \, M_{\odot}$. It decreases to the CNO equilibrium value for giant stars of $M \leq 1 \, M_{\odot}$ in globular clusters. During the AGB phase, it is possible for CBP to continue its operation, thus converting part of the primary $^{12}\text{C}$ mixed with the envelope by TDU into $^{14}\text{N}$ (Wasserburg et al. 1995).

When our analysis is extended toward low metallicities, the task of reproducing carefully the abundance distributions of individual sources by operating such a dilution is complicated by the need to consider the possibly highly nonsolar initial composition, characterized by a large scatter in the initial abundances of heavy nuclei. Here it is worth showing some examples in order to demonstrate that, despite this, new pieces of information can be achieved on the mass and evolutionary status of the target stars.

We therefore show in Figure 13 three examples of a thorough comparison between nucleosynthesis predictions and spectroscopic observations. For the sake of these examples, the initial abundances of the stellar envelopes have been scaled to the appropriate metallicity, following the already mentioned average trends of heavy-element abundances in the Galaxy, published by Gratton & Sneden (1994).

The cases shown were chosen because of their heterogeneity (representing high, intermediate, and low metallicities, including a Ba star [extrinsic AGB], a post-AGB supergiant, and a suspected extrinsic dwarf, and belonging to the giant, supergiant, and dwarf luminosity classes, respectively). Their characteristics and detailed fits are discussed below.

4.1. HR 774: A Ba II Giant Star in the Galactic Disk

After the pioneering work by Warner (1965), a large number of studies considered the heavy-element abundances in classical Ba II giants. HR 774, being very bright ($m_\pi = 5.96$ according to Smith 1984), has been the object of several spectroscopic observations (Tomkin & Lambert 1979, 1983; Smith 1984). Smith (1984) emphasized the relatively low $^{12}\text{C}/^{13}\text{C}$ ratio, a feature noticed in extrinsic AGB stars (in CH stars) by Wallerstein & Greenstein (1964). The set of observations adopted here is the one compiled in Paper II (Table 2) through averages of the various original observations. In particular, we accept a metallicity [Fe/H] = $-0.3 \pm 0.2$. The data are modeled by generating the expected photospheric composition by dredging up carbon- and s-process–rich material from the He intershell to the envelope, according to the TDU efficiency of the stellar code, pulse after pulse. As shown in Figure 13a, our best fit to the abundances comes from a binary system having a primary component of initially 3 $M_{\odot}$, with a rather high efficiency in s-processing (ST $\times 2$) and a low-mass secondary. In this example, the same results are obtained with two
different mass transfer approaches. One assumes a single phenomenon of accretion, at the 20th TP, with a dilution of 0.2 (i.e., one part of the AGB envelope per five parts of the atmosphere of the secondary component). The second assumes a continuous process, up to the 20th pulse, and yields a dilution of 0.4. Because of the uncertainties of mass-loss rates and our poor knowledge of how and when mass transfer phenomena occur, we do not claim that these are the only or even the best solutions. They, however, indicate that a moderately massive primary component is necessary here. In this way, we reach an agreement also for the carbon abundance (values of [C/Fe] in the 0.5–0.7 range can be obtained, depending on the assumptions made, to be compared with the 0.7 ± 0.1 observation). We found this datum difficult to reproduce otherwise.

4.2. IRAS 07134+1005: A Post-AGB Supergiant

This star belongs to the group of supergiants showing the 21 μm feature in their mid-infrared spectra, which is suspected to derive from C-rich compounds (Kwok, Volk,
& Hrivnak 1989). Observations of molecular bands from CO, CN, HCN, and C$_2$ have been reported by various authors (Bakker & Lambert 1998a, 1998b; Bujarrabal, Alcolea, & Planesas 1992), so that both the C/O ratio and the $^{12}$C/$^{13}$C ratio are known. Optical spectroscopic observations of high precision were recently presented by Van Winckel & Reyniers (2000). They found it impossible to reproduce the measured $s$-element abundances with the parameterized calculations by Malaney (1987). The more metallicity ($[\text{Fe/H}]$ instead perform this task using cases of the appropriate reproduce the measured $s$-element abundances with the parameterized calculations by Malaney (1987). The more complex $s$-process distributions of stellar models can instead perform this task using cases of the appropriate metallicity ($[\text{Fe/H}] = -1$). In the exercise shown in Figure 13b, we found a good fit to the data with a 1.5 $M_\odot$ model with a relatively low efficiency in $s$-processing (ST/3). With our choice for mass loss, the fit requires 10 pulses; at this phase, the carbon and nitrogen enrichment are also compatible with observations ($[\text{C/Fe}] = 1.3$, $[\text{N/Fe}] = 0.9$), in which observed values are $1.1 \pm 0.1$ and $0.85 \pm 0.15$, respectively. The suggested number of pulses is highly model-dependent. Anyway, it indicates that the parent star was probably of an initial mass lower than 1.5 $M_\odot$, therefore experiencing only a limited number of TDU episodes.

4.3. HD 25329: A Star From an $s$-enriched Cloud or a Metal-poor Ba Dwarf?

HD 25329 is currently classified as a halo dwarf and is not particularly C-rich, but is very N-rich. Beveridge & Sneden (1994) conclude that the star has a metallicity $[\text{Fe/H}] = -1.8$ (possible uncertainty is of the order of $\pm 0.2$ dex). These authors derived C, N, and O abundances as well as abundances of light, iron peak, and heavy elements. Gay & Lambert (2000) showed that HD 25329 is marked by an apparently high abundance of the isotopes $^{25}$Mg and $^{26}$Mg relative to $^{24}$Mg. It shows $^{26}$Mg/$^{24}$Mg $\approx 0.09$, where this ratio is 0.03 in the normal subdwarf HD 103095 of a slightly higher metallicity.

Spectroscopic observations revealing enrichment in heavy elements were presented early by Peterson (1981a, 1981b), who attributed them to explosive nucleosynthesis. Subsequently, Beveridge & Sneden (1994) obtained high signal-to-noise ratio spectra from which they derived the abundances of $s$-elements that we analyze here. These authors suspected that the enhancements of heavy nuclei might originate in the He-burning shell of an AGB star but, since they could not confirm this star to be a spectroscopic binary, suggested that HD 25329 formed from gas polluted by ejecta from one or more AGB stars. The higher than expected abundance of $^{25}$Mg and $^{26}$Mg relative to $^{24}$Mg suggests that the ejecta came from intermediate-mass AGB stars. Our attempts to fit the abundances of this $s$-enriched dwarf may confirm this conclusion (see below).

We addressed the problem through two exercises whose results are shown in Figure 13c. In the first attempt (lower panel), excluding for the moment Mg isotopes, we succeed in reproducing the observed $s$-process data within their uncertainties as well as the relatively low C abundance by adopting a model of very low efficiency in neutron production (ST/12). The fit shown adopts an initial mass of $M = 1.5 M_\odot$. The $s$-element abundances must not grow too much in the AGB primary star because the observed enhancements are rather small. This can be obtained, for example, if the primary component experiences only a limited number of TDU episodes (less than 10, as assumed in the figure; this may be rather typical for these metallicities and also allows one to limit the carbon enrichment, which in our model is $[\text{C/Fe}] = 0.5$, against an observation of $0.6 \pm 0.1$). A good fit to the $s$-abundances can be obtained either with a unique mass transfer episode at the eight TDU episode, yielding a dilution of 0.33 (i.e., one part of the AGB envelope over three parts of the companion’s atmosphere) or with a continuous addition, lasting from the first to the eighth TDU episode (and in this case, a larger fraction of the observed material would come from the AGB envelope, yielding a dilution of 0.54 because of the lower $s$-enrichment in the first pulses). These details are, however, very model-dependent. In this example the enhancements of N and $^{25,26}$Mg cannot be explained, and we would be forced to assume that these anomalies are inherited from the parent cloud. In a second exercise (upper panel), we showed that $s$-process abundances might also derive from a mass transfer episode from an IMS primary of initially 5 $M_\odot$. This second exercise needs a noticeable $^{13}$C concentration in the pocket (for the assumptions in IMSs and the definition of what is the “ST case” there; see, e.g., Travaglio et al. 2001). This solution is, however, not completely satisfactory for the light elements. Indeed, to reach the observed abundances, we have to assume that several pulses were made by the primary component to compensate for the large dilution in the massive AGB envelope. This leads to a C-rich secondary (C/O $> 1$), which is contrary to the observations. We might obviously assume that HBB burns this extra carbon (Lattanzio & Forestini 1999), but we did not apply a proper model to this. Also, $^{26}$Mg becomes too high, with an $^{26}$Mg/$^{24}$Mg ratio close to 0.3 for an initially solar Mg isotopic mix.

We therefore prefer the idea advanced by Beveridge & Sneden (1994), according to which this source might have formed from a natal cloud previously contaminated in $s$-process elements by a few AGBs, including at least one IMS. Unfortunately, our arguments are not strong enough to exclude completely the alternative hypothesis that it is a low-metallicity Ba dwarf born with somewhat anomalous light-element abundances. From Figure 13c, we can, however, at least get a tool to discriminate the mass of the contaminating sources. As shown by the two distributions, the requirements imposed by the other $s$-elements yield in the two cases very different predictions for Pb, which is expected to be very high if IMSs were at play here. We leave this tentative suggestion to future observational tests.

5. CONCLUSIONS

In this paper we have shown how present AGB modeling can satisfactorily account for the $s$-element enrichment observed at the surface of intrinsic and extrinsic AGB stars of different metallicities, from solar down to extreme halo composition. Agreement between model predictions and average observed abundances for heavy (Ba-peak group) and (light Zr-peak group) $s$-elements can be obtained by varying over a rather narrow interval the abundance of $^{13}$C burnt per nucleosynthesis episode. The almost linear relationship between the neutron flux–sensitive parameter [hs/ls] and [Fe/H], which roughly holds at Galactic disk metallicities, breaks down for halo stars. The reason for this is primarily that at very low [Fe/H]-values, the number of neutrons captured by iron seeds and their progeny becomes so large that the $s$-process path is followed to its end at
\[^{208}\text{Pb}\] and (at a lower extent, at \[^{209}\text{Bi}\]) The [hs/ls] parameter grows with the total s-enrichment [s/Fe] in the envelope, with a functional relationship that appears roughly linear for post-AGB stars (as noticed by Van Winckel & Reyniers 2000) but in reality displays a looplike trend and is different for AGB and post-AGB stars, reflecting different dilution factors of the s-processed material with the envelope. We also showed how the models can account for the detailed distributions of s-elements and for the abundance of CNO nuclei, when they are available, and how this type of comparisons can add new pieces of information concerning the initial mass, the number of TPs occurred, and the dilution efficiency for extrinsic AGB stars.

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