1995ApJ...446..775B

THE ASTROPHYSICAL JOURNAL, 446:775–792, 1995 June 20
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NUCLEOSYNTHESIS AND MIXING ON THE ASYMPTOTIC GIANT BRANCH. II. CARBON AND BARIUM STARS IN THE GALACTIC DISK

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Received 1994 August 29; accepted 1994 December 22

ABSTRACT

We study the role played by nucleosynthesis processes in thermal pulses and by mixing episodes (the third dredge-up) in determining the abundances of intrinsic and extrinsic asymptotic giant branch (AGB) stars. This is done by comparing results from AGB models with observations of *s*-process and CNO nuclei in C stars (N-type) and in various classes of Ba stars (Ba dwarfs, CH subgiants, and Ba II giants) with metallicities typical of the disk population. The complementary information coming from abundances of Li and Mg isotopes is also discussed. According to a generally accepted scenario, the main neutron source at the origin of *s*-process nucleosynthesis is assumed to be the reaction $^{13}C(\alpha, n)^{16}O$; a minor contribution derives also from the marginal activation of the reaction $^{22}Ne(\alpha, n)^{25}Mg$ at the end of each flash. Making use of the latest neutron-capture cross sections and parameterizing the amount of ^{13}C burnt per pulse, we compute the nucleosynthesis occurring in the He shell and the dredge-up of material to the surface according to recent AGB models. Using envelope abundances after the first dredge-up derived from observations of first-ascent red giants and adopting standard prescriptions for mass loss, we succeed in fitting the photospheric compositions of C and Ba stars within their uncertainties. Our results confirm that C stars (N-type) are evolutionary descendants of normal (Tc-rich) S stars and are characterized by the same spread in mean neutron exposures (0.2–0.4 $mbarn^{-1}$). As for the binary Ba stars, their abundances are compatible with the from an AGB primary component to a dwarf or giant secondary. We show that several constraints, including the Mg isotope ratios and the neutron density derived from the Rb/Sr ratio, require that *s*-processing occur in low-mass AGB stars but exclude the possibility that barium stars derive from primaries of intermediate mass ($3 \leq M/M_\odot \leq 8$) efficiently burning the neutron source ^{22}Ne. The *s*-process–enriched binary Ba giants show mean neutron exposures covering a wider range, reaching higher values (up to 1.0 $mbarn^{-1}$) than for normal (single) C stars. An inverse correlation of the mean neutron exposure with metallicity is also present. Hence, the higher efficiency in *s*-processing shown by several Ba stars is interpreted as an indication that the metallicity range they cover is larger than for intrinsic AGB stars commonly observed. In fact, if the amount of primary ^{13}C burnt is roughly constant for the studied stars, their effectiveness in producing neutron-rich nuclei must increase (nonlinearly) toward lower metal contents. In this scenario the exponential distributions of neutron exposures provided by low-mass AGB stars can account well for the *s*-process abundances observed in Population I AGB stars, with no need to invoke strong single neutron exposures, as sometimes suggested in the past.

Subject headings: nuclear reactions, nucleosynthesis, abundances — stars: AGB and post-AGB — stars: carbon: — stars: evolution — stars: interiors

1. INTRODUCTION

Thermally pulsing asymptotic giant branch (TP-AGB) stars were recognized 20 years ago as a suitable site for the nucleosynthesis of neutron-rich elements (Ulrich 1973) because the repeated occurrence of He-shell thermal instabilities can give rise to an exponential distribution of neutron exposures, as is required to account for the solar system *main s*-process component, i.e., *s*-nuclei with $A \geq 85$ (Seeger, Fowler, & Clayton 1965).

The first quantitative calculations of nucleosynthesis in TP-AGB models were made for intermediate-mass stars ($3 \leq M/M_\odot \leq 8$, hereafter IMSs) which, during the convective pulses, develop hot He-burning shells ($T_{bottom} \geq 3 \times 10^8$ K), thus activating the neutron source $^{22}Ne(\alpha, n)^{25}Mg$ (Iben 1975; Truran & Iben 1977). Subsequently, new observational evidence shed doubts on the idea that IMSs were the main site where *s*-process nucleosynthesis occurs. First, the models predicted that thermally pulsing red giants would become carbon stars (N-type) with magnitudes brighter than $M_{bol} \sim -6.5$, while most Magellanic Cloud C stars are fainter than $M_{bol} \sim -4$ (Blanco, McCarthy, & Blanco 1980; Iben & Renzini 1983). Second, the distribution of *s*-elements created by the $^{22}Ne(\alpha, n)^{25}Mg$ reaction differs from the solar system distribution for intrinsic reasons of nuclear physics (Despain 1980; Howard et al. 1986; Busso et al. 1988).

There is, however, evidence (Wood, Bessell, & Fox 1983) that some very luminous long-period S-type variables exist on the AGB; they are oxygen rich instead of carbon rich, probably due to the consumption of carbon through the CN cycle at the bottom of the convective envelope (so-called hot bottom burning, hereafter HBB). The pulsation periods and luminosities suggest that they are IMSs (Vassiliadis & Wood 1993). Hence, IMSs and their thermal pulses still have to be invoked, in conjunction with models for the HBB process (Blöcker & Schönberner 1991; Boothroyd & Sackmann 1992) to account

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1995ApJ...446..775B

for the brightest AGB stars in both our Galaxy (Wood 1981; Jones et al. 1982; Luck, Bond, & Lambert 1990) and the Magellanic Clouds (Smith & Lambert 1989), enriched in *s*-elements and in ^{7}Li (Plez, Smith, & Lambert 1993).

For the much more common *s*-process–rich and Li-poor AGB stars of lower luminosity, an alternative picture had to be developed (Iben & Renzini 1982a, b; Hollowell & Iben 1988; Gallino et al. 1988). According to it, some mixing of protons from the envelope into the intershell region after each pulse can lead to the formation of a tiny layer enriched in ^{13}C (and ^{14}N). At ingestion of this layer by the next He-shell instability neutrons are released through the ^{13}C(α, n)^{16}O reaction. This reaction is efficient at temperatures lower than the ^{22}Ne(α, n)^{25}Mg one and can hence occur in low-mass stars ($M \leq 3\ M_{\odot}$, hereafter LMSs) evolving at relatively low luminosities.

The nucleosynthesis induced by the ^{13}C(α, n)^{16}O neutron source in LMSs has been shown to match a number of other important observational constraints. First of all, it can reproduce both the main *s*-process component in the solar system and several isotopic anomalies in interstellar grains recovered from pristine meteorites (Käppeler et al. 1990; Gallino et al. 1990b; Gallino, Raiteri, & Busso 1993; Wasserburg et al. 1994). Second, it accounts for the nearly solar Mg isotopic ratios observed in low-mass AGB stars of the Galactic disk, while the alternative ^{22}Ne(α, n)^{25}Mg source would produce large enhancements of ^{25}Mg and ^{26}Mg (Clegg, Lambert, & Bell 1979; Tomkin & Lambert 1979; Malaney & Lambert 1988). Finally, the *primary* production mechanism of ^{13}C (Clayton 1988; Gallino 1989), i.e., its being synthesized directly from hydrogen through H- and He-burning processes, naturally predicts the increase in the neutron exposure observed for low-metallicity stars (Luck & Bond 1991; Vanture 1992; Smith 1993; Plez et al. 1993) and the constancy of the [Ba/Fe] ratio in unevolved disk stars (see, e.g., Mathews, Bazan, & Cowan 1992). It also offers an astrophysical scenario for the so-called strong *s*-process component, where a substantial fraction of ^{208}Pb is synthesized (Gallino et al. 1990a).

Production of an adequate amount of ^{13}C to run the neutron source relies on subtle partial mixing processes at the interface between the envelope and the He zone. Such mixing has to date been predicted to occur only for models of Population II stars (Iben & Renzini 1982a, b; Hollowell & Iben 1988). Therefore, for models of Population I stars it has become necessary to derive external constraints on the amount of ^{13}C that is required to explain the *s*-process distributions in various Galactic environments (solar system, unevolved stars, evolved red giants). Such an analysis can then be used as a guideline for improving our understanding of how the ^{13}C neutron source is activated.

Among these constraints, of particular importance are the direct observations of red giants with enhanced *s*-element abundances. Following Lambert (1991) we divide them in two classes: (1) intrinsic TP-AGB stars—they include MS, S, and C (N-type) stars showing the unstable nucleus ^{99}Tc ($t_{1/2} = 2 \times 10^5$ yr) as evidence that they are presently undergoing nucleosynthetic activity, and (2) extrinsic TP-AGB stars—they include the various classes of G- and K-type Ba stars and the cooler S and C stars not showing Tc that are thought to be former Ba stars which have evolved up to the red giant tip or to the early AGB phase.

In a previous paper (Busso et al. 1992, hereafter Paper I) we used a simplified scheme of AGB evolution (assuming mass loss and dredge-up) and extensive computations of nucleosynthesis in thermal pulses to analyze MS and S giants (both with and without Tc), showing how their photospheric abundances can be explained on the assumption that the reaction ^{13}C(α, n)^{16}O is the main neutron source. Here we continue that analysis by considering the constraints provided by the C giants (N-type), AGB stars more evolved than the MS and S giants, and by the extrinsic AGB stars, which are commonly believed to result from mass transfer across a binary system as a thermally pulsing primary star transfers mass to the secondary which we now see as *s*-process enriched (Lambert 1985).

Most of the optically visible N-type giants are probably LMSs (below 2 $M_{\odot}$; see Claussen et al. 1987). They show strong enhancements of *s*-process elements (Utsumi 1985) and have a C/O ratio close to 1 (Lambert et al. 1986; see also Olofsson et al. 1993a, b).

It has been often assumed (Renzini 1981) that mass loss grows along the AGB continuously, reaching high rates (the so-called superwind) only at the end, when the star is at high luminosity. The wind is accompanied by dust grains which shroud the star and drive the wind itself through radiation pressure. Willems & de Jong (1986) have proposed an alternative scenario, in which the visually bright carbon stars are seen as a transition regime with low wind rates. High mass-loss efficiency is instead ascribed to the Mira (pulsating) phases. Oxygen-rich Mira variables are assumed to lose mass in a radiation-pressure–driven wind containing silicate grains. This model assumes that, when dredge-up of carbon converts the envelope from oxygen to carbon rich, formation of silicate grains is inhibited and the dust-enshrouded oxygen-rich star is exposed to view as a carbon star with C/O $\sim$ 1. After one to a few additional thermal pulses (Kwok, Volk, & Hrivnak 1989; Claussen et al. 1987; Olofsson et al. 1993a, b) mass loss may resume at high rates as radiation pressure on carbon dust grains like SiC drives a strong wind. Hence, infrared carbon stars may be formed. Willems & de Jong's idea does account for the fact that the C/O ratios of optically bright carbon stars are in the main close to unity but the C/O ratios of carbon-rich planetary nebulae extend to higher values.

In conclusion, according to both the above models, visually bright carbon stars may not be fully representative of the most evolved stars on the AGB; indeed, at the high mass-loss rates that seem to characterize the end of AGB evolution, the star is likely to be obscured by circumstellar dust grains. One must keep in mind that, in evolving from an optically bright carbon star to a dust-enshrouded one, the star may undergo significant additional changes of composition. Some constraints on the composition of these obscured stars may be gathered indirectly from compositions of planetary nebulae (PNs).

At the highest luminosities achieved by the most massive AGB stars ($M > 5\ M_{\odot}$) the base of the convective envelope is predicted to be so hot that H burns and, through the CN cycle, the C/O ratio may be reduced again below unity to produce an oxygen-rich (now also nitrogen-rich) star. The AGB stars experiencing this reconversion may also synthesize lithium. "Super-Li" AGB stars are known in the Galactic disk, but little data is yet available on their compositions. Li-rich stars in the Small Magellanic Cloud (Plez et al. 1993) are *s*-enriched, but fall at the lower end of the metallicity range considered here and shall not be discussed in detail in this paper.

There is now evidence that C stars of a population intermediate between low-mass N-type giants (Claussen et al. 1987) and very bright, Li-rich and O-rich AGB objects do exist: see,

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1995ApJ...446..775B

e.g., Zuckerman & Dyck (1989) and Barnbaum, Kastner, & Zuckerman (1991). However, for this class of red giants, having probably initial masses of 3–4 $M_{\odot}$, and whose energy is radiated mainly at infrared wavelengths, no data on *s*-process abundances are available.

As for those binary systems in the Galactic disk showing Ba star peculiarities (i.e., an overabundance of *s*-process nuclei and the presence of a white dwarf companion), the most plausible scenario leading to their formation was recently summarized by Jorissen & Mayor (1992). According to that scheme, they result from binaries which, due to their rather wide separation, avoid the Roche lobe overflow and subsequent common envelope evolution, which would lead to the formation of a cataclysmic variable. Once the more massive primary has reached the AGB, those systems having orbital periods in a critical interval undergo a phase of *wind accretion* mass transfer (Boffin & Jorissen 1988), during which the secondary component captures part of the material escaping from the AGB star envelope and, hence, becomes enriched in C and *s*-process isotopes, while the primary evolves to a white dwarf. Rare objects, like HDE 332072 (Jorissen & Mayor 1992) and HD 191589 (Brown et al. 1990), characterized by an AGB primary with a main-sequence companion, are probably systems observed very close to the time of mass transfer and before primary has completed its transition to a white dwarf.

The abundance determinations used to constrain the models for the above-mentioned classes of peculiar stars are summarized in §§ 2 and 3. We try to account for these abundances, and for the evolutionary status of the sample stars, adopting the same technique as in Paper I; i.e., the ascent of a star along the AGB is followed, taking into account the growth of the core mass due to nuclear burning in the H and He shells, the dredge-up of nucleosynthesis products from the intershell region to the surface, and the envelope erosion by mass loss. The models used to predict the photospheric abundance distributions are outlined in § 4. They complement what has already been described in Paper I by considering, aside from the simplified scheme of thermal pulse structure assumed there, a more detailed description of the convective instabilities and of their changes from one cycle to another, as derived from recent AGB models. In § 5 the main results of the analysis are discussed for the various classes of sources considered. The question of the neutron density experienced by TP-AGB stars during the neutron irradiations and the proposed alternative scenario of a single neutron exposure are examined in § 6. Finally, the main conclusions are drawn in § 7.

2. *s*-ELEMENT ABUNDANCES OF C AND Ba STARS

We focus attention on C and Ba stars in the Galactic disk which share the characteristics of low mass ($M < 2\ M_{\odot}$; see Feast 1989) and a metallicity [Fe/H] > -0.8. More metal-poor AGB and barium stars are, of course, known. In what follows we make no more than a few allusions to the observed compositions of these metal-poor stars; we expect to discuss them in a dedicated work.

In this and in the next section, we collate and comment on the data relating to chemical compositions of the carbon, S, and barium stars. Of particular interest are the abundances of the *s*-process elements, including the ratio of the *light* (Sr, Y, and Zr; hereafter ls) to the *heavy* (Ba, La, Nd, and Sm; hereafter hs) elements, that is a measure of the neutron exposure. Complementary to these are the abundances of carbon, nitrogen, and oxygen, the $^{12}C/^{13}C$ ratio, as well as the metallicity. Additional constraints are set by the lithium abundance and by the isotopic ratios of Mg. Our emphasis is on relations between the compositions of intrinsic AGB stars—the mass donors in the binary systems—and the various forms of barium stars—the mass gainers in the binary systems. We do not search here for correlations between the composition of the barium stars and the orbital characteristics of the binaries.

For the carbon stars, we take data on compositions from Lambert et al. (1986) for C, N, and O and from Utsumi (1985) for the heavy (*s*-process) elements.

Intrinsic AGB stars are presumed to be representative of the original mass-losing red giant in a binary system that now holds a Ba star. In the LMS case considered here, if mass loss steadily increases along the AGB (Renzini 1981), the red giant primary donating mass to the companion due to these winds will most likely be a carbon star; i.e., repeated dredge-up from the He shell has made carbon more abundant than oxygen before mass loss becomes efficient enough to start mass transfer.

In principle, if Willems & de Jong's scenario (in which the mass-loss rate is not monotonically growing) is instead accepted, the mass transfer of Ba stars might also occur while the primary is in an (actively mass-losing) O-rich Mira phase, before the C star is formed. We shall try to derive some constraints on these two alternative views from the different expected nucleosynthesis patterns (see end of § 5.1)

Since even a small difference in the initial masses of the two stars provides for a companion on the main sequence at the time the primary has evolved to the AGB, on cessation of mass transfer the secondary is most probably a dwarf or a subgiant with chemical peculiarities (Green, Margon, & MacConnell 1991; Jorissen & Boffin 1992)—in rare cases, a classical Ba giant (Lambert 1985; Barbuy et al. 1992) with a white-dwarf companion, the remnant of the previous AGB primary. Subsequently, the dwarfs evolve into Ba giants. In this framework, S stars without Tc should be in most cases evolved Ba stars that have reached the tip of the red giant branch or are evolving to the AGB (see Smith & Lambert 1987; Jorissen & Mayor 1988; Brown et al. 1990); afterward they too will experience thermal pulses, becoming "born again" extrinsic S stars. These S stars may dredge up sufficient carbon to be converted to carbon stars. Such an evolutionary sequence requires that there be continuity in the compositions of the Ba stars: for example, the abundances of *s*-process elements should be similar across a sample of Ba dwarfs and giants, but a systematic lowering of the carbon abundances in Ba giants is expected as a result of the first dredge-up experienced as a star evolves up the red giant branch for the first time. (Of course, the evolutionary sequence may be altered if mass transfer is again initiated as the Ba star swells in size—see Jorissen & Mayor 1992 for a full discussion of alternative scenarios.) There must also be similarities between the compositions of the intrinsic S and carbon stars and the various classes of Ba stars.

2.1. *Carbon Stars*

Optical spectra of carbon stars are marked by a dense picket fence of molecular lines primarily from C_2 and CN. Infrared spectra are only a little less crossed with molecular lines. Molecular lines, including many which cannot be correctly identified on the basis of limited laboratory spectroscopy, are so numerous that searches for lines of trace elements such as those attributable to the *s*-process seem set to end in frustration. Fortunately, one or two "windows" do exist between

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1995ApJ...446..775B

molecular bands. Utsumi (1967, 1970, 1985) searched two windows (4750–4900 Å and 4400–4500 Å) for lines of *s*-process elements. For a sample of 12 carbon stars Utsumi (1985) gives abundances of Y, Zr, Ba, La, Nd, and Sm (relative to Ti). (We do not discuss results for the ^{13}C-rich *J*-type cool carbon stars RY Dra, Y CVn, and WZ Cas, nor for a set of ^{13}C-rich R stars which are not significantly enhanced in the *s*-process elements; Dominy 1984.) The analysis was based on empirical curves of growth for the heavy elements and titanium using theoretical *gf*-values. Utsumi states the accuracy of the abundance ratios with respect to Ti to be $\sim$0.4 dex. He gives the abundances relative to solar values tabulated by Allen (1976), which differ noticeably from more recent and more accurate values (Anders & Grevesse 1989): corrections to Utsumi's values of [N_i/Ti] to account for revisions of the solar abundances range from -0.62 for Y to $+0.20$ for La.

For the most part, the individual ratios for a particular star seem consistent with Utsumi's estimated accuracy of 0.4 dex. For example, the mean (corrected) difference between [Y/Ti] and [Zr/Ti] is -0.2 ± 0.4 for the 12 stars and -0.05 ± 0.25 if TU Gem with a large difference between [Y/Ti] and [Zr/Ti] is excluded. Predicted abundance patterns (see below) require [Y/Ti] and [Zr/Ti] to be almost equal, as found by Utsumi with an observational scatter that is seemingly dominated by the estimated uncertainty of 0.4 dex. The La/Nd/Sm ratios are similarly equal from star to star within the 0.4 dex uncertainty: [La/Nd] = 0.4 ± 0.3 and [La/Sm] = 0.0 ± 0.4. The [Ba/La] ratio (= -0.4 ± 0.7) shows a larger scatter that we presume is due to the greater difficulty of measuring the Ba abundances.

The [ls/Ti] from Y and Zr ranges from 1.0 to 1.8 for a mean value of [ls/Ti] = 1.3 ± 0.2, where the spread suggests that intrinsic scatter is small. An index [hs/Ti] from Ba, La, Nd, and Sm ranges from 0.8 to 1.5 for a mean value 1.2 ± 0.2. Our measure of the neutron-exposure–related parameter [hs/ls] ranges from -0.8 to 0.1 for a mean value of -0.15 ± 0.3. If two possibly discrepant or exceptional stars (ST Cam and RS Cyg) are dropped, the remaining 10 stars give a mean [hs/ls] = -0.05 ± 0.15. This small dispersion again suggests that the intrinsic scatter is small.

Results for other groups of stars are generally expressed relative to the iron abundance. Formally, carbon star data can be put under this same notation by applying the appropriate correction to transform [Ti/Fe] from the solar abundances selected by Allen (1976) to current values which for Ti and Fe are taken from Grevesse & Noels (1993). Meteoritic and solar Ti abundances differ by 0.1 dex; we adopt the former which is the value given by Anders & Grevesse (1989). On the assumption that [Ti/Fe] = 0 for the carbon stars, the modified values of [ls/Ti] and [hs/Ti] from Utsumi should be decreased by 0.1 dex to give [ls/Fe] and [hs/Fe]; [hs/ls] is, of course, unaffected by changes to the adopted solar Ti and Fe abundances. Should the carbon stars (whose metallicity is not well known) be metal poor ([Fe/H] < -0.4), then the [Ti/Fe] would be expected to be slightly greater than 0 (Edvardsson et al. 1993).

2.2. *MS and S Stars*

Elements contributing to the "ls" and "hs" indices vary from sample to sample. If indices compiled from different mixes of elements are combined, there will be small offsets between them. We have therefore adjusted the indices for unobserved elements using the relative abundances of a $\tau_0 = 0.4$ mbarn^{-1} calculation (see § 4, and in particular Fig. 5, which is discussed there).

As an example, abundances of the heavy elements Y, Zr, and Nd for a sample of intrinsic and extrinsic MS and S stars were determined by Smith & Lambert (1985, 1986, 1990). In order to express their results in the same scale used for carbon stars, we have to correct [Nd/H] to [hs/H], where [hs/H] is the mean abundance of Ba, La, Nd, and Sm. In order to do this we estimate, from the calculations reported in § 4, that the original abundance of Nd (an element which is only at 50% of *s*-origin) has to be increased by 0.11 dex before the data for MS and S giants are, as in Figure 1, compared with those of other types of stars.

Since the predicted abundances of Sr, Y, and Zr are very nearly the same, in the element distribution with $\tau_0 = 0.4$ mbarn^{-1} we make no correction to the reported [ls/H] to account for unobserved elements from this trio.

2.3. *Barium Giant Stars*

The heavy-element abundances of classical (or giant) barium stars have been the subject of many investigations, with Warner's (1965) as the first rather comprehensive study. Our selection from the literature has concentrated on recent analyses and emphasized those studies that used high-S/N spectra, model atmospheres, and ionized lines. Neutral lines have been considered only if the analysis was done differentially with respect to a similar giant; the reason for this criterion is that there are evidently quite severe non-LTE effects as demonstrated by Tomkin & Lambert (1983), who also showed that these effects cancel almost completely in a differential analysis. Figure 1 presents the abundances [Fe/H] and [hs/ls] for 16 barium giants; the index [hs/Fe] is corrected, as described above, for unobserved elements. The original data were from Tomkin & Lambert (1983, 1986), Kovacs (1985), Smith (1984); Smith & Suntzeff (1987), Luck & Bond (1991), Tech (1971), and Smith & Lambert (1984).

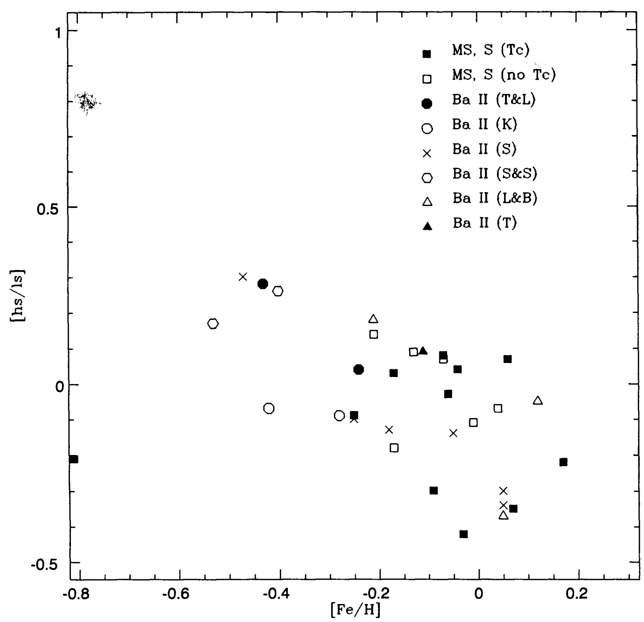

FIG. 1.—Trend of [hs/ls] as a function of the iron abundance [Fe/H] for 16 barium stars and for MS and S stars with and without Tc. The data for barium stars are from Tomkin & Lambert (1986), Kovacs (1985), Smith & Suntzeff (1987), Smith (1984), and Luck & Bond (1991). For MS and S stars, the data are from Smith & Lambert (1990). The corrections discussed in § 2.2 have been applied to put the data on the same scale.

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1995ApJ...446..775B

Inspection of Figure 1 suggests that [hs/ls] increases with decreasing [Fe/H]: the increase is ~ 0.2 dex in [hs/ls] for a drop in [Fe/H] from 0 to about -0.5. This result should probably be considered tentative as it is based on a combination of analyses made by different authors in slightly different ways and the spread in [hs/ls] is barely larger than the errors of measurement of some or even all of the analyses. It should be noted that the effect, if real, is intrinsic to barium stars and not a general property of slightly metal-poor stars—see Edvardsson et al.'s (1993) sample of F dwarfs for which [Ba/Nd] is independent of [Fe/H] over the range shown in Figure 1. We comment below on a similar trend of [hs/ls] in barium dwarfs and CH subgiants. Metal-poor barium stars continue the trend shown in Figure 1—see Figure 2 where we include CH giant stars analyzed by Vanture (1992), as well as the S star HD 35155 from Smith & Lambert (1990) with an [hs/ls] placing it outside the range covered by Figure 1.

Apart from its tendency to increase with decreasing [Fe/H], [hs/ls] shows little or no scatter from star to star. The mean for the 16 stars is [hs/ls] $= 0.03 \pm 0.18$ and is consistent with the mean for the carbon stars. (The metallicity of the carbon stars is poorly known so that it is not possible to compare them with barium stars of the same metallicity.)

Few barium stars have been investigated so thoroughly that a detailed study of the heavy-element abundances is warranted. For the few cases in which the information exists we have made a detailed fit to the abundance pattern: examples are HD 44796 from Smith (1984), HR 774 from Tomkin & Lambert (1983), and ζ Cap (see summary given by Lambert 1985). These comparisons are given in Figures 11 and 12 (see § 5.2).

In contrast to the case of the carbon stars analyzed by Utsumi (1985), there is in the sample of barium giants a clear range in the level of the *s*-process enrichment, as anticipated in the labels "classical" and "mild" attached to these stars from inspection of their spectra. Kovacs (1985) remarked upon the correlation between [Ba/Fe] and [Fe/H]: the metal-poor stars showed the greater enrichment of the *s*-process elements. The present collection of barium giants shows a less well defined correlation, but the upper envelope in the [hs/Fe] (or [ls/Fe]) versus [Fe/H] plane shows the correlation noted by Kovacs. Mild barium stars fall below the upper envelope and impair the correlation. This impairment is expected, on the mass transfer hypothesis, as the result of a higher dilution of mass transferred from the AGB primary to the envelope of the companion. The AGB stars instead, as in general for the cool carbon stars discussed in § 2.1, probably did not show a large spread in their heavy-element abundances; this is consistent with the expectation that many thermal pulses and subsequent dredge-up of *s*-processed material occur before the envelope of an AGB star is converted from oxygen rich to carbon rich (see also § 5); the atmosphere's *s*-process enrichment is substantial before the S star is converted to a C star. (A mild selection effect has also been introduced into the carbon star sample as we omitted the J-type [^{13}C-rich] stars which are known not to be enriched in the heavy elements; Dominy 1984.)

2.4. *Barium Dwarf and Subgiant Stars*

Barium dwarfs predicted by the mass transfer hypothesis long eluded discovery. The CH subgiants found by Bond (1974) are obvious relatives but appeared in a restricted range of effective temperature for which there was no obvious explanation according to the mass transfer hypothesis. Now, a sample of barium dwarfs at earlier spectral types is known, thanks largely to the work of North and his colleagues in studying stars classified by Bidelman (1981, 1983, 1985) as F dwarfs with strong Sr lines—see also Tomkin et al. (1989), Luck & Bond (1991), and Edvardsson et al. (1993).

North, Berthet, & Lanz (1994, hereafter NBL) provide a detailed abundance analysis of more than 10 of Bidelman's "F str 4077" stars. They noted that their index [hs/ls] was well correlated with [Fe/H]. In Figure 3 we show [hs/ls] from the above authors' abundances as a function of the metallicity [Fe/H] given by a few Fe II lines. NBL used [Fe/H] derived from the larger sample of Fe I lines. The correlation in Figure 3

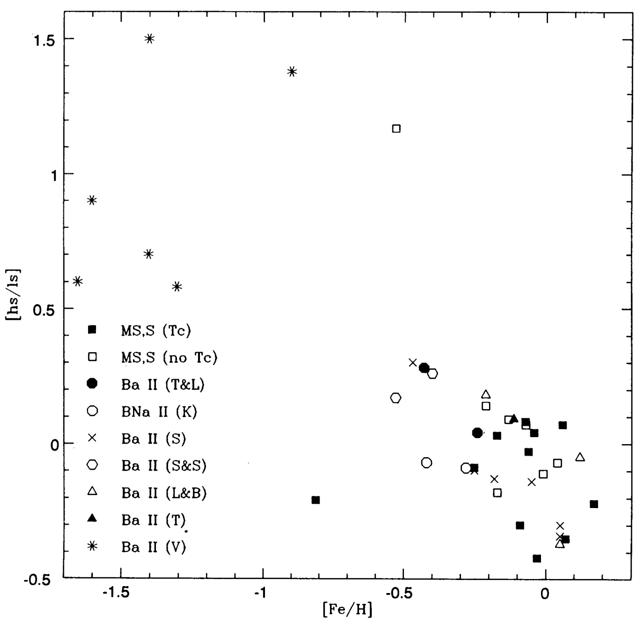

FIG. 2.—Same as Fig. 1, but including the stars observed by Vanture (1992) and the Nd-rich S star (without Tc) HD 35155 from Smith & Lambert (1990).

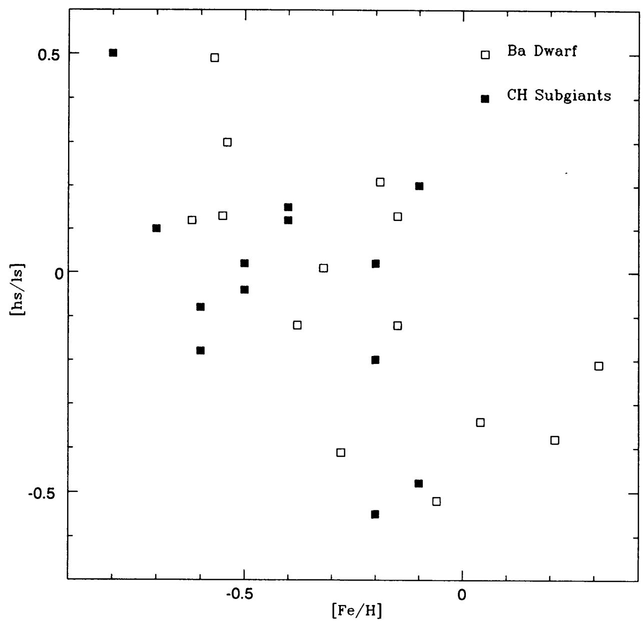

FIG. 3.—Same as Fig. 1, but illustrating the trend of Ba dwarfs (from North et al. 1994) and for CH subgiants (from Luck & Bond 1991).

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1995ApJ...446..775B

is evident and agrees well with that inferred from the barium giants and the MS/S stars (Fig. 1). We compute the *s*-process abundances for the barium dwarfs from the ratios [*s* I/Fe I] and [*s* II/Fe II], where NBL use the Fe abundance from the Fe I lines throughout their discussion. Except for a few stars for which Sr I lines were used, the *s*-process abundances were derived from lines of singly charged ions, and the [hs/ls] ratios are identical to the values found by NBL. Use of Fe II lines in place of Fe I lines has a substantially greater (0.2–0.3 dex) effect on the adopted metallicity [Fe/H] because NBL's analysis led to a temperature-dependent difference between the Fe (and Cr) abundances from neutral and ionized lines. At present it is not possible to determine how best to extract the "true" metallicity from these alternative choices. We chose to use the ionized lines because then the Ba dwarfs scatter about the relation between [hs/ls] and [Fe/H] suggested by the evolved stars (Fig. 1). If the neutral lines are preferred, the slope and quality of the correlation is unaffected but the [Fe/H] are all 0.2 to 0.3 dex smaller. NBL noted that the data assembled by Luck & Bond (1991) for CH subgiants fitted the trend established by the "F str 4077" stars. Detailed analyses of two CH subgiants—HD 4395 and HD 216219—by Krishnaswamy & Sneden (1985) give appreciably lower values of [hs/ls]; for example, HD 216129 is reported to have [hs/ls] $= -0.24$ at [Fe/H] $= -0.55$, a point lying well below the general trend of Figures 1 and 3. These authors recognized this difference in a comparison of HD 216219 and HD 4395 with the barium giant HR 774. Further study of these and other CH subgiants should be made.

NBL also note that there is a correlation between the average overabundance of *s*-process elements and the metallicity, an echo of Kovacs's (1985) discovery for the barium giants. (This has an easy explanation in the models, because distributions with higher τ_0-values have also higher production factors; see, e.g., Fig. 5.) Since mild barium dwarfs might not have been selected by Bidelman for labeling as "F str 4077" stars, we suppose that the present sample considered by NBL lacks mild barium dwarfs, which would impair the correlation but presumably leave the upper envelope delineating the increase of the *s*-process abundances with decreasing [Fe/H]. It is, of course, quite possible that mild barium dwarfs are rare even though mild barium giants are not; remember that a giant's convective envelope will dilute *s*-process enrichments that are confined to a thin layer on a dwarf.

2.5. *Summary*

According to the mass transfer hypothesis the abundance pattern for the heavy (*s*-process) elements in the carbon stars should be quite similar to that in the Ba dwarfs, giants, and extrinsic S stars. We have used the index [hs/ls] to characterize this pattern. This similarity is found: the index [hs/ls] $= -0.05 \pm 0.15$ for carbon stars put these stars within the [Fe/H]-dependent spread of values for the other groups of stars (see Figs. 1 and 3). To the extent that [hs/ls] for the *s*-process–enriched AGB star differs from that of the initial star and, hence, of the mass-gaining companion, dilution of *s*-processed material after mass transfer will induce a difference between the [hs/ls] indices of carbon stars and the various classes of barium stars. This difference should, however, become evident only for consistent dilution factors.

Dilution will be signaled by the indices [ls/Fe] and [hs/Fe], which for the barium stars should approach but not exceed the values displayed by the carbon stars. Even mild enrichments will occur when the mass transferred is greatly diluted. The maximum values of the indices for the Ba stars are consistent with those found for the carbon stars. This suggests, as previous studies have noted (e.g., Lambert 1985) that considerable amounts of mass may be transferred in the creation of a Ba star.

3. ABUNDANCES OF LIGHT AND INTERMEDIATE-MASS ELEMENTS IN C AND Ba STARS

3.1. *Carbon, Nitrogen, and Oxygen*

The mass transfer hypothesis for the origin of barium stars makes qualitative predictions about the relative C, N, and O abundances of the barium dwarfs and giants and those of intrinsic AGB stars. Two predictions are obvious. First, the convective envelope that develops as a dwarf evolves to a red giant will dredge up CN-cycled material, as occurs in normal stars, and the carbon enrichment of the barium dwarfs will be reduced for the barium giants. Second, since the observed *s*-process abundances of the barium dwarfs and giants approach the maximum levels of enrichment reported for the carbon stars, it is apparent that a large amount of mass must be transferred to create the barium stars and, hence, also that the carbon enrichment of barium dwarfs should approach levels similar to that reached in the intrinsic AGB stars. Several previous discussions of the compositions of barium and AGB stars have concluded that the observed compositions are in general accord with predictions of the mass transfer hypothesis (Lambert 1985, 1988; Smith 1993; Barbuy et al. 1992). Here we summarize this conclusion and, in particular, comment on recent analyses of barium dwarfs (NBL) and subgiants (Smith, Coleman, & Lambert 1993).

In the simplest of pictures, the mass transferred from the AGB star forms a coating on the unevolved companion. Alternatively, if the companion is evolved, the transferred material mixes with its convective envelope, but in doing so it is in any case simply diluted, without experiencing H-burning reactions capable of changing the CNO isotopic mix. Then, the maximum carbon abundance of a barium dwarf will be close to the maximum observed for carbon or more evolved AGB stars. (Barbuy et al. 1992 discuss a scenario in which mixing driven by a difference in molecular weight between the transferred material and that of the original envelope may lead to partial processing by the CN cycle such that the $^{12}C/^{13}C$ ratio of the material is lowered but little carbon is converted to nitrogen in the envelope of the freshly created barium dwarf.)

Carbon, nitrogen, and oxygen abundances of the mass-losing AGB star may be inferred from analyses of AGB stars and PNs. Onset of the mass loss via the wind that is necessary for the creation of a barium star is presumed to occur when the AGB star is near its terminal luminosity. In the simplest picture of AGB evolution, the third dredge-up has driven the C/O ratio of the envelope above unity before these stars lose mass in large amounts. Then, the mass-losing stars in the barium binary stars were equivalent to the carbon-rich AGB stars and C-rich PNs. Very luminous AGB stars are, however, predicted and observed to develop such high temperatures at the base of their convective envelopes that H burning may reduce the C/O ratio of the envelope again below unity; i.e., the star is once again an S star but more N-rich than before. Then, there is a possibility that the AGB star that created the barium star may have been O-rich. A common assumption is that the ionized gas of PNs is related closely to that of the convective

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1995ApJ...446..775B

envelope of the progenitor AGB stars. One presumes that the convective envelope so sampled has a composition similar to that of AGB stars. PNs may be either oxygen rich (C/O < 1) or carbon rich (C/O > 1). The former may be created from M, MS, or S stars that eject their envelopes before the third dredge-up has driven the atmospheric C/O ratio above unity (this, for example, is possible in the already quoted Willems & de Jong scenario, predicting strong dust-driven mass loss even before the C-rich phase) or from more massive S stars, which can be created from intermediate-mass ($M > 4$–$5\ M_{\odot}$) carbon stars whose C/O ratio was driven back below unity by the operation of H burning in the envelope (HBB).

These considerations lead us to compare the C/O ratios obtained for PNs and AGB stars with those reported recently for Ba dwarfs and subgiants. We then compare the barium giants and their putative progenitors, the barium dwarfs and subgiants, for evidence of changes attributable to the first dredge-up in this family of barium stars. Since some mixing of the transferred mass with the envelope mass of the receiving star may occur, the C/O ratio of this last will lie between that of the AGB primary and that of a normal main-sequence star of the system's metallicity. Indeed, as mentioned, Barbuy et al. argue that such mixing should occur due to the higher mean molecular weight of the transferred material.

Carbon abundances for PNs are based on either the weak C II $\lambda4267$ recombination line or the intercombination ultraviolet C III $\lambda1909$ line. Often, these lines have given discrepant results. Our discussion draws on the recent discussion by Rola & Stasińska (1994) who suggest that the 1909 Å line gives the more reliable results; we adopt the C/O ratio tabulated by Rola & Stasińska (their Table 2) from observations of the C III $\lambda1909$ and [O III] $\lambda5007$ lines. If a few PNs with remarkably and possibly spuriously high C/O ratios are omitted, Rola & Stasińska's sample gives a mean C/O ratio of 0.91 with $\sigma = 0.53$ from 41 PNs, and as noted by them, a relatively small fraction of the sample (35%) are "definitely" (i.e., C/O > 1.2) carbon rich. Very carbon-rich (C/O > 2) PNs are rare. The distribution function of C/O ratios for C/O > 1 bears some resemblance to that derived by Lambert et al. (1986) from a sample of 30 bright Galactic cool carbon stars: C/O < 1.3 for all but two of the 30 stars. (An earlier compilation for PNs, by Zuckerman & Aller 1986, gave a mean C/O of 1.6 ± 1.2.)

These results for PNs and C-rich AGB stars have interesting implications for the C/O ratios of the barium stars. Smith et al. (1993) derived C and O abundances for nine CH (i.e., barium) subgiants from C I and O I lines. The results are generally in good agreement with an earlier analysis by Luck & Bond (1982). The C/O ratios range from 0.35 to 2.1 for a mean value of 1.1 ± 0.5. This is clearly larger than the ratios seen in normal main-sequence and subgiant stars: the mean [O/Fe] = 0.19 ± 0.16 for CH subgiants is appropriate for normal stars with the mean metallicity ([Fe/H] = -0.26 ± 0.10) of the sample but carbon with [C/Fe] = 0.40 ± 0.19 is clearly enriched in the barium stars. NBL using the same C I and O I lines as Smith et al. (1993) derived C and O abundances for their sample of barium dwarf stars: the mean C/O ratio is 0.56 from 10 stars with individual ratios spanning the range 0.33–0.91 (NBL). NBL indicate that their oxygen abundances are probably overestimates because non-LTE effects in the O I $\lambda7770$ triplet were neglected in the analysis. This indication may be quantified using Clegg, Lambert, & Tomkin's (1981) empirical analysis of the same O I lines in conjunction with weaker O I lines and the [O I] $\lambda6300$ line. At the equivalent widths reached by the O I triplet in the barium dwarfs an LTE analysis overestimates the O abundance by at least 0.2 dex in most of the barium dwarfs considered by NBL. Therefore, the 0.3 dex difference between the mean C/O ratios found by Smith et al. (1993) and by NBL is likely due to the use of an LTE analysis. (The O I triplet in the CH subgiants is also subject to non-LTE effects, but these should generally be smaller than for the barium dwarfs.) The [C/Fe] abundances reported by NBL for Ba dwarfs and by Smith et al. (1993) for CH subgiants are in agreement when the Fe abundances for the dwarfs are taken from the Fe II lines (see comments in § 2): $\langle$[C/Fe]$\rangle$ = 0.33 ± 0.15 from 10 barium dwarfs and $\langle$[C/Fe]$\rangle$ = 0.40 ± 0.19 from nine CH subgiants. (The mean [C/Fe] of the dwarfs is increased by ~ 0.2 dex if the Fe abundance is taken from the Fe I lines.)

The mean C/O ratio (1.1 ± 0.5) of the CH subgiants is identical to that of the sample of PNs collated by Rola & Stasińska (1994), for which C/O = 0.9 ± 0.5 for O-rich and C-rich PNs combined. Since the maximum *s*-process enrichment of barium stars and carbon stars are very similar, it is apparent that at least some barium stars are created without substantial dilution of the transferred material. In such cases we expect the C/O ratios to be similar for extreme barium and carbon stars. This seems to be the case. There is a hint in the distribution of the C/O ratios for the CH subgiants that carbon-rich stars (C/O > 1.2) are more common than among the PNs. Additional stars should be analyzed to explore this hint; one should be aware that a sample of CH subgiants selected spectroscopically or photometrically will likely be biased in favor of the C-rich stars because the less C-rich stars will have weaker CH bands and may be overlooked.

A correlation between the C and *s*-process enrichments was noted by Smith et al. (1993) for CH subgiants—see also NBL (Fig. 6), who comment on the positive correlation between [*s*/Fe] and [Fe/H] and a similar correlation between [C/Fe] and [Fe/H]. These correlations between carbon and the *s*-process elements are to be expected if mass transfer is complete before the AGB star develops HBB (or if the primary is not massive enough to drive HBB).

If, however, the primary star is massive enough and mass transfer occurs only after the carbon has been reduced by HBB, the star will have a lower [C/Fe] for its [*s*/Fe]. Thus, scatter will be introduced into the carbon versus *s*-process element correlation. Material exposed to HBB will be N-rich, but unfortunately, nitrogen abundances have not yet been measured for Ba dwarfs and subgiants—indeed, this may be an impossible task except for stars where lines of the CN violet system are detectable. The only information on N available to date are estimates ([N/Fe] $\simeq 0.1$) for two CH subgiants (Sneden & Bond 1976).

In the evolution of barium dwarfs and subgiants to barium giants, the convective envelope that develops as a giant ascends the red giant branch for the first time will change the surface C and N abundances by mixing the outer layers with deeper layers exposed to mild processing by the CN cycle. This episode, known as the first dredge-up, is predicted and observed to increase a giant's surface abundance of N at the expense of the carbon abundance. Lambert & Ries (1981) found [C/Fe] = -0.23 ± 0.13, and Kjaergaard et al. (1982) reported [C/Fe] = -0.22 ± 0.14 for similar and overlapping samples of G and K giants. Smith & Lambert (1990) found a similar change for M giants: [C/Fe] = -0.19 ± 0.12. Nitrogen increases were clearly found in two of these three studies:

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1995ApJ...446..775B

[N/Fe] = 0.37 ± 0.11 (Lambert & Ries) and 0.31 ± 0.13 (Smith & Lambert), but Kjaergaard et al. reported a mean value [N/Fe] = 0.09 ± 0.16. Since, according to Lambert & Ries (1981) and Smith & Lambert (1990), the total number of C and N nuclei is unchanged (i.e., [(C + N)/Fe] = 0), as expected for the CN cycle, we suppose that their studies are a closer reflection of the composition changes brought by the first dredge-up.

If barium giants are similarly affected by the first dredge-up, the spread and mean C/O ratios may be predicted from those of barium dwarfs and subgiants. That the barium giants are C-rich relative to normal giants has long been known and is suggested by the enhanced strength of the C_2 lines. The mean C/O ratio for barium giants is 0.68 ± 0.21 from 16 stars with a published C, N, and O analysis (Tomkin & Lambert 1979; Smith 1984; Sneden, Lambert, & Pilachowski 1981; Kovacs 1983, 1985; Barbuy et al. 1992). If the C/O ratios of the nine subgiants are reduced by the 0.2 dex observed for normal giants, the predicted mean C/O ratio for barium giants is 0.64 ± 0.32, which agrees very well with the observed mean C/O ratio. Oxygen has a normal abundance in barium giants, as it does in the barium dwarfs and subgiants. Nitrogen is enhanced in the barium giants relative to normal dwarf stars of the same metallicity: published analyses for the barium giants give a mean [N/Fe] = 0.42 ± 0.16, which is close to the means given above for K and M giants. Note too that the very limited data on the N abundances of CH subgiants ([N/Fe] = 0.1 for two stars) also indicate that the N enrichment of the barium giants is a fruit of the first dredge-up in these stars rather than a characteristic of the mass transferred at the creation of the barium star. Certain barium giants may be additionally enhanced in N by a moderate amount. There is, however, little evidence for the severely N-enhanced stars that might be expected if the AGB star experiences HBB before transferring mass to create the barium star. This is a first hint against a statistically relevant presence of Ba stars deriving from massive ($M > 4\ M_{\odot}$) primaries.

A second signature of HBB would be a low $^{12}C/^{13}C$ ratio. The limited data on $^{12}C/^{13}C$ for CH subgiants, coming from analyses of CH lines in the blue, show no evidence of low $^{12}C/^{13}C$ ratios (Sneden 1983). More extensive data on the $^{12}C/^{13}C$ ratio have been published for barium giants from analyses of the CN red system primarily. Results range from $^{12}C/^{13}C > 40$ for ζ Cap (Smith, Sneden, & Pilachowski 1980) to low ratios (5–8) reported by Smith (1984) and Barbuy et al. (1992) for several stars. These low ratios are suspiciously similar to what would be expected from an AGB star with HBB. However, these barium stars with a low $^{12}C/^{13}C$ ratio are not abnormally rich in nitrogen, and this suggests a mild exposure to protons such that ^{13}C is made but little is processed further to ^{14}N. Discussion of $^{12}C/^{13}C$ ratios must not overlook that the range of $^{12}C/^{13}C$ values found in normal K giants (say 4–40) exceeds that predicted by standard models of the first dredge-up. Unknown processes operating preferentially in low-mass main-sequence or evolved stars (Gilroy 1989) drive the $^{12}C/^{13}C$ ratio below the standard prediction. We cannot suppose that none of these same processes operate in the barium dwarfs and giants. Of course, a giant's $^{12}C/^{13}C$ ratio depends on the initial ratio for the envelope of the main-sequence progenitor. Observations of the $^{12}C/^{13}C$ ratio in AGB stars show that it tends to increase as the C/O ratio is increased through the third dredge-up; for example, the $^{12}C/^{13}C$ ratios of carbon stars fall in the range 30–100, with the exception of the ^{13}C-rich (J-type) stars that are not enriched in *s*-process elements (Lambert et al. 1986), and the M and MS stars with C/O ratios intermediate between those of the M giants and carbon stars show on average intermediate $^{12}C/^{13}C$ ratios (Smith & Lambert 1990). Even if the transferred mass from the AGB star has $^{12}C/^{13}C \simeq 30$, "standard" evolution of a dwarf to a giant will not reduce the $^{12}C/^{13}C$ ratio to values as low as 5–7, as found for some barium giants. Barbuy et al. (1992) sketch a scheme for mixing and mild H burning occurring as mass is transferred. While such a process may decrease the barium dwarf's initial $^{12}C/^{13}C$ ratio, we suppose that one of the processes operating in normal stars may also be responsible for barium giants with a $^{12}C/^{13}C$ too low for explanation by "standard" evolutionary models. In short, the $^{12}C/^{13}C$ ratio is not yet a refined tool for probing the evolution of barium stars. Refinement may be possible when information on the oxygen isotopes is available from infrared spectroscopy.

Summing up, examination of the data on barium giants shows, as found for the barium dwarfs and subgiants, that the carbon and *s*-process enrichments are correlated (Lambert 1988; Smith 1993). The C-*s* correlation is similar to that seen among the barium dwarfs and subgiants except that, as noted above, the dwarfs and subgiants have more carbon for a given *s*-process enrichment. The simplest interpretation of the correlations is that (1) different amounts of mass are transferred to create barium stars of differing degrees of *s*-process enrichment and (2) the transferred mass has the composition of the cool carbon stars (C/O near unity, [*s*/Fe] ≃ 1.2). An alternative is that the mass transferred has a range of compositions reflecting the evolutionary state of the AGB star at the time that heavy mass transfer is initiated. Since the intrinsic MS and S stars show a C-*s* correlation (Smith & Lambert 1990) similar to that of the barium stars, we cannot distinguish between these two origins for the C-*s* correlation without invoking other constraints. Hence, this point will be examined again, in the light of our modeling, in § 5.

3.2. *Lithium in Barium Stars*

In addition to the *s*-process and the C, N, and O abundances, the lithium abundance may be used to test the hypothesis that barium stars are formed by mass transfer. As before, the test comprises two parts: Are the Li abundances of the barium dwarfs and subgiants consistent with the Li abundances expected for the AGB stars which donate the *s*-process–enriched material? Do the Li abundances of the barium giants reflect the dilution expected from the first dredge-up that evidently affects the C and N abundances?

Previously, attention has focused on the second question. Lithium has been reported as present in barium giants, and Li abundances have been derived by Pinsonneault, Sneden, & Smith (1984) and Barbuy et al. (1992). Lithium has not yet been detected in the Ba dwarfs and subgiants. The range of the published Li abundances for barium giants overlaps the spread in the *upper* limits set on the Li abundance in CH subgiants (Smith & Lambert 1986). Since the barium giants have evidently experienced the first dredge-up, the Li in the giants should be at least a factor of ∼50 less than the upper limit in a CH subgiant. This is evidently not the case for some of the barium giants. Lambert, Smith, & Heath (1993) show, however, that the Li I λ6707 doublet in barium stars is blended with an unidentified line of an *s*-process element in addition to known blends such as various CN lines. It appears that the unidentified line is responsible for the (erroneous) reports of

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1995ApJ...446..775B

the Li I λ6707 doublet in barium giants. Revised (uncertain) upper limits on Li in barium giants are roughly consistent with the upper limits for CH subgiants and the dilution of Li expected from the first dredge-up; the mass transfer hypothesis passes this test despite some initial doubts.

Luminous AGB stars synthesize lithium as HBB converts ^{3}He produced on the main sequence to ^{7}Li via ^{7}Be (Cameron & Fowler 1971). Well-known Galactic examples of Li-rich stars include WZ Cas, a carbon star, and T Sgr, an S star. The luminosities of such stars are, of course, uncertain, but observations of AGB stars in the Magellanic Clouds show that almost all stars within a magnitude of the limiting luminosity for the AGB ($M_{\rm bol} = -7.1$) are Li-rich S stars (Smith & Lambert 1989, 1990; Smith et al. 1995). As HBB produces ^{7}Li, the CN cycle reduces the C/O ratio below unity and converts a carbon star back to an oxygen-rich or S star. Calculations (Boothroyd & Sackmann 1992) suggest that Li production is limited to stars with masses of 5–6 $M_\odot$. Their 7 $M_\odot$ model ignited carbon in the core and did not develop HBB. The 4 $M_\odot$ model developed HBB but did not enrich the envelope in lithium. These estimates refer to models with a solar metallicity. Lithium enrichment at the surface occurs because production exceeds destruction in the HBB. Unless severe mass loss terminates a star's evolution along the AGB, destruction may later outrun production and the Li enrichment be reduced or even eliminated. In light of this possibility and the prediction that sutface enrichment of Li may be restricted to a narrow range in mass, it seems likely that Li-rich barium dwarfs may be quite rare. This expectation is quite consistent with the fact that none have yet been detected. On the other hand, barium stars enriched in the products of CN cycling in HBB could be more common, but the leading product is nitrogen about which little is known for the barium dwarfs and CH subgiants. Barium giants with an N enrichment greater than expected from a "normal" first dredge-up seem to be quite rare, as we indicated in § 3.1. We note this interesting indication and call for searches for N-rich barium stars. In extreme cases, the barium star that results from the transfer of mass from an AGB star with HBB will not be very carbon rich.

3.3. *Isotopic Magnesium Abundances*

The isotopic ratios ^{24}Mg:^{25}Mg:^{26}Mg are diagnostics of the neutron source that drove the *s*-process in the AGB star's He-burning shell. In IMSs (3–8 $M_\odot$) neutrons are provided by the reaction ^{22}Ne(α, n)^{25}Mg, where the ^{22}Ne is synthesized from the initial C, N, and O abundances. In LMSs ($M \leq 3$ $M_\odot$) the ^{22}Ne reaction is no more than a minor contributor of neutrons. The dominant source of neutrons is the reaction ^{13}C(α, n)^{16}O. Operation of the ^{22}Ne but not the ^{13}C source is predicted to lead to a distinctive mix of Mg isotopes in the He shell and, thanks to the third dredge-up, also in the atmosphere of AGB stars (Truran & Iben 1977; Scalo 1978; Malaney 1987): e.g., IMSs with *s*-process surface enrichments of a factor of 10 are expected to have isotopic ratios of ^{24}Mg:^{25}Mg:^{26}Mg $\simeq$ 1:1:4 instead of the ratios of 8:1:1 found for the Sun and normal stars of near-solar metallicity (Malaney & Lambert 1988).

Magnesium isotopic ratios are measurable for stars with the MgH *A–X* lines in their spectra. Analyses of MgH in barium giants and several intrinsic and extrinsic MS/S stars have discovered no examples of even mild enrichment of ^{25}Mg (or ^{26}Mg) (see Barbuy et al. 1992, and papers referenced by Lambert 1991). Attempts to detect ^{26}Mg have not been reported for barium dwarfs and CH subgiants. Indeed, most of these latter two groups of stars are too warm to provide useful MgH lines. The conclusion has been drawn that the examined barium giants including the extrinsic MS/S stars were created by mass transfer from low-mass and not intermediate-mass AGB stars.

The appearance of HBB in principle allows a ^{25}Mg and ^{26}Mg excess to be reduced or even eradicated as these Mg isotopes are destroyed by protons: ^{25}Mg(p, γ)^{26}Al and ^{26}Mg(p, γ)^{27}Al and some ^{25}Mg may end up as ^{27}Al via ^{25}Mg(n, γ)^{26}Mg (see Lambert 1991 for additional discussion). Barbuy et al. (1992) remark that if almost all the ^{26}Mg in the intermediate-mass AGB star's envelope is converted to ^{27}Al, the surface Al abundance will increase 30-fold, but their determinations of the Al abundance in eight barium giants show no excess of Al greater than a factor of 2. Then, to the extent that these stars are representative, HBB did not destroy the ^{25}Mg and ^{26}Mg nuclei that would have betrayed the ^{22}Ne neutron source.

Although the MgH test has not been applied to all the barium stars or AGB stars mentioned here, the evidence is that the majority were created from low-mass and not intermediate-mass AGB stars. A key part of the evidence is the normal Mg isotopic ratios found for barium giants.

4. MODELING AGB EVOLUTION, NUCLEOSYNTHESIS, AND MIXING

In TP-AGB stars of low mass, due to the moderate temperature at the base of the convective He shell the neutron source that can efficiently operate is the reaction ^{13}C(α, n)^{16}O. Only a minor contribution to the neutron flux can come from the ^{22}Ne(α, n)^{25}Mg reaction, which is marginally activated in advanced pulses, when the convective instabilities spread over their maximum amplitude, and the bottom temperature increases for a short duration of time (Hollowell & Iben 1988).

Nucleosynthesis calculations for LMSs in the TP-AGB phase, performed by Gallino et al. (1988) and Käppeler et al. (1990), show that such stars may account for the main *s*-process component in the solar system, provided the mean neutron exposure τ_0 reaches $\sim$0.28–0.30 mbarn^{-1}. For lower τ_0-values, various isotopic anomalies in the solar system can be reproduced (Gallino et al. 1990b, 1993; Wasserburg et al. 1994). In Paper I we showed that this scenario can reproduce the observed abundances of C and *s*-process elements at the surface of MS and S stars; in the same work the main open questions related to the activation of the ^{13}C source were discussed.

The application of the above models to the sample of C and Ba stars discussed in §§ 2 and 3 is possible on the condition that these stars are of low mass, too. While this is probable for most C stars (Feast 1989) and for the low-luminosity S stars, both intrinsic and extrinsic, the situation is more complex for Ba stars. Indeed, the evolutionary status of many of them (clump giants) allows for a wider spread in the initial mass (Jorissen & Mayor 1992). Hence, on evolutionary grounds we cannot exclude the possibility that the primaries (now evolved to white dwarfs) of some Ba stars could have been IMSs.

In § 3 we commented on the fact that indications from the ^{12}C/^{13}C ratio and from the N abundance cannot be conclusive in discriminating between an LMS or an IMS primary. We have mentioned that the measured abundances of Mg isotopes, though not available for all Ba stars, support the idea that LMSs are involved. Since, on the other hand, activation of the

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1995ApJ...446..775B

$^{13}C(\alpha, n)^{16}O$ reaction and that of the $^{22}Ne(\alpha, n)^{25}Mg$ reaction imply different nucleosynthesis patterns, we may test the alternative hypothesis that some Ba stars derive from an IMS primary through a comparison of model predictions with observations. Such a test has already been attempted by Malaney & Lambert (1988) on the basis of parameterized *s*-process distributions. They suggested that the ^{22}Ne source had to be excluded, but found problems also with the ^{13}C source, especially for elements like Rb, whose production depends not only on the neutron exposure but also on the neutron density. Malaney (1987) suggested that a single neutron exposure with a low neutron density, possibly ensuing from the core He flash could reproduce the abundance observations in the various classes of Ba stars better than exponential distributions of neutron exposures coming from thermal pulses. This, however, is at odds with the prediction that only minimal (if any) neutron production arises at the He flash (Deupree 1986). We reexamine in § 6 the question of neutron density and Rb abundance for low-mass AGB stars.

The opportunity has been taken here to refine some aspects of the calculations reported in Paper I, by taking into account recent results from revised models of AGB evolution. Some of these models (Busso et al. 1993, 1994; Straniero et al. 1995a, b) now predict directly, above a core mass of $\sim 0.65\ M_{\odot}$, the occurrence of the so-called third dredge-up, i.e., of the downward extension, after a thermal pulse, of envelope convection into the intershell region, leading to the mixing of He-burning products to the surface. The structure of the intershell region in this phase is schematically reproduced in Figure 4, where two adjacent pulses, together with the dredged-up mass and the overlapping factor *r* between pulses, are (qualitatively) shown.

In a typical 3 $M_{\odot}$ model from Busso et al. (1994) the amount of intershell material dredged to the surface varies in time, between $(2\text{–}3) \times 10^{-4}\ M_{\odot}$ and $(1\text{–}2) \times 10^{-3}\ M_{\odot}$.

Before the onset of the third dredge-up, the main characteristics of the models (convective shell mass, interpulse duration,

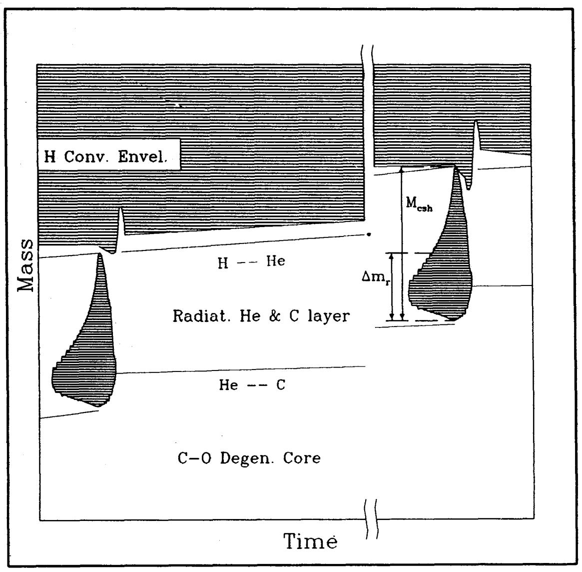

FIG. 4.—Simplified sketch of the structure of the stellar layers outside the degenerate C-O core during thermal pulses. Shaded regions are convective, and dredge-up from the convective envelope is shown after each pulse. Of the whole convective shell mass (M_{csh}), the part indicated as Δm_r has already been involved in a previous pulse: hence, the ratio $r = \Delta m_r/M_{csh}$ is called the *overlap* between adjacent pulses.

and overlapping between adjacent pulses) are determined solely by the core mass M_H, and in particular, the shell mass is a decreasing function of M_H. Such characteristics match well those found in earlier published results (see, e.g., Paczyński 1970; Schönberner 1979; Boothroyd & Sackmann 1988a, b, c).

We have computed the *s*-process nucleosynthesis in the He shells of the new models assuming that a pocket containing a few $10^{-6}\ M_{\odot}$ of ^{13}C is formed by proton mixing from the envelope after each pulse, during or near the occurrence of dredge-up. As discussed in Paper I, for the moment this assumption has to be made without the support of adequate modeling, especially for disk-metallicity stars, due to the probable dependence of ^{13}C formation on local phenomena at the convective border not accounted for by stellar calculations. The moment at which the growth of a convective instability reaches the mass zone involved in the previous dredge-up episode, where ^{13}C may be present, is in any case fixed by the stellar model and so is the rate of ingestion of this zone, which is determined by the shape of the convective profile and by the degree of overlapping between successive pulses, as shown in Figure 4.

In our models, the bottom temperature at ^{13}C ingestion is slightly increasing from pulse to pulse, being around $T = 1.6 \times 10^8$ K for a core mass near 0.65 $M_{\odot}$, when the third dredge-up is found to start. At such temperatures the energy production by the ^{13}C source may be important in controlling the shape of the convective region, and hence the neutron density, when ^{13}C burns convectively during the pulse. However, Bazan & Lattanzio (1993) showed that this does not remarkably modify the distribution of *s*- and *r*-elements produced, and hence we shall not discuss this point in detail. We simply recall that recently the more realistic hypothesis of a radiative burning of ^{13}C just before ingestion has been shown to avoid any problem of energy generation, giving rise to neutron densities even lower than those found by us and still maintaining all the general characteristics of the *s*-distribution of interest here (see Straniero et al. 1995a, b).

As the core mass M_H grows with time, we find that, if the amount of ^{13}C burnt per pulse is assumed to be constant, the decreasing convective shell mass leads to an increasing neutron exposure per pulse, $\Delta\tau$. At the same time, the pulse shape also changes: in particular, the dilution factor *D* (the ratio between the shell mass at ^{13}C ingestion and that at maximum convective expansion) decreases monotonically. The combined effect of increasing $\Delta\tau$ and decreasing *D* causes the mean neutron exposure to reach a value depending only on the amount of ^{13}C burnt.

The nucleosynthesis results of the new models are not qualitatively different from those previously obtained using a series of identical pulses. Quantitatively, the main changes can be summarized as follows: (1) for a given ^{13}C mass burnt, the asymptotic value of τ_0 is higher typically by a factor of 1.5, due to the smaller average shell mass, and (2) due to the combined variations of $\Delta\tau$ and *D*, it takes more pulses to reach the asymptotic value of τ_0 (~ 20 instead of ~ 15). In this respect, one has to stress that stars of sufficiently low mass, experiencing only a limited number of pulses before mass loss consumes the envelope (see Paper I, Table 5) might be unable to reach an asymptotic distribution of *s*-elements.

For purposes of comparison, we shall present two sets of results here: those labeled "model A" use the assumptions and technique described in Paper I, while those labeled "model B" adopt the new scenario.

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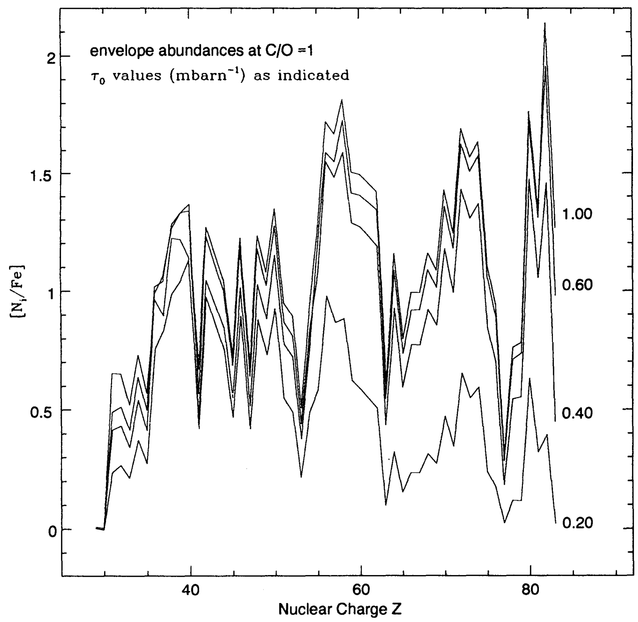

FIG. 5.—Logarithmic abundances of elements heavier than Cu achieved in the envelope when C/O = 1, by mixing *s*-process nuclei of different neutron exposures from the He shell (See text for details). Long-lived unstable nuclei, like ^{93}Zr, are still present, and this explains the drop at Nb (Z = 41) abundance.

In Paper I we showed that, for the purpose of fitting atmospheric abundances, the particular choice of the mass-loss criterion is in general not critical (we used either Reimers's 1975 or Baud & Habing's 1983 parameterizations). However, in case extremely high mass-loss rates are assumed, like those derived from observations of Mira variables and OH/IR stars by Vassiliadis & Wood (1993), the number of pulses that a given star can experience is reduced, and this may halt the growth of the core mass at values below the limit at which present models can find dredge-up. Indeed, Vassiliadis & Wood's (1993) models do not explain the formation of C stars below an initial mass of 5 $M_\odot$. In any case, for the LMSs considered here mass-loss rates should be, on average, moderate (a few 10^{-6} $M_\odot$ yr^{-1} at most, when the C star phase is reached; see, e.g., Olofsson et al. 1993a, b) and the above-mentioned parameterizations should be sufficiently reliable.

In order to account for the Ba star abundances, the mass transfer is simulated by further diluting the photospheric composition reached when C/O = 1 with a variable amount of matter, whose composition reproduces that of a unevolved star or that of a giant after the first dredge-up.

As far as α-capture rates, β-decay lifetimes, and neutron-capture cross sections are concerned, we have used the same sources as in Paper I. We have, however, implemented the compilation of cross sections by Beer, Voss, & Winters (1992) including, for ^{138}Ba, the new results by Beer et al. (1993), which are of help in reproducing the Ba/Nd ratios observed in AGB stars, as already mentioned in the note added in proof to Paper I.

We have assumed that, when dredge-up operates, it takes to the surface a constant amount of matter (10^{-3} $M_\odot$) with the composition reached by the He shell at that moment. Thus, the composition of the envelope evolves in time; it starts from a solar mix (for elements heavier than CNO) scaled to the metallicity of the star we consider, and then is enriched due to the mixing episodes, while the envelope mass is decreased by mass loss. The pulse at which dredge-up starts, the frequency of dredge-up episodes, and the mass-loss rate can be varied parametrically (see Paper I for details).

Figure 5 shows typical distributions in the envelope when the C/O number ratio reaches unity, for different choices of the mean neutron exposure τ_0. The sequences plotted have been obtained by mixing intershell matter only after asymptotic distributions were achieved, and then repeating the dredge-up at each pulse, each time carrying to the surface a constant amount of mass (10^{-3} $M_\odot$). A solar composition scaled to [Fe/H] = −0.3, as is typical of several AGB stars, was assumed for the photosphere. The figure shows how the surface abundances change when passing from low ($\tau_0 = 0.20$ mbarn^{-1}) to high ($\tau_0 = 1.0$ mbarn^{-1}) neutron exposures. Above $\tau_0 = 0.4$ mbarn^{-1} the *s*-process distributions tend to crowd at low values of the nuclear charge (Z) and a clear distinction between different cases requires consideration of heavy nuclei. As extreme examples, the two sequences obtained by mixing to the envelope distributions achieving $\tau_0 = 0.6$ and 1.0 mbarn^{-1} in the He shell are separated only by 0.1 dex in the ratio Ba/Zr, and by 0.15 dex for Nd/Zr and Sm/Zr, but reach 0.4 and 0.5 dex of separation for Pb/Zr and Bi/Zr, respectively. This fact suggests that observations of abundances in the Pb-Bi peak would be of high importance. This is even more so for Population II AGB stars, showing very high neutron exposures (Vanture 1992; Plez et al. 1993; see also Gallino et al. 1990a).

5. RESULTS AND DISCUSSION

5.1. *Carbon Stars*

A comparison between observed and predicted abundances of heavy elements is presented in Figure 6 for intrinsic and extrinsic AGB stars. Solid lines represent model predictions,

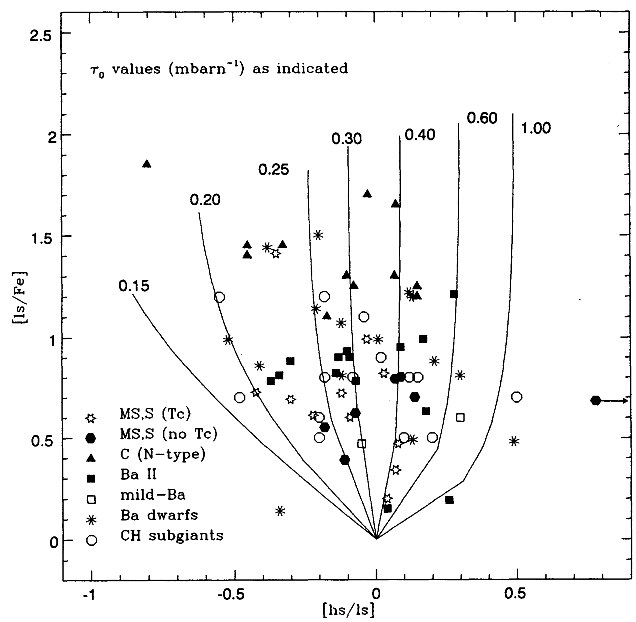

FIG. 6.—Comparison of theoretical predictions of surface abundances for different neutron exposures (*solid lines*) with observations of intrinsic and extrinsic AGB stars. The abscissa represents the average logarithmic ratio of the abundances of the heavy *s*-elements Ba, La, Nd, and Sm ("hs") to the lighter *s*-elements Sr, Y, and Zr ("ls"). The ordinate is the logarithmic enhancement in ls with respect to iron. The references for the observations are the same as in Figs. 1–3. The data have been put on the same scale by applying the shifts discussed in the text (see § 2.2). All the terminal points of model curves correspond to a mixing ratio of 4.5×10^{-2}.

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1995ApJ...446..775B

obtained by mixing *s*-process–enriched material from the intershell region to the envelope, as the envelope itself is progressively consumed by mass loss according to the Reimers (1975) parameterization (similar results are obtained using the Baud & Habing 1983 relation). The mixing process assumed in Figure 6 is started after asymptotic abundances for elements up to Sm have been achieved, and hence the distributions of *s*-nuclei can be simply characterized by their mean neutron exposure (τ_0), which is indicated near each sequence. The theoretical curves obtained in this way from models A and B are virtually identical, provided that the mean neutron exposure is the same.

Figure 6 is similar to Figure 2 of Paper I. However, as suggested in Luck & Bond (1991), and discussed in § 2, the abscissa now represents the average enhancement (in the usual logarithmic scale) of the heavy elements Ba, La, Nd, and Sm, collectively indicated by "hs," with respect to the lighter elements, Sr, Y, and Zr, indicated by "ls." The change to hs from exclusive use of Nd in Paper I is made because the average *s*-process contribution to the species from Ba to Sm is higher than that to Nd, whose solar abundance is known to come partly (50%) from the *r*-process. When the original observations from which Figure 6 was compiled did not include all the above-mentioned elements, the corrections discussed in § 2 have been applied to put the data on the same scale.

Concerning carbon stars (*filled triangles*), their enhancements [ls/Fe] clearly separate them from MS and S stars in Figure 6 and correspond to a more extensive dredge-up of nucleosynthesis products, i.e., to a higher mixing ratio between the total amount of material coming from the intershell zone and the residual mass of the envelope. This is a feature already noticed by Lambert (1989); from our models typical mixing ratios for these C stars turn out to be in the range (1–3) $\times$ 10^{-2} (i.e., 1%–3% of He-shell matter in 97%–99% of original envelope material).

The large uncertainties (at least 0.4 dex) affecting the observed abundances of *s*-elements in cool C stars make practically all the available observational data compatible with the range $0.2 \leq \tau_0 \leq 0.4$ mbarn^{-1} already derived for MS and S stars in Paper I. In other words, it is easy to reproduce the present observations of MS, S, and C stars (N-type) using the same nucleosynthesis models. Typical N star compositions (characterized by *s*-element enrichments by factors of 15–100) are naturally obtained by the time the envelope C/O ratio exceeds unity. Then, the neutron exposure τ_0 of the adopted model determines both the abundance pattern of *s*-nuclei and the average *s*/C ratio.

Contrary to what happens for MS and S giants (see Paper I, Figs. 5 and 6), the particular way in which dredge-up is assumed to occur is in general unimportant for carbon stars. The quality of the fits to photospheric abundances does not depend on whether dredge-up occurs after each pulse from the beginning of the TP-AGB phase or whether it starts later, when asymptotic conditions have been reached, provided the same C/O ratio is attained. This fact is illustrated by the sequences of Figure 7. They refer to two models, achieving mean neutron exposures $\tau_0 = 0.44$ and 0.22 mbarn^{-1}, in which mixing occurs either from the beginning (cases with $n_0 = 1$, n_0 being the pulse number at which dredge-up starts) or after asymptotic conditions are established (cases with $n_0 = 20$). In fact, the curves with the same τ_0-value but with different mixing schemes approach each other for C/O $\sim$ 1 and, hence, become equivalent within the typical observational uncertainties. One has to remember that for MS and S stars the situation is quite different (see Paper I), both because at lower mixing ratios the curves representing different mixing schemes can be widely separated and because the uncertainty in the observational data is considerably lower, allowing for a clearer discrimination.

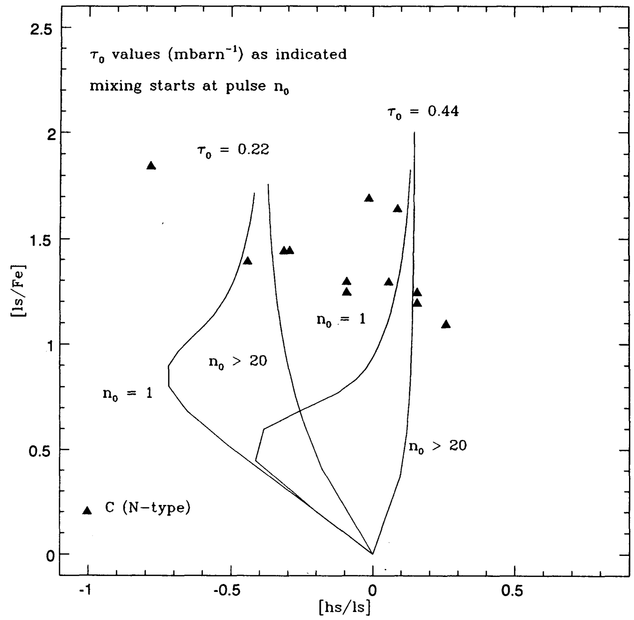

FIG. 7.—Observations of C star abundances from Utsumi (1985) compared to predictions from models of envelope enrichment with material coming from the He shell, exposed to $\tau_0 = 0.22$ and 0.44 mbarn^{-1}. The composition of the He shell in the models was mixed to the surface either from the first pulse ($n_0 = 1$) or after asymptotic conditions were established ($n_0 \geq 20$). The terminal points of the model sequences correspond to a mixing ratio of 4.5×10^{-2}.

In any case, the fact that the observational data are compatible with asymptotic distributions shows that N-type carbon stars have experienced at least the $\sim$15–20 pulses necessary to build an asymptotic pattern of *s*-nuclei. With our choice of mass-loss rates this means that stars more massive than 1.4–1.5 $M_\odot$ can become carbon stars. (This limit would be considerably higher when extreme mass-loss rates are adopted, as in Vassiliadis & Wood 1993.) The most likely conclusion is that N-type C stars, thanks to their mass and age, have reached an evolutionary status subsequent to that of current MS and S giants; they are probably experiencing the same nucleosynthesis process, but have undergone a higher number of dredge-up episodes, thus carrying to their surface higher concentrations of freshly produced nuclei. According to the already quoted evolutionary scenario by Willems & de Jong (1986), an optical C star might have already experienced the phase of dust-embedded Mira variable. If this is the real scheme, the occurrence of this pulsating phase and that of carbon and *s*-process element dredge-up should be independent of each other: indeed, on one side several *s*-enriched MS and S stars studied in Paper I and in Smith & Lambert (1985, 1986, 1990) have not yet reached the pulsational stage; on the other, *o* Cet and other intermediate-period Mira variables (P = 300–450 days) are probably only at the beginning of their dredge-up history, since they already show Tc in their spectra (Little, Little-Marenin, & Bauer 1987), but not yet significant enhancements of other *s*-process elements (see also Vanture et al. 1991). This can be understood if, in nature like in theoretical

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1995ApJ...446..775B

models, dredge-up occurs only above a certain core mass M_H (see, e.g., Lattanzio 1989). The mass-loss and dredge-up history of Mira variables and C stars would be difficult to understand if instead a simple, continuously increasing mass loss is assumed, as in the classical superwind hypothesis. Probably, the two scenarios should be merged: short phases of enhanced wind intensities should occur near pulses, imposed over a lower continuous mass-loss rate, which however is increasing with time.

The following comprehensive picture can tentatively be sketched for the AGB envolution of stars with different masses:

1. In the mass range relevant to the most common AGB stars ($M < 2\ M_\odot$) those giants having smaller initial mass (say, near or below 1.2 $M_\odot$) are likely to reach the critical value of M_H for dredge-up only during the Mira stage, while those with a higher mass can mix carbon and heavy elements to the surface before pulsations start. The first group probably never reach the N-type star phase, losing the envelope before C/O ~ 1; the second probably gives rise to the usual C stars with moderate C enrichment and moderate mass loss, as observed by Claussen et al. (1987) and Olofsson et al. (1993a, b).

2. Above $\sim 2\ M_\odot$ and possibly up to $\sim$4–5 $M_\odot$ the brighter infrared C stars observed by Barnbaum et al. (1991) are formed. Before this stage of evolution, these giants probably pass through that of O-rich Mira variables of relatively long period.

3. Finally, above 4–5 $M_\odot$ and below the limiting mass for nondegenerate core carbon burning, the establishment of HBB in the envelope may prevent the star from becoming C-rich, giving rise to high-luminosity S stars like those observed in the SMC and LMC (Plez et al. 1993). The relative rareness of these stars is probably due to a very fast evolution off the AGB, thanks to the combined effects of HBB and high mass-loss rates (Baud et al. 1981; Blöcker & Schönberner 1991; Boothroyd & Sackmann 1992).

For the most common carbon stars (mentioned in point 1), the requirement that they undergo at least $\sim$15–20 pulses says that the mean mass-loss rate cannot be (on average) much stronger than Reimers's prescription. Hence, possible phases of enhanced wind intensity must be so short that they do not significantly alter the integrated loss over the AGB lifetime. With this limitation, the idea of a final superwind and that of various short episodes of strong mass loss can be reconciled. This also implies that the majority of the envelope mass is lost near the end of the AGB evolution and, hence, also that mass transfer in Ba stars is more likely to occur at the end. The fact that the highest *s*-process abundances shown by Ba stars are similar to those typical of C stars is in agreement with this suggestion.

5.2. *Barium Stars*

Coming to the various classes of Ba stars, the abundances of light *s*-nuclei ([ls] in Fig. 6) reveal, on average, mixing ratios similar to those of MS and S stars. The mass transfer hypothesis implies that these ratios are a result of the dilution of higher abundances achieved on the primary component of the binary system, by mixing with material of the mass-gaining companion. The chemical compositions of the donated material were probably similar to (if not more extreme than) those of presently observed N-type carbon stars (Lambert 1991). Hence, the effect of mass transfer is to shift the representative points for Ba stars in Figure 6 from the region of N stars to that of S stars. Different ratios of the transferred mass to that of the original envelope of the secondary component lead to different degrees of C and *s*-enrichment, so that the C-*s* correlation mentioned in § 3.1 naturally finds its explanation.

In Figure 6, the various classes of Ba stars are characterized by neutron exposures covering a large interval, reaching values often in excess of 0.4 mbarn^{-1} and up to 1.0 mbarn^{-1}, contrary to intrinsic AGB objects, which are limited to the interval 0.2–0.4 mbarn^{-1}. An extension toward the region of high τ_0-values was already noticed in Paper I for extrinsic (Tc-poor) S stars; hence, the strict relationship between Ba stars and extrinsic S stars is confirmed. In the light of the discussion presented in § 2, where a tentative anticorrelation between neutron exposure and metallicity is shown for a number of Ba and S stars, this means that we are sampling Ba stars down to lower average metallicities than intrinsic S or C giants, and this in turn is most probably due to the longer evolutionary times of the Ba star binary systems.

The above anticorrelation is actually expected on theoretical grounds, if the amount of (primary) ^{13}C producing neutrons is roughly constant over the metallicity range of interest (see also Clayton 1988). Indeed, let us recall that, for thermal pulses that overlap by a factor r:

$$\tau_0 = \frac{\Delta\tau}{-\ln r}$$

(see Ulrich 1973) and

$$\Delta\tau = \int \bar{n}_n(t) v_T(t)\, dt ,$$

where $\Delta\tau$ is the neutron exposure per pulse, $\bar{n}_n$ is the average neutron density, and v_T is the thermal velocity. Assuming equilibrium between production and destruction rates for neutrons, one has

$$\bar{n}_n \simeq \frac{N_{13} N_\alpha \lambda_{(13,\alpha)}}{\Sigma N_k \langle\sigma v\rangle_{(k,n)}} ,$$

where N_k is the abundance by number of nuclei of type k and $\langle\sigma v\rangle_{(k,n)}$ is the Maxwellian-averaged product of the neutron-capture cross section and the particle velocity. Then, if N_{13} does not vary with the metallicity Z, $\bar{n}_n$ decreases for increasing metallicity, due to the growing values of N_k, and one has $\tau_0 \sim \bar{n}_n \sim 1/Z$.

In our numerical models, the real scaling with Z is more complex. Indeed, some of the neutron positions (^{22}Ne and ^{25}Mg) have part of their abundance built through the primary ^{14}N introduced into the pulse with ^{13}C and part built (in a secondary way) from the original CNO nuclei of the star. Hence, some of the N_k scale in a more complex way with metallicity, and then so do $\bar{n}_n$ and τ_0. However, the qualitative expectation that τ_0 increases when Z decreases remains (see also Gallino et al. 1988; Malaney & Fowler 1988) and can be a tool for explaining the behavior of classical Ba stars. It is remarkable to notice that the increase of τ_0 with decreasing Z seems also to be verified in stars of metallicity lower than considered here, as recently pointed out by Vanture (1992) and by Plez et al. (1993).

One can also note that among the stars that in Figure 6 lie on the right side of the plot, toward high [hs/ls] ratios, only two are outside the interval covered by model curves. These include one extrinsic S star observed by Smith & Lambert

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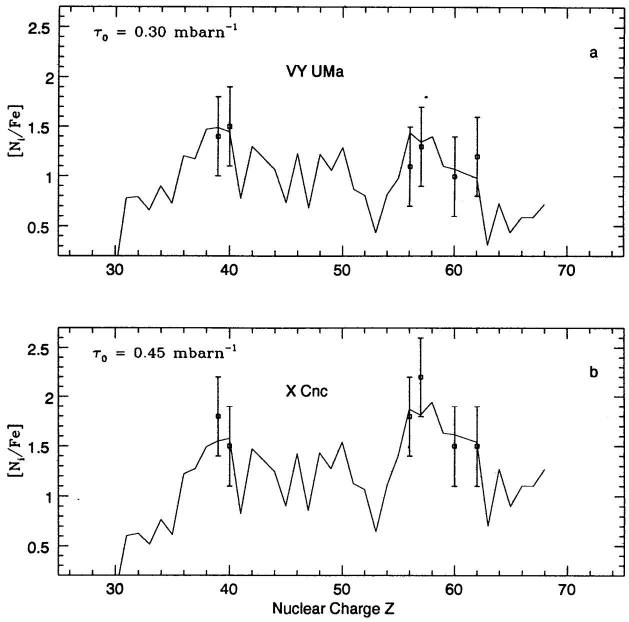

FIG. 8.—Examples of the detailed fitting of predicted abundance patterns to C star abundances. Both cases reach C/O ratios very close to 1.0 and final core masses, M_H, in the range 0.6–0.7 $M_\odot$. As in Fig. 5, ^{93}Zr is still mostly alive, due to the short duration of interpulse periods; hence, the abundance of Nb ($Z = 41$) is low. Observations are from Utsumi (1985).

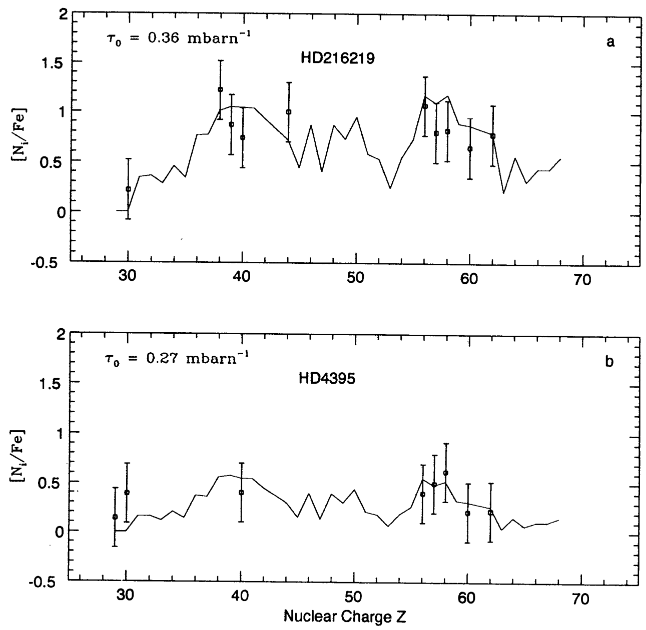

FIG. 9.—Examples of the fitting of predicted to observed abundances of two subgiant CH stars. All the ^{93}Zr that was alive in the C star atmosphere has been allowed to decay to Nb ($Z = 41$) after mass transfer. The accreted material is (*a*) 50% and (*b*) 20% of the envelope mass in the secondary component. Observational data are from Lambert (1985) and Krishnaswamy & Sneden (1985).

(1990) and one (suspected) Ba star observed by Smith & Suntzeff (1987). In both cases, the metallicities of the sources are near the lowest extreme of the range considered here, reaching [Fe/H] = −0.5 and −0.7, respectively.

A more detailed analysis of the abundance distributions has been performed for selected stars, as shown in Figures 8–11 for representative C stars (N-type), CH subgiants, mild Ba stars, and classical Ba giants. The adopted values of τ_0 are indicated. For the sake of simplicity, only the more realistic models of type B are used; however, as shown in Figure 12 for the case of HR 774, very similar fits (to the point that the differences are generally undistinguishable) can be obtained with the set of models (type A) used in Paper I.

Examples of fits to the observations are also presented in Tables 1 and 2, where CNO nuclei are included. In this respect one has to remember, as summarized in § 3.1, that CNO isotope abundances and especially the excesses of ^{13}C observed in LMSs give clear evidence that mixing processes unaccounted for by standard evolutionary models exist on or near the main sequence. Recently, VandenBerg & Smith (1988) verified that stellar models assuming such extra mixing processes can reproduce the observed trend, a fact anticipated by Lambert & Ries (1981). Among the mechanisms so far suggested to drive this mixing we recall meridional circulation

TABLE 1

FIT OF TX PSC (Nb; C7, 2): MIXING AT EACH PULSE

Element	Model A Abundances[a]	Model B Abundances[b]	Observed Abundances[c]
^{12}C/^{16}O	1.16	1.13	1.03 ± 0.10
^{12}C/^{13}C	47.2	42.6	43 ± 2
[Fe/H]	−0.35	−0.4	−0.4 ± 0.10
[Y/Fe]	1.4	1.3	1.3 ± 0.4
[Zr/Fe]	1.4	1.3	1.2 ± 0.4
[Ba/Fe]	1.6	1.5	1.9 ± 0.4
[La/Fe]	1.5	1.4	1.2 ± 0.4
[Nd/Fe]	1.3	1.1	1.2 ± 0.4
[Sm/Fe]	1.2	1.1	1.4 ± 0.4

NOTE.—Initial ^{12}C/^{13}C adopted = 12; mixing ratio = 0.02.
[a] $\tau_0 = 0.51$; $M = 1.5\ M_\odot$; 21st pulse.
[b] $\tau_0 = 0.47$; $M = 1.5\ M_\odot$; 27th pulse.
[c] From Utsumi 1985; Lambert et al. 1986.

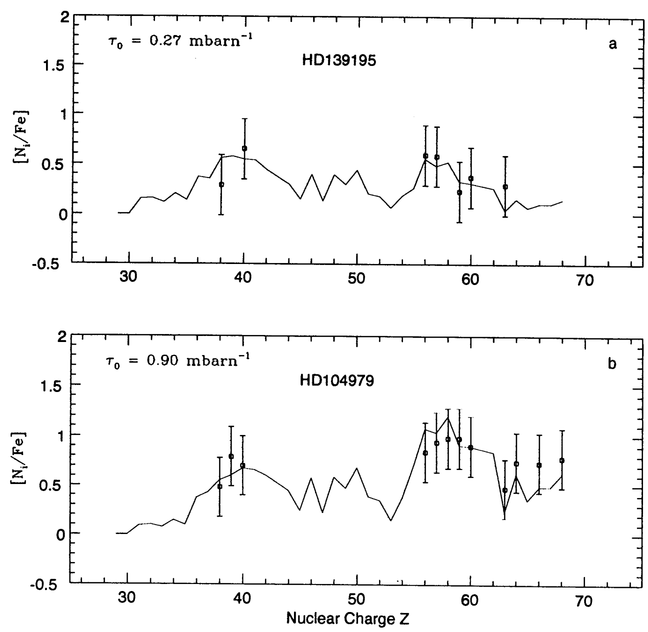

FIG. 10.—Same as Fig. 9, but for two mild Ba stars. The accreted material is (*a*) 20% and (*b*) 50% of the final envelope mass in the secondary star. Observational data are from Tomkin & Lambert (1986) and Sneden et al. (1981).

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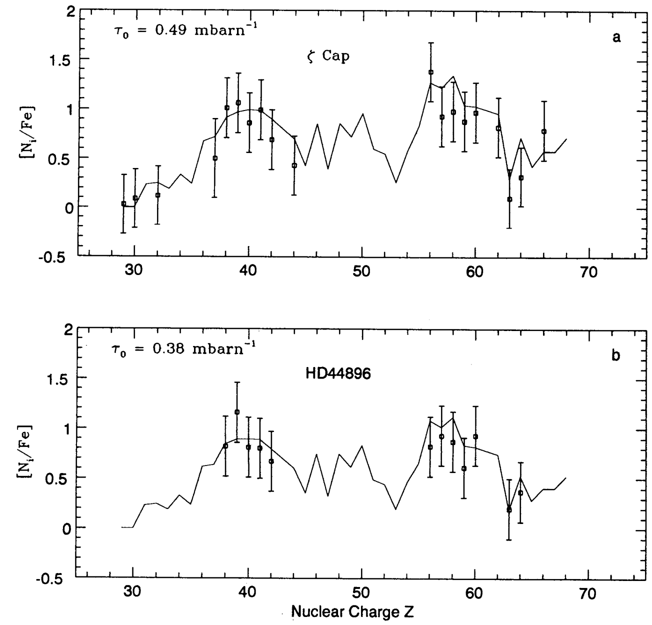

FIG. 11.—Same as Fig. 9, but for classical Ba II giant stars (see text). The accreted material contributes 50% for ζ Cap and 70% for HD 44796 to the final envelope masses. Observational data were taken from Tech (1971), Smith (1984), Smith & Lambert (1984), and Pinsonneault et al. (1984).

(Dearborn, Eggleton, & Schramm 1976) and turbulent diffusion (Genova & Schatzmann 1979). For Ba stars, the extra mixing might have occurred twice (for the primary and for the secondary component). Moreover, the diffusion mechanisms suggested by Barbuy et al. (1992) should also be considered.

With these limitations in mind, we did not attempt to reproduce the lowest $^{12}C/^{13}C$ ratios observed in Ba stars: as mentioned in Paper I, we start the models with $^{12}C/^{13}C$ values on the red giant branch as taken from observations; then, in deriving the data presented in Table 2, we did not consider further dredge-up episodes on the secondary component, which would further reduce the final $^{12}C/^{13}C$ ratio.

A second problem concerns nitrogen abundances; in view of the discussion in § 3.1, it is likely that the observed N abundances of Ba stars are not very reliable data; it is even more the case for N abundances of carbon stars (see, e.g., Gustafsson 1989). For this reason we have not considered this constraint in our fits.

6. NEUTRON DENSITY TESTS AND THE ORIGIN OF Ba STARS

A tool to discriminate between the possible origins of Ba stars is to derive constraints not only on the neutron exposure, but also on the neutron density they have experienced. Such a test was applied first by Tomkin & Lambert (1984) and then by Malaney (1987) and Malaney & Lambert (1988) from observations of Rb and Sr lines. These two elements have an abundance ratio which is dependent on neutron density due to the operation of a branching in the *s*-process path at ^{85}Kr (see, e.g., Käppeler et al. 1982; Käppeler, Beer, & Wisshak 1989 for details).

Malaney & Lambert (1988) compared the observational data for Ba stars with *s*-process calculations in IMSs and with results for the ^{13}C neutron source in LMSs by Malaney (1986). Subsequent studies (Gallino et al. 1988; Hollowell & Iben 1990; Käppeler et al. 1990; see also Straniero et al. 1995a, b) have made clear that the neutron densities associated with the ^{13}C source can be two orders of magnitude smaller than evaluated by Malaney (1987). Due to this we have repeated the

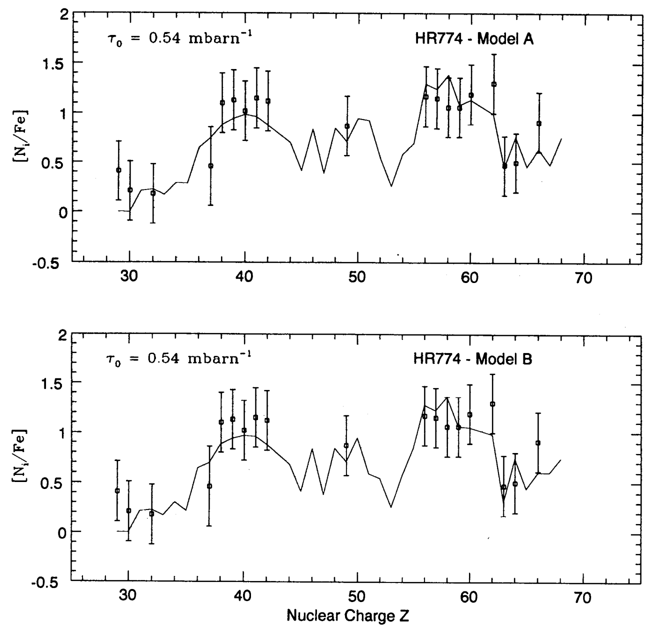

FIG. 12.—Fits to the abundances of the classical Ba II giant HR 774 using models A and B (see text). In both cases, the accreted material accounts for 50% of the envelope mass. Observational data are arithmetic averages of those by Smith (1984) and by Tomkin & Lambert (1979, 1983) which are compatible within error bars. The data for Ru (*Z* = 44) and Gd (*Z* = 64), which have large uncertainties, have been excluded.

TABLE 2

FIT OF HR 774 (G8; Ba 3): MIXING AT EACH PULSE

Element	Model A Abundances[a]	Model B Abundances[b]	Observed Abundances[c]
$^{12}C/^{16}O$	0.60	0.58	0.72 ± 0.10
$^{14}N/^{12}C$	0.40	0.42	0.50 ± 0.10
$^{12}C/^{13}C$	25	24.4	23 ± 2
[Fe/H]........	−0.32	−0.32	−0.32 ± 0.10
[Cu/Fe]	0.03	0.03	0.41 ± 0.3
[Zn/Fe]	0.00	0.00	0.21 ± 0.3
[Ge/Fe]	0.22	0.22	0.18 ± 0.3
[Rb/Fe]	0.75	0.69	0.46 ± 0.3
[Sr/Fe]	0.88	0.88	1.10 ± 0.3
[Y/Fe]........	0.94	0.94	1.13 ± 0.3
[Zr/Fe]	0.98	0.97	1.02 ± 0.3
[Nb/Fe]	0.96	0.96	1.15 ± 0.3
[Mo/Fe]......	0.88	0.87	1.12 ± 0.3
[In/Fe]	0.70	0.70	0.87 ± 0.3
[Ba/Fe].......	1.29	1.28	1.17 ± 0.3
[La/Fe].......	1.24	1.22	1.15 ± 0.3
[Ce/Fe].......	1.38	1.36	1.06 ± 0.3
[Pr/Fe]	1.08	1.06	1.06 ± 0.3
[Nd/Fe]	1.13	1.05	1.19 ± 0.3
[Sm/Fe]	0.99	0.98	1.30 ± 0.3
[Eu/Fe]	0.44	0.31	0.47 ± 0.3
[Gd/Fe]	0.76	0.74	0.50 ± 0.3
[Dy/Fe]	0.63	0.60	0.91 ± 0.3

NOTE.—Initial $^{12}C/^{13}C$ adopted = 12; mixing ratios = 0.01 (from dredge-up) × 0.5 (from mass transfer).

[a] $\tau_0 = 0.54$; $M = 1.5\ M_\odot$; 29th pulse.

[b] $\tau_0 = 0.54$; $M = 1.5\ M_\odot$; 26th pulse.

[c] From Tomkin & Lambert 1979, 1983; Smith 1984.

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1995ApJ...446..775B

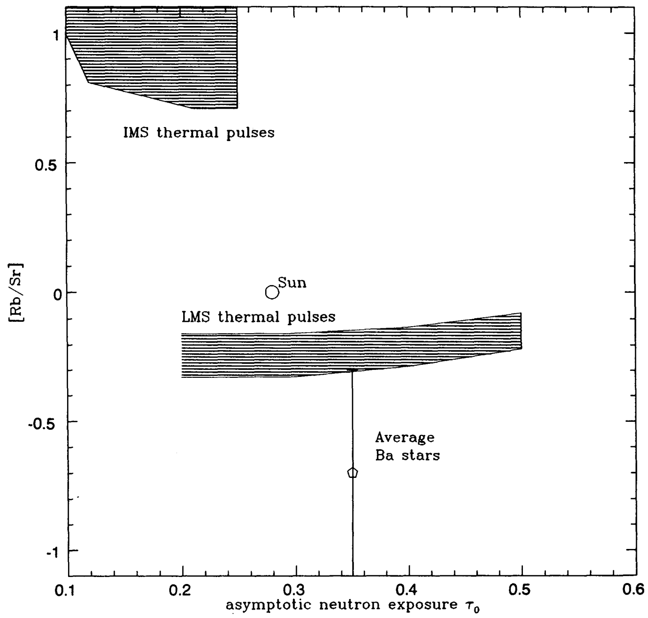

FIG. 13.—Average logarithmic ratio [Rb/Sr] as derived from the work of Malaney & Lambert (1988), compared with model predictions for the envelopes of AGB stars when C/O = 1. Both the LMS and the IMS regions are shown. Also indicated are the solar normalization ratio ("Sun"). An uncertainty of 0.4 dex was assumed on the observational data.

analysis of Rb abundances using our AGB models. The results are shown in Figure 13, where we compare the average Rb/Sr ratio derived by Malaney & Lambert (1988) for the envelopes of Ba II giants with our predictions for thermal pulses in LMSs and subsequent mixing into the envelope. We also show predictions from the models by Busso et al. (1988) for IMSs where the ^{22}Ne source is at play. In this last case, we use results obtained with the lower choice of the neutron-capture cross section of ^{22}Ne ($\sigma_{22} \simeq 0.05$ mbarn, very close to the presently accepted value given by Beer et al. 1991).

We have assumed a relatively large error bar for the Rb/Sr ratio (0.4 dex) because the observational data were derived from one Rb line and Sr abundances were taken from other sources. It is evident from the figure that, even at this level of uncertainty, the Rb data are only marginally compatible with thermal pulses where the ^{13}C neutron source is at play; they are in any case incompatible with the operation of the ^{22}Ne-neutron source in IMSs. Depending on the ingestion rates, on the convective masses (which vary from pulse to pulse), and on the value of τ_0 reached, the maximum (average) neutron densities experienced by the LMS models shown in Figure 13 during ^{13}C burning are in the range (4×10^8)–(1.4×10^{10}) cm^{-3} (the upper limit being reached only in the extreme $\tau_0 =$ 1.0 mbarn^{-1} case). Concerning IMS thermal pulses, from Figure 13 they appear to be inconsistent with the observed ratios for two different reasons, having both too high neutron densities and too low neutron exposures. Actually, on the basis of the neutron exposure alone, one can exclude the possibility that the operation of the ^{22}Ne source in IMSs is a plausible explanation for *s*-process enhancements Ba stars: indeed, it would be unable to reproduce the high [hs/ls] ratios that generally characterize these stars (see Fig. 6). The LMS scenario clearly offers a better chance to fit the observed Rb/Sr ratio; however, the present models where ^{13}C burns convectively in the pulses are still only marginally compatible with the data. This is another indication in favor of *s*-processing occurring in LMSs, but at even lower neutron densities, as is the case in Straniero et al.'s (1995a, b) results. This problem will be analyzed in detail in a forthcoming paper, on the basis of new observations of Rb and Zr isotopes in MS and S stars (Lambert et al. 1995).

Thanks to the above comparisons and to the information provided by Mg isotope ratios we believe that Ba stars owe their abundances to the mass transfer from a low-mass ($M < 2$ $M_\odot$) carbon star in which *s*-processing was run by the ^{13}C neutron source. We also do not find any need to invoke a single very large neutron exposure during core He flash, as suggested by Malaney (1987), to account for the Ba star abundances in the Galactic disk.

7. CONCLUSIONS

In this paper we have presented new calculations of AGB evolution and of thermal pulse nucleosynthesis in LMSs and we have compared our predictions with abundance determinations in carbon stars (N-type) and in the various classes of barium stars with Galactic-disk metallicity.

Low-mass carbon stars show *s*-process distributions characterized by mean neutron exposures in the range 0.2–0.4 mbarn^{-1}, as was already ascertained for MS and S stars in Paper I. They appear to be evolutionary descendants of these last red giants, having reached higher mixing ratios between the shell matter and the envelope and having probably experienced at least 15–20 thermal pulses. Hence, C stars cannot be formed by giants of very low mass (e.g., $M < 1.2$ $M_\odot$), for which mass loss terminates the AGB evolution before this limit is reached. Most optical carbon stars probably derive from a relatively narrow mass range ($1.5 < M/M_\odot < 2$). This fact is confirmed by their kinematic properties.

Concerning Ba stars, their abundances can be well reproduced on the simple hypothesis that they received *s*-process–enriched material in a mass transfer from a companion, while this last was in the C star phase. This fact suggests that possible episodes of enhanced mass loss before the C star stage, while useful for interpreting the complex interplay between dredge-up and pulsation on the AGB, should not involve large fractions of the envelope, letting the maximum probability of mass transfer be reached near the end of evolution, when dredge-up has increased the C/O ratio above unity.

Constraints deriving from Mg isotope ratios, from the low neutron densities necessary to explain the Rb/Sr ratios and from the large mean neutron exposures, which cannot be produced by the ^{22}Ne source operating in IMSs, all suggest that the primaries, from which mass was accreted on the Ba-type secondaries we now see, were of low mass.

The sample of Ba stars actually observed appears to be distributed on a wider metallicity range than for intrinsic AGB stars, probably due to the longer evolutionary time of the low-mass binary systems. Over this metallicity range an inverse correlation between the neutron exposure (monitored by the parameter [hs/ls]) and the iron content [Fe/H] is shown by all the Ba star subclasses. The maximum neutron exposures achieved by the members of the sample having the lowest metallicities reach $\tau_0 = 1.0$ mbarn^{-1}. This fact is easily interpreted in the light of the *primary* nucleosynthesis nature of the neutron source, ^{13}C.

In any case, we find that exponential distributions of neutron exposures of the type achieved in thermal pulses can

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1995ApJ...446..775B

account for all the constraints based on Ba stars' abundances in the Galactic disk, including those based on the neutron density, without the need to invoke single, very efficient neutron bursts, as previously suggested by other authors.

We are indebted to O. Straniero and A. Chieffi for continuous discussion of and help with the thermal pulse models. This work was supported in part by grants from the Robert A. Welch Foundation and from the National Science Foundation (grants AST 91-15090 and AST 93-15124), as well as by a special project of the Gruppo Nazionale di Astronomia del Consiglio Nazionale delle Ricerche (CNR-GNA).

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1995ApJ...446..775B

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