CHEMICAL COMPOSITION AS A SIGNATURE OF STELLAR EVOLUTION - THE BARIUM STARS

David L. Lambert
Department of Astronomy
The University of Texas
Austin, TX 78712 USA

ABSTRACT: The hypothesis that Barium stars are the product of mass transfer across a binary system is reviewed with special attention given to the chemical composition of AGB stars (the mass-losing star in the binary) and the Ba stars (the mass-gaining star).

1. INTRODUCTION

Preparation of a spectroscopic attack on an outstanding question of stellar evolution or nucleosynthesis must review the basic questions: signal-to-noise (S/N) ratio? spectral resolution? wavelength coverage? magnitude limit? sample size? As telescopes of larger aperture and spectrometers of greater sensitivity have become available, this observer has enjoyed exploiting the less restrictive compromises. My initial intent was to illustrate how the sharpened observational attacks have led to new insights into and critical tests of theories of stellar evolution. Although some current progress is directly traceable to the acquisition of high S/N high resolution spectra, other key developments have come as the new telescopes and spectrometers have yielded modest S/N ratio and low resolution spectra of faint stars; for example, such spectra of the Magellanic Cloud's asymptotic giant branch (AGB) stars have provided novel and unanticipated results.

A review of how the panoply of stellar evolution and nucleosynthesis can be pierced by quantitative spectroscopic determinations of the stars' surface chemical composition might be organized in several ways:

- stars could be discussed according to their positions in the Hertzsprung-Russell diagram.
- abundance anomalies (i.e., an abundance differing from that expected for the star's main sequence progenitor) could be ordered by element and isotope.
- physical processes (e.g., deep convection, mixing induced by rotation, mass loss) responsible for production of the anomalies could be isolated for comment.
- principal areas of agreement and disagreement between observation and theory could be stressed.

This fourth scheme could be the basis for a fascinating review constructed around a series of observing proposals aimed at resolving the key areas of disagreement. With the editors' insistence that invited reviews not exceed a mere nine pages, the review becomes a brief essay. Through this essay on the classical Barium stars, I hope to illustrate how the 'new' spectroscopy including high S/N spectroscopy can address outstanding issues in stellar evolution.

G. Cayrel de Strobel and M. Spite (eds.), The Impact of Very High S/N Spectroscopy on Stellar Physics, 563–576.

2. THE BARIUM STARS

2.1. The Mass-Transfer Hypothesis

Barium (Ba) stars were isolated as a class by Bidelman and Keenan (1951): the low dispersion spectra of these G and K giants show enhanced absorption due to Ba II, Sr II, CH, CN, and C_2. Quantitative analyses have shown that the atmosphere of a Ba star is enriched in carbon and the heavy elements synthesized by the neutron capture s-process (see review by Lambert 1985). Enrichments range from slight in the mild Ba stars to substantial (say [s/Fe] ~ 1) in the classical Ba stars. Here, I shall refer to these stars as Ba stars. The CH stars identified by Keenan (1942) are metal-poor giants with the spectroscopic characteristics of Ba stars. Bond (1974) introduced the class of subgiant CH stars which extended detection of C and s-process enhancements to the warmer subgiants, and even the main sequence. I focus on those clues to the origin of the stars that are provided by the chemical composition of Ba and related stars. A reader to whom Ba stars are a novelty is urged to read McClure's (1984) thorough review, and several contributions in *Cool Stars with Excesses of Heavy Elements*, notably Catchpole and Feast (1985), Lambert (1985), McClure (1985), and Wood (1985).

The hypothesis under test was suggested by the radial velocity surveys conducted by McClure and colleagues at the Dominion Astrophysical Observatory. An initial survey of Ba stars and a control sample of K giants showed that the Ba stars were binary systems (McClure, Fletcher, and Nemec 1980): "all stars in the sample that have Ba II star features stronger than Ba1 on the Warner (1965) scale show velocity variations" (McClure 1985). Direct evidence that the mild Ba stars (strengths less than Ba1) belong exclusively to binary systems is not so strong but, as McClure points out, the sample is contaminated by stars that may not be Ba stars "but only stars that were suspected from objective prism plates". McClure further notes that preliminary results suggest that the giant and subgiant CH stars are also binary systems. These surveys in which an accuracy of 0.5 km s^{-1} or better is achieved exemplify, in my view, one impact of high S/N stellar spectroscopy.

For this essay, I shall assume that the origin of the Ba stars is intimately related to the fact that they belong to a binary system. In particular, I shall review the hypothesis of mass transfer. (Four alternative explanations for the occurrence of Ba stars as binary systems are listed and dismissed by McClure (1985)). Consider a wide binary in which mass transfer via Roche lobe overflow or a stellar wind cannot occur until the primary has evolved to the AGB and dredged up C and the s-process elements to its surface. Through the mass transfer from the AGB star, the companion is converted to a Ba star. The transferred mass may be mixed with the outer envelope of the companion. The companion may be a main-sequence star. On evolution to the red giant branch, the convective envelope should thoroughly erase composition gradients and, as in normal stars, dredge up material lightly exposed to the CN-cycle. When the transferred mass is much less than the mass contained within the red giant's convective envelope, the striking abundance anomalies will be diluted and the giant may appear almost normal. Some mass-gaining stars may be red giants at the time of mass transfer. I adopt the plausible assumption that all of the transferred mass is provided by the AGB star's envelope, and hence, its composition is that of the AGB star's atmosphere I suppose that the AGB star is commonly a cool carbon star. Mass transfer in a few cases may occur before the AGB star has completed its conversion from an O-rich to a C-rich star.

To an observer, the mass transfer hypothesis has four attractive features: (i) AGB stars are predicted and observed to be enriched in C and s-process elements, whereas the competing source of these elements - the He-core flash - has not been shown on either theoretical or observational grounds to be capable of mixing products of nucleosynthesis to the stellar surface, (ii) mass transfer between components of a binary will be delayed in wide systems until the more massive star has evolved to the AGB, (iii) the chemical composition of Ba stars is, in principle, predictable given the composition of the AGB stars, and (iv) the core of the mass-losing AGB star should be detectable as a white dwarf companion to the Ba star.

In the following section, I shall explore whether the mass transfer hypothesis with the derived compositions of AGB stars can account for the compositions of the Ba stars. Then, I comment briefly on the question "Do all Ba stars have a white dwarf companion?"

2.2 Chemical Compositions of AGB and Ba Stars

Recent explorations of the chemical compositions of both Ba and the MS, S, and C stars on the AGB permit simple tests of the mass-transfer hypothesis. I shall examine the following aspects of the compositions:

- Are the correlated enhancements of carbon and the s-process elements in the Ba stars consistent with those seen in AGB stars?
- Are the principal characteristics of the s-process products similar for the Ba and the AGB stars? Such characteristics include
    - the identity of the neutron source
    - the neutron exposure parameter τ_0
    - the effective neutron density at the s-process site N(n)

Comments on the mass-transfer hypothesis and the abundances of the trace species Li, ^{13}C, ^{17}O, and ^{18}O may be found elsewhere: Li (Lambert 1985; Smith and Lambert 1986a), ^{13}C (Sneden 1983; Lambert 1985); ^{17}O and ^{18}O (Harris, Lambert, and Smith 1985, 1987).

2.2.1. Carbon and the s-process elements. For Ba stars there is a correlation between the overabundances of carbon and s-process elements: mild Ba stars are only slightly enriched in these species, but the classical Ba stars show strong enrichments amounting to [s/Fe] ~ 1 and [C/Fe] ~ +0.3. (I use the conventional notation: [X] = log X (star) - log X (standard) where the sun is often adopted as the standard.) In Figure 1a, I show the [s/Fe] - [C/Fe] correlation compiled from analyses based on high S/N spectra and model atmospheres.

On the mass-transfer hypothesis one expects the most severe transfers of mass to create classical Ba stars with a chemical composition that is generally close to that of the AGB mass-losing star. Of course, the composition of the Ba star may be modified as the star evolves from its initial condition (say, on the main sequence) to its present status as a red giant with a deep convective envelope; i.e., the C/O ratio of the Ba giant will be less than that of the main sequence progenitor which may have a C/O ratio somewhat less than that of the AGB star. This expectation for carbon and the s-process elements is confirmed by recent analyses of the O-rich M, MS, and S and the C-rich cool carbon AGB stars (Figure 1).

After years of near-complete neglect, quantitative spectroscopy of the cool AGB stars has begun. A principal reason for current interest is the ability to obtain high resolution high S/N spectra in the infrared atmospheric windows that provide molecular lines, and hence, the abundances of the isotopes of C, N, and O, all of which are sensitive in differing ways to stellar evolution. For the O-rich stars (spectral types M, MS, S), the following molecules were considered in our CNO analysis: CO, OH, NH, and CN (Smith and Lambert 1985, 1986b, SL). For the comparable analysis of the cool carbon stars, the primary molecules were CO, CN, and C_2 (Lambert *et al.* 1986).

To obtain the s-process enhancements of the MS and S stars, we scoured near-infrared windows between molecular bandheads for suitable lines. Abundances of 'light'

(Sr, Zr, Y) and 'heavy' (Ba,Nd) s-process elements were obtained differentially with respect to the K5 giant α Tau (SL); a differential analysis reduces the systematic errors due to non-LTE effects. For the s-process abundances of cool carbon stars, I draw on Utsumi's (1985) curve-of-growth analyses based on lines in two regions (4750-4900 Å, 4400-4500 Å) not dominated by molecular lines. For his sample of 12 stars of which 10 were analyzed for CNO by Lambert *et al.* (1986), the mean enhancement [s/Fe] is +1.7 for the 'light' s-elements (Zr,Y) and +1.1 for the 'heavy' s-elements (Ba,La,Nd,Sm); I adopt [s/Fe] = +1.3 ±0.4 as characteristic of cool carbon stars. The chosen sample does not include the ^{13}C-rich (J-type) stars for which the s-process abundances are "nearly normal".

Figure 1 clearly shows that the C and s-process overabundances in the extreme classical Ba stars approach the levels reported for the cool carbon stars - see the line in Figure 1a showing how the composition of a GK giant is changed as an increasing fraction of C-star material (here, [C/Fe] = + 0.3 and [s/Fe] = + 1.2) is added. The fact that this line runs through the points representing the Ba stars would support a claim that the latter are created through mass-transfer onto a *giant* rather than a *dwarf*. Addition of material to a dwarf followed by reduction of C at the first dredge-up would lead to a Ba giant having at most [C/Fe] ~ 0.0, not +0.3. By their position in Figure 1a, the subgiant CH stars appear to be the progenitors of the Ba stars. The mass-transfer hypothesis also shows why C-rich

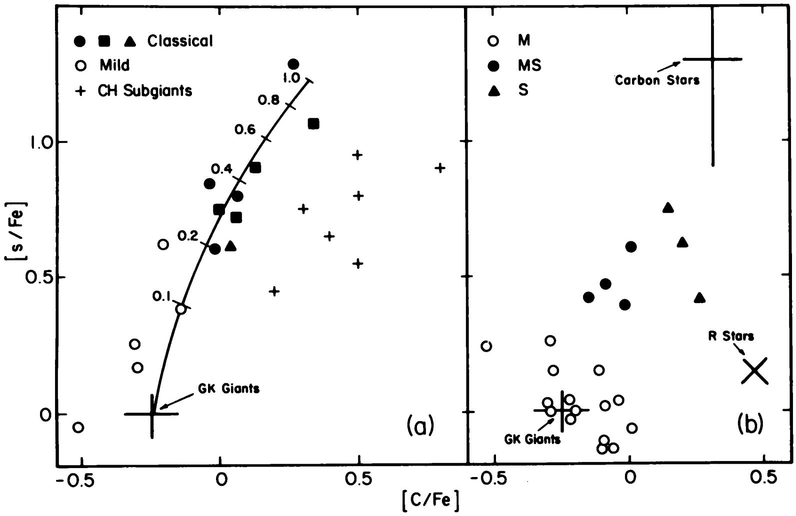


Fig. 1. - The abundance of s-process elements and carbon in (a) Ba stars and CH subgiants and (b) M, MS, S, cool and warm (R type) carbon stars. The location in this plane of the GK giants is shown in both panels. The line in panel (a) shows how the composition of a GK giant is changed as an increasing fraction of material from a cool carbon star is added. Data for mild Ba stars are from Sneden *et al.* (1981) and for classical Ba stars from: circles - Sneden *et al.* (1981), Tomkin and Lambert (1979), squares - Smith (1984), and triangle - Kovács (1983). Data for CH subgiants are from Sneden (1983) and Luck and Bond (1982). Points for GK giants and R stars are taken from Lambert and Ries (1981) and Dominy (1984), respectively. Points for M, MS, and S strs are taken from SL. The representative point for the cool carbon stars is based on Utsumi's (1985) s-process abundances (see text) and [C/O] from Lambert *et al.* (1986), with the assumption [O/Fe] = 0.0.

Ba stars appear to be rare; since the C/O ratio is close to unity in the majority of carbon stars (Lambert *et al.* 1986), a slight mixing of the transferred mass with the envelope of the companion for which C/O < 0.6 will ensure that C/O ≤ 1 for the Ba star. Nonetheless, some C-rich Ba stars could result; the class of CH-like stars may include examples (Yamashita 1972, 1975). A minority of the MS and S stars may be evolved Ba stars - see Smith and Lambert (1987) for comments on Tc-poor MS and S stars.

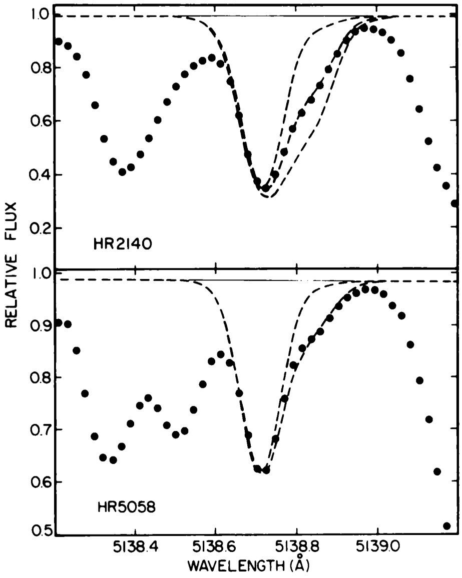
The N and O abundances of the Ba stars (Lambert 1985) and the MS-S stars (SL) are identical within the measurement errors to those found for G and K giants. This conclusion holds also for the O abundances of the cool carbon stars (Lambert *et al.* 1986), but not for the N abundances. The unexpectedly lower N abundances in the carbon stars may reflect a systematic error associated with the use of CN as the primary N indicator. It would be an over-reaction to consider the N abundance as grounds for rejecting the mass-transfer hypothesis. The pattern of CNO abundances in the AGB stars supports the idea that, after a first dredge-up as a K giant, the thermal pulses added (almost) pure ^{12}C (and s-process elements) to the envelope.

Although a reader of these recent papers - and especially a theoretician interested in tests of stellar evolution - should note the discussions of the major sources of error, two conclusions seem clear: (i) the enhancements of C and the s-process elements in the Ba and AGB stars are consistent with the mass-transfer hypothesis, and (ii) the mass-gaining star may be a giant at time of the transfer. Since the relative rates of C and s-process production within a star are not an invariant property of any nuclear-reaction network, but reflect the detailed structure of particular zones within the interior, one may plausibly expect mixing resulting from the He-core flash in a low-mass star and mixing from thermal pulses in an AGB star to produce different surface enhancements of C and s-process elements. Moreover, except for a few very peculiar stars (e.g., U Aqr, a RCrB star with an unusual pattern of s-process overabundances), the Ba and AGB stars are the only objects with marked overabundances of C and the s-process; i.e., there is no need to invoke operation of the s-process in multiple sites of radically different properties. The close correspondence between the compositions of Ba and AGB stars surely suggests that abundance anomalies come from sites with similar characteristics. In short, a common site - the He-shell of a AGB star - is strongly suspected, as required by the mass-transfer hypothesis.

2.2.2. The s-process. Physical conditions at the s-process site may be estimated from the relative abundances of key sensitive elements and isotopes. Sophisticated analyses of the accurate abundance data for the solar system (i.e., meteorites) provide mean estimates of the neutron density N(n), the total density and the temperature T_n together with limited information on their time-dependence during processing. Although full duplication of these analyses will never be possible for stars, acquisition and analysis of high S/N stellar spectra is yielding some interesting results.

The neutron source: Before discussing the physical conditions at the s-process sites, I shall comment on the neutron source. The two most likely neutron-producing reactions are the $^{13}C(\alpha,n)^{16}O$ and $^{22}Ne(\alpha,n)^{25}Mg$ reactions. The latter reaction is expected to operate in the thermal pulses of intermediate-mass stars and the former in the pulses of low-mass stars (see Wood 1985). In addition to composition differences resulting from the different physical conditions in low and intermediate mass stars, the two neutron sources are distinguishable through the Mg isotopic ratios. Operation of the ^{22}Ne source results in production of significant amounts of ^{25}Mg and ^{26}Mg; classical Ba stars are predicted to have $^{25}Mg/^{24}Mg$ and $^{26}Mg/^{24}Mg \gtrsim 1$ (Scalo 1978; Malaney 1987a). Production of the heavier isotopes through operation of the ^{13}C-source may occur, but is less efficient (Arnould and Jorissen 1986). Presence of MgH lines in the spectra of red giants provides the opportunity to determine the Mg isotopic ratios for both Ba and AGB stars.

Fig. 2. - Observed and synthetic spectra near 5139 Å showing the coincident ^{24}MgH 0-0 $Q_1(22)$ and 1-1 $Q_1(14)$ lines at 5138.7 Å in HR2140, an old disk giant, and HR5058, a classical Ba giant. Synthetic spectra are shown for ^{24}Mg:^{25}Mg:^{26}Mg = (100:0:0) and (80:10:10 ≡ solar) for both stars and for (90:5:5) for HR2140 only.



None of the stars analyzed to date show evidence for the ^{22}Ne-source. Smith and Lambert (1986b) analyzed two normal M and three similar but s-process enhanced stars; all showed Mg isotopic ratios similar to the solar (the presumed initial) ratios. Earlier, Clegg, Lambert, and Bell (1979) obtained a similar result for the S star HR 1105. Isotopic analyses for two classical and two mild Ba stars also give ratios near the terrestrial values (Tomkin and Lambert 1979; McWilliam and Lambert 1987) - see Figure 2. Recently, a modest overabundance of ^{25}Mg and ^{26}Mg has been found for the cool classical Ba star HD178717 (Malaney and Lambert 1987): ^{24}Mg:^{25}Mg:^{26}Mg = 60:25:15 where 80:10:11 is the terrestrial mix. These enhancements are substantially less than those predicted for the ^{22}Ne-source (e.g., ^{26}Mg/^{24}Mg ~ 3), but may be compatible with the ^{13}C-source (Arnould and Jorissen 1986). Although the samples are still small, we may conclude that the ^{13}C-source rather than the ^{22}Ne-source appears to have been ignited in both the Ba and AGB s-process sites. This conclusion is consistent with the mass-transfer hypothesis. Identification of the source with the ^{13}C(α,n) reaction also serves as a crude effective thermometer for the s-process site, say $10^8 < T_n < 2 \times 10^8$ K.

The neutron density N(n): Sensitivity of the s-process to N(n) occurs when the s-process path encounters an unstable nucleus with a half-life comparable to the mean time between neutron captures. Estimates of N(n) appear to be possible for the coolest O-rich AGB stars from the ZrO lines and the derived Zr isotopic abundances, and for the Ba stars from the Rb abundance. Unfortunately, a direct comparison between the two groups of stars using the same lines seems to be impossible: the ZrO lines are absent or very weak in spectra of Ba stars and the Rb resonance lines appear to be irretrievably blended in the AGB stars. The s-process path enters at ^{90}Zr and passes through ^{91}Zr and ^{92}Zr to the unstable ^{93}Zr. However, ^{93}Zr is so long-lived ($\tau_{1/2} \sim 1.5 \times 10^6$ y) that the path continues through ^{94}Zr to the unstable ^{95}Zr which with a β-decay half-life of 65 days provides the branch that is sensitive to N(n). At low densities, ^{95}Zr decays to ^{95}Nb and so avoids a n-capture. At high densities, ^{95}Zr captures a neutron to produce ^{96}Zr, the heaviest stable Zr isotope. If we define the critical density to be that at which the mean time between n-captures is equal to the β-decay half-life, ^{95}Zr gives N(n) ~ 10^{10} cm^{-3}. Detection of significant amounts of ^{96}Zr among s-processed material would suggest N(n) $\gtrsim 10^{10}$ cm^{-3}.

Rubidium monitors branching in the s-process path due to unstable ^{85}Kr where the critical density is near 10^8 cm^{-3}; this branch is also sensitive to temperature because low-lying states of ^{85}Kr β-decay more quickly than the ground state. At low densities, ^{85}Rb is synthesized. ^{85}Rb is by-passed at high densities and ^{87}Rb is produced. Thanks to a large difference in the n-capture cross-sections (σ(85) = 360 mb and σ(87) = 11 mb), the Rb abundance relative to neighboring Sr, Y, and Zr increases by about an order of magnitude between the low and high density limits.

Initial determinations of the Zr isotopic ratios used photographic spectra of the ZrO γ(0-0) band near 6370 Å (Schadee and Davis 1968; Peery and Beebe 1970). Later, Zook (1978, 1985) exploited the larger isotopic wavelength shifts provided by the B-X (0-1) band near 6931 Å. Recently, we have been acquiring spectra near 6930 Å for a number of S stars using the McDonald Observatory's 2.7m telescope and coudé spectrometer equipped with a Reticon detector. Our spectra at a resolution of 0.08 Å are ratioed with the featureless spectrum of a hot star to remove telluric lines. In addition to the B-X k0-1) bandhead, the γ (1-2) R_1 bandhead at 6923.4 Å (^{90}ZrO) is present and may be of sufficient strength to provide a second source of the isotopic ratios.

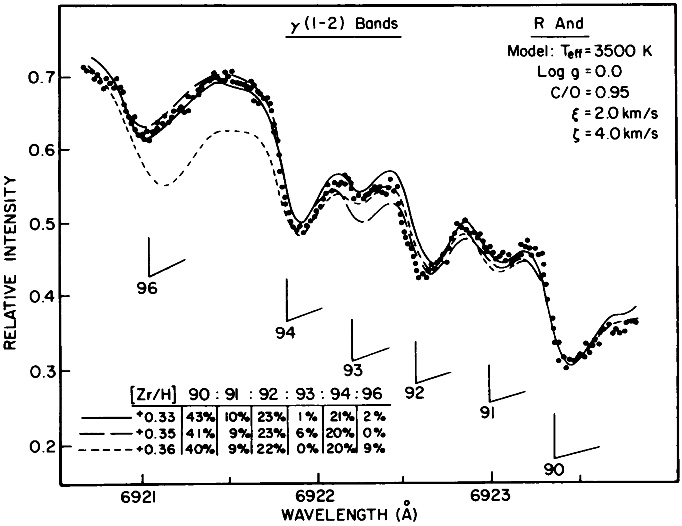


Fig. 3. - The observed spectrum of R And (filled circles) and three synthetic spectra with differing Zr-isotopic mixtures for the γ(1-2) isotopic ZrO bandheads. Locations of the bandheads are shown. The isotopic mixtures and the adopted model atmosphere are characterized by the keys on the figure.

To date, a preliminary analysis is complete for R And and R Gem (Smith 1987). In Figure 3, I show the region near the $\gamma(1\text{-}2)$ head in R And. Synthetic spectra were computed from a line list of 3500 ZrO lines and a handful of atomic lines; the mean density of ZrO lines is 100 per Å! Since ^{96}Zr is the density indicator, I draw attention to the weakness of the ^{96}ZrO bandhead; the feature that appears to be the bandhead is dominated by ^{90}ZrO lines from the $\gamma(5\text{-}6)$ band. This coincidence highlights the need for a complete and accurate linelist; wavelengths *and* oscillator strengths are required. For R And, the B-X (0-1) head provides a second estimate of the isotopic ratios. *Preliminary* results are summarized in Table 1; note the similar ratios for R And (both bands) and R Gem where the $\gamma(1\text{-}2)$ band is too weak to be used reliably. A full error analysis is in progress. Our synthetic spectra are a substantially better fit to the observed spectra than in the comparisons offered by Zook (1985).

Table I. Isotopic Zr-Abundances by Fraction

Star and Bandhead		^{90}Zr	^{91}Zr	^{92}Zr	^{93}Zr	^{94}Zr	^{96}Zr
R And	$\gamma(1\text{-}2)$	.42	.10	.22	.02	.21	.02
R And	B-X 0-1	.32	.18	.14	.05	.24	.07
R Gem	B-X 0-1	.35	.20	.13	.02	.26	.04

The observed isotopic ratios for R And and the solar system material are compared in Figure 4 with Malaney's (1987b) predicted ratios for the low ($N(n) = 10^8$ cm^{-3}) and high density ($N(n) = 10^{11}$ cm^{-3}) limits at a neutron exposure parameter $\tau = 0.5$ mb^{-1} (see below). Malaney's predictions for ^{96}Zr were adjusted to account for the recommended lower cross-section ($\sigma = 25 \pm 15$ mb, Bao and Käppeler 1987). After a simple mixing of s-processed and unprocessed material, the observed (o), primordial (p, unprocessed), and s-processed (s) isotopic fractions are related by the equation

$$f_s(i) = [(1 + E_s)\, f_o(i) - f_p(i)]/E_s$$

where E_s is the observed enhancement of the elemental abundance. For these S stars, we expect $E_s \sim 10$, and hence, $f_s(i) \sim f_o(i)$ for an approximately solar $f_p(i)$.

Inspection of Figure 4 suggests that $N(n) \sim 10^{10}$ cm^{-3} may offer the best fit to the Zr isotopic abundances for R And. This suggestion is based on both the apparent detection of ^{96}Zr and on the overall pattern for the more abundant isotopes. Estimates of the ^{96}Zr abundance are likely to be overestimates because the ^{96}ZrO head may be blended. The solar abundances fit the low density limit; ^{96}Zr is ascribed to the r-process. In both stars, ^{93}ZrO is observed, and this is consistent with the presence of the shorter-lived ^{99}Tc in these stars (Merrill 1952).

Rubidium and neighboring elements have been analyzed to provide N(n) estimates for three Ba stars: HR 774 (Tomkin and Lambert 1983; Käppeler 1986), ζ Cap (Smith and Lambert 1984), and HD 178717 (Malaney and Lambert 1987). The estimates are quite similar N(n) ~ 2 x 10^7 cm^{-3}, a value just above the low density limit for the ^{85}Kr-branch. It will be noted that this estimate is less than that suggested by the *preliminary* analyses of

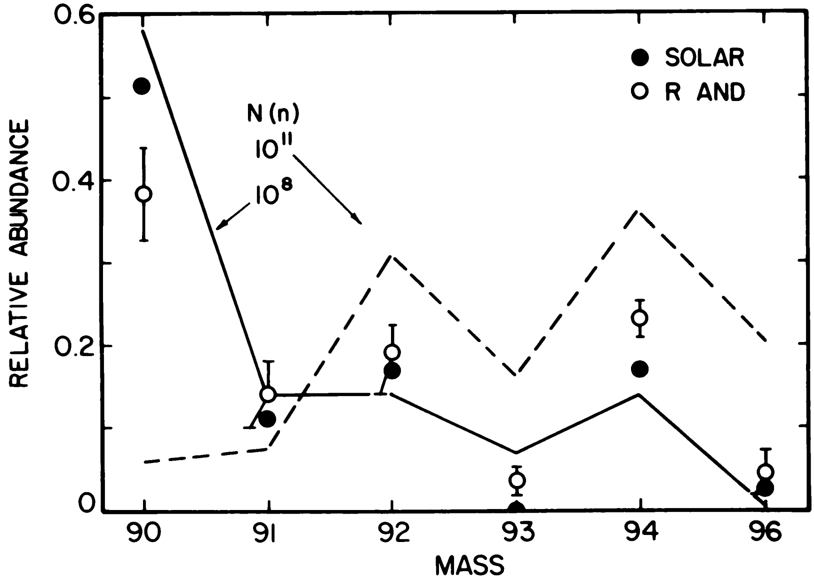


Fig. 4. - Observed and predicted Zr isotopic fractions. These fractions are normalized to unity for the sum over the stable isotopes ^{90}Zr, ^{91}Zr, ^{92}Zr, ^{94}Zr, and ^{96}Zr. Solar-system fractions are the observed values; the s-process is the dominant contributor to all isotopes except to ^{96}Zr which is ascribed to the r-process. The predicted abundances adapted from Malaney (1987b) include ^{93}Zr at the level attained 10^5 yr after the s-process occurred.

ZrO in the S stars R And and R Gem. Before rejecting the mass-transfer hypothesis on the basis of these apparently disparate N(n) estimates, the error analyses for the S stars must be completed. Since the depth of the bandheads and the degree of overlap increases progressively from ^{96}ZrO to ^{90}ZrO, there is a possibility that systematic errors show a similar trend. In addition, ZrO and Rb should be studied in more stars; R And and R Gem may not be representative of the stars that gave their mass to create a Ba star.

The predicted neutron densities of AGB stars are typically in the range of 10^9 - 10^{12} cm^{-3} (Cosner, Iben, and Truran 1980; Malaney 1986, 1987). This is true even in low-mass AGB stars as a result of the high reaction rate of $^{13}C(\alpha,n)^{16}O$ relative to $^{22}Ne(\alpha,n)^{25}Mg$. It would appear that a high N(n) is obtained for R And and R Gem. If mass transfer from an AGB star creates a Ba star, then the observed Rb/Sr in Ba stars would appear to be incompatible with current low-mass AGB models. In order to remedy this situation, temperatures at the intershell base of low-mass AGB stars are required to be higher than presently predicted (Mathews *et al.* 1986; Malaney and Boothroyd 1987). It is interesting to note that recent stellar evolution calculations indicate such a trend (Boothroyd 1987).

The neutron exposure τ_0: The neutron exposure is

$$\tau = \int N(n)\, v\, dt$$

where N(n) is the neutron number density, v is the mean relative velocity of neutrons and seed nuclei, and the integral is taken over the duration of the event; τ is commonly given in the unit millibarn^{-1}. A distribution function exp $(-\tau/\tau_0)$, is attractive not only because the exact solution for the s-processed abundances is known, but because mixing in AGB stars may simulate this distribution of exposures rather than a single burst (Ulrich 1973, Clayton and Ward 1974). The parameter τ_0 is obtained by matching predicted and derived abundances for the s-processed material; see Tomkin and Lambert (1983) for a simple recipe relating the observed and derived s-processed abundances.

Results for 7 O-rich (MS,S) AGB stars suggest that τ_0 increases with increasing enrichment of carbon (SL). This trend is confirmed by a qualitative discussion of an additional 30 stars (Smith, Lambert and McWilliam 1987). For the most extreme of the analyzed S stars, $\tau_0 \approx 0.4$-0.5, a value found for the classical Ba stars (Tomkin and Lambert 1983; Smith 1984). At least some of the mild Ba stars contain material exposed to $\tau_0 \sim 0.5$: Tomkin and Lambert (1986) showed that the element-to-element ratios in o Vir and 16 Ser are essentially identical to those in the classical Ba stars. Estimates of τ_0 should now be obtained for a larger sample of mild Ba stars. A detailed analysis of two subgiant-CH stars (Krishnaswamy and Sneden 1985; see also Luck and Bond 1982) showed moderate s-process enhancements ([light-s/Fe] ~ 0.5 to 0.8), but an abundance pattern characterized by a low neutron exposure of $\tau_0 \sim 0.2$. The subgiants are slightly metal-poor ([Fe/H] = -0.5 and -0.3), but some classical and mild Ba stars show similar deficiencies. The difference in τ_0 is one factor suggesting that Ba and subgiant-CH stars may have (slightly?) different origins - see below for a second factor.

The τ_0 estimates and the overall level of s-process overabundances (see above) support the mass-transfer hypothesis. If transfer occurred before the AGB star had undergone many thermal pulses, the transferred material would have a lower τ_0 (< 0.5) and so create a mild Ba star with modest enhancements of the 'light'-s elements (Sr, Y, Zr), but minor enhancements of the 'heavy'-s elements (Ba, La, Nd). This scenario seems unlikely to account for the subgiant CH stars because they are quite C-rich (Figure 1a); the observed (i.e., post-transfer) abundances are in the range [C/Fe] = 0.2 to 0.6 (Sneden 1983; Luck and Bond 1982) and exceed those observed ([C/Fe] ~ 0.0) in MS stars with $\tau_0 \sim 0.2$, and may even exceed the enhancements ([C/Fe] ~ + 0.3 on the assumption that [O/Fe] ~ 0.0) reported for carbon stars.

Were it not for the apparent difference in τ_0, the locations of the subgiant CH and the Ba stars in Figure 1a would support the idea that the former are the latter's main-sequence progenitors. The first dredge-up experienced by giants decreases [C/Fe] by about 0.2 to 0.3 dex for standard models. A slightly larger cut (say 0.5 dex) would superimpose the subgiant CH stars on the Ba stars in Figure 1a. The first dredge-up would also reduce the high $^{12}C/^{13}C$ ratios of the subgiants (Sneden 1983) to the lower values reported for the Ba stars (Tomkin and Lambert 1979; Harris, Lambert, and Smith 1985). This scenario encounters a problem when Li abundances are examined. Smith and Lambert (1986a) searched unsuccessfully for the Li I 6707 Å doublet in 10 subgiant CH stars. Observed upper limits to the Li abundance in the subgiants with the predicted Li dilution factor for the first dredge-up provide predicted upper limits for classical Ba stars that are less than the observed Li abundances (Pinsonneault, Sneden, and Smith 1984) by as much as a factor of 10. Two explanations may be offered. First, the subgiant CH stars are not progenitors of the classical Ba stars. Since the predicted Li abundances overlap those of the mild Ba stars, it is possible that some of the mild Ba stars are descended from the subgiant CH stars. If, as Böhm-Vitense, Nemec, and Proffitt (1985) claim, all mild Ba stars have a hot white dwarf companion, the evolutionary ties between the two groups must be in doubt because Bond (1984) was unable to detect white dwarfs around the subgiant CH stars. Second, the Li I doublet in Ba stars may be severely blended with an unidentified 's-process' line so that the Li abundances are systematically overestimated.

A comparison of the Li abundances in cool carbon stars with those reported for Ba stars suggests that the latter were probably created as giants and have not evolved from Ba dwarfs. Torres-Peimbert and Wallerstein (1966) give a "Li-index" which Wallerstein and Conti (1969) convert to an abundance: $\log \varepsilon(\mathrm{Li}) \sim 1.1$ for a sample of seven cool carbon stars. The "super-Li" carbon stars are excluded because Utsumi's (1985) analysis shows them not to be enriched in s-process elements. This mean Li abundance is close to the upper limit reported for the Ba stars, a coincidence consistent with production of the Ba stars as giants. If, however, the stars were created as dwarfs, the Li abundance in the giant should be at least a factor of 50 lower ($\log \varepsilon(\mathrm{Li}) < -0.6$). Unless the Li I feature is severely blended, the observed Li abundance exceeds this prediction by such a margin that we must suppose the Ba giants to have been created as giants.

In light of the differences in τ_0 and Li, it seems necessary to consider the subgiant CH and classical Ba stars as unrelated. I suggest that the subgiant CH stars are created by transfer of a small amount of mass and the abundance anomalies are effectively eased by the deep convective envelope as these stars evolve up the red giant branch. Then, two leading questions are 'where are the main-sequence progenitors of the classical Ba stars? or 'Are these Ba stars produced directly as giants?'

3. DO ALL Ba STARS HAVE A WHITE DWARF COMPANION?

After mass-transfer, the core of the former AGB star remains as a white dwarf companion to the Ba star. Radial velocity variations show that the mass of the companion is below the Chandrasekhar limit for white dwarfs: McClure (1983) estimates $m_2 \sim 0.5\ M_\odot$ for an assumed Ba star mass $M_1 \sim 1.5\ M_\odot$, and this estimate for M_2 is likely to be an overestimate (Dominy and Lambert 1983 ≡ DL).

Spectroscopic detection of the white dwarf would provide more direct support for the mass-transfer hypothesis. Low dispersion IUE spectra have led to discovery of white dwarf companions around several mild and classical Ba stars including the luminous Ba star ζ Cap (Böhm-Vitense 1980). DL were unable to detect a hot white dwarf companion to the classical Ba star HR 5058 and the mild Ba star 16 Ser. For distances derived from the Ca II K-line, the ultraviolet flux limits suggest that the white dwarf companion must have cooled for in excess of 10^9 yr. Since its lifetime as a red giant is shorter than the lower limit to the cooling time, the Ba star must have been created as a main sequence star. In view of an apparent lack of main sequence Ba stars, DL suggested that the mass-transfer hypothesis be discarded.

This suggestion deserves a reconsideration. Böhm-Vitense, Nemec, and Proffitt (1984) claim that DL may have underestimated the stellar distances, and hence, overestimated the ages of the white dwarfs. Other authors have suggested that the main sequence Ba stars do exist but "perhaps we just don't recognize them" (McClure 1985). If, as Halbwachs (1985) has estimated, the Ba stars created by mass-transfer comprise 5% of all main-sequence stars of type F6 or later, they ought not be too hard to identify by means of quantitative spectroscopy. The subgiant CH stars may be too rare, too confined in spectral type, and too unlike the classical Ba stars (τ_0, Li) to be the "missing" stars.

There remains the possibility that main sequence Ba stars are not created by the mass-transfer process. I have noted that the C and Li abundances in Ba stars would support a claim that these stars were created as giants. If transfer onto either a main sequence or a giant companion occurs via Roche lobe overflow at a high rate, it appears likely that a common envelope is created around the two stars, and rapid collapse of the orbit (a "spin-down") is followed by ejection of the envelope to create a planetary nebula with the binary evolving to become a cataclysmic variable (Paczyński 1976; Meyer and Meyer-Hofmeister 1979). Discoveries of close binaries as the central objects of planetary nebulae (Bond, Liller, and Mannery 1978) support this scenario.

At lower mass-transfer rates, main-sequence Ba stars should be created. At moderate mass-transfer rates, the main-sequence star develops an extended envelope resembling a giant. This is the expected result for rates $M_{tr} > M_{ms}/\tau_{KH} \approx 3 \times 10^{-8} M_{\odot} yr^{-1}$ for a 1 $M_{\odot}$ star where M_{tr} is the mass-transfer rate, M_{ms} is the main-sequence star's mass, and τ_{KH} is its Kelvin-Helmholz time. Such transfer rates might occur as the star accretes mass lost from the AGB star through a wind or an ejection of the envelope. On the cessation of mass transfer, the envelope collapses and the secondary reassumes a main-sequence appearance, albeit now with a peculiar composition. Since the collapse back to the main sequence occurs quickly (on a Kelvin-Helmholtz time scale), this scenario cannot account for the majority of the giant Ba stars (Iben and Tutukov 1985). At low mass-transfer rates, $M_{tr} < M_{MS}/\tau_{KH}$, the main-sequence companion is simply coated with mass from the AGB star. Although the thin convective envelope of the main-sequence star may mix the outer layers and so slightly reduce the abundance anomalies, the atmosphere should have a peculiar composition.

The apparent absence of main sequence Ba stars might reflect the more efficient production of Ba giants. Large amounts of mass (M_{tr}) must be transferred to create the extreme Ba stars with carbon and s-process enhancements close to those estimated for the carbon AGB stars, say $M_{tr} \sim 0.5 M_{\odot}$. We speculate that the giant with its larger cross section captures substantially more material than a main-sequence companion would. Unless it is of low mass, the latter lacks a deep convective envelope, and so little mass is required to produce marked abundance anomalies; on the other hand, the hot wind off the main-sequence star may inhibit accretion. Perhaps transfer occurs mainly through the "superwind" that is thought to lead to a planetary nebula. Then, it may be no coincidence that the estimate M_{tr} is similar to the mass of planetary nebulae. Since the lifetime of a giant is less than the cooling time of a white dwarf, hot white dwarfs should accompany the Ba stars. Hopefully, ultraviolet observations with the Hubble space Telescope will provide a definitive test of this prediction.

4. CONCLUDING REMARKS

This review of the chemical compositions of Ba and AGB stars provides evidence to support the hypothesis that the former are created by mass-transfer across a binary. The strongest evidence is provided by the correlations between the carbon and s-process abundances (see Figure 1) and by the similar neutron exposures (τ_0) reported for Ba and extreme AGB stars. An apparent difference in the derived neutron densities for the s-process sites of the two groups needs to be resolved. There is observational evidence involving the carbon and lithium abundances, and the presence of white dwarfs to suggest that Ba stars are created primarily as giants and that few have evolved from a Ba dwarf. The subgiant CH stars may be not Ba dwarfs, but stars in which so small amount of mass is transferred that the abundance anomalies are erased by the giant's convective envelope.

My research is supported in part by the National Science Foundation (grant AST 86-14423) and the Robert A. Welch Foundation.

REFERENCES

Arnould, M. and Jorrisen, A. 1986, in *Advances in Nuclear Astrophysics*, ed. E. Vangioni-Flam, J. Audouze, M. Chasse, J. P. Chieze, and J. Tran Thanh Van (Gif sur Avette: Editions Frontières), p. 419.

Bao, Z. Y. and Käppeler, F. 1987, *At. Data and Nucl. Data Tables*, **36**, 411.

Bidelman, W. P. and Keenan, P. C. 1951, *Ap. J.*, **114**, 473.

Böhm-Vitense, E. 1980, *Ap. J. (Letters)*, **239**, L79.

Böhm-Vitense, E., Nemec, J. and Proffitt, C. 1984, *Ap. J.*, **278**, 726.

Bond, H. E. 1974, *Ap. J.*, **194**, 95.

_____. 1984, in *Future of Ultraviolet Astronomy Based on Six Years of IUE Research*,

Bond, H. E., Liller, W. and Mannery, E. J. 1978, *Ap. J.*, **223**, 252.

Boothroyd, A. I. 1987, Ph.D. Thesis, California Institute of Technology.

Catchpole, R. M. and Feast, M. W. 1985, in *Cool Stars with Excesses of Heavy Elements*, ed. M. Jaschek and P. C. Keenan (Dordrecht: Reidel), p. 113.

Clayton, D. D. and Ward, R. A. 1974, *Ap. J.*, **193**, 397.

Clegg, R. E. S., Lambert, D. L. and Bell, R. A. 1979, *Ap. J.*, **234**, 188.

Cosner, K., Iben, I., Jr., and Truran, J. W. 1980, *Ap. J. (Letters)*, **238**, L91.

Dominy, J. F. 1984, *Ap. J. Suppl.*, **55**, 27.

Dominy, J. F. and Lambert, D. L. 1983, *Ap. J.*, **270**, 180.

Halbwachs, J. L. 1985, in *Cool Stars with Excesses of Heavy Elements*, ed. M. Jaschek and P. C. Keenan (Dordrecht: Reidel), p. 337.

Harris, M. J., Lambert, D. L. and Smith, V. V. 1985, *Ap. J.*, **292**, 620.

_____. 1987, *Ap. J.*, in press.

Iben, I., Jr., and Tutukov, A. V. 1985, *Ap. J. Suppl.*, **58**, 661.'

Käppeler, F. 1986, in *Nucleosynthesis and Its Implications on Nuclear and Particle Physics*, ed. J. Audouze and N. Mathieu (Dordrecht: Reidel), p. 253.

Keenan, P. C. 1942, *Ap. J.*, **96**, 101.

Kovács, N. 1983, *Astr. Ap.*, **124**, 63.

Krishnaswamy, K. and Sneden, C. 1985, *Pub. A. S. P.*, **97**, 407.

Lambert, D. L. 1985, in *Cool Stars with Excesses of Heavy Elements*, ed. M. Jaschek and P. C. Keenan (Dordrecht: Reidel), p. 191

Lambert, D. L., Gustafsson, B., Eriksson, K. and Hinkle, K. H. 1986, *Ap. J. Suppl.*, **62**, 373.

Lambert, D. L. and Ries, L. M. 1981, *Ap. J.*, **248**, 228.

Luck, R. G. and Bond, H. E. 1982, *Ap. J.*, **259**, 792.

McClure, R. D. 1983, *Ap. J.*, **268**, 264.

_____. 1984, *Pub. A. S. P.*, **96**, 117.

_____. 1985, in *Cool Stars with Excesses of Heavy Elements*, ed. M. Jaschek and P. C. Keenan (Dordrecht: Reidel), p. 315.

McClure, R. D., Fletcher, J. M., and Nemec, J. M. 1980, *Ap. J. (Letters)*, **238**, L35.

McWilliam, A. and Lambert, D. L. 1987, *M.N.R.A.S.*, in press.

Malaney, R. A. 1986, *M.N.R.A.S.*, **223**, 683.

_____. 1987a, *Ap. J.*, **321**, 832.

_____. 1987b, in Proc. 2nd IAP Rencontre on *Nucl. Astrophys*, in press.

Malaney, R. A. and Boothroyd, A. I. 1987, *Ap. J.*, **320**, 866.

Malaney, R. A. and Lambert, D. L. 1987, in Proc. ACS Symposium on *The Origin and Distribution of the Elements*, in press.

Mathews, G. J., Ward, R. A., Takahashi, K., and Howard, W. M. 1986, in *Nucleosynthesis and Its Implications on Nuclear and Particle Physics*, ed. J. Audouze and N. Mathieu (Dordrecht: Reidel), p. 277.

Merrill, P. W. 1952, *Ap. J.*, **116**, 21.

Meyer, F. and Meyer-Hofmeister, E. 1979, *Astr. Ap.*, **78**, 167.

Paczyński, B. 1976, in *IAU Symposium 73, Structure and Evolution of Close Binary Systems*, ed. P. Eggleton, S. Mitton and J. Whelan (Dordrecht: Reidel), p. 75.

Peery, B. F. and Beebe, R. F. 1970, *Ap. J.*, **160**, 619.

Pinsonneault, M. H., Sneden, C., and Smith, V. V. 1984, *Pub. A. S. P.*, **96**, 239.

Scalo, J. M. 1978, *Ap. J.*, **221**, 627.

Schadee, A. and Davis, D. N. 1968, *Ap. J.*, **152**, 169.

Smith, V. V. 1984, *Astr. Ap.*, **132**, 326.

_____. 1987, in Proc. ACS Symposium on *The Origin and Distribution of the Elements*, in press.

Smith, V. V. and Lambert, D. L. 1984, *Pub. A. S. P.*, **96**, 226.

_____. 1985, *Ap. J.*, **294**, 326.

_____. 1986a, *Ap. J.*, **303**, 226.

_____. 1986b, *Ap. J.*, **311**, 843.

_____. 1987, *A. J.*, in press.

Smith, V. V., Lambert, D. L., and McWilliam, A. 1987, *Ap. J.*, in press.

Sneden, C. 1983, *Pub. A. S. P.*, **95**, 745.

Sneden, C., Lambert, D. L., and Pilachowski, C. A. 1981, *Ap. J.*, **247**, 1052.

Tomkin, J. and Lambert, D. L. 1979, *Ap. J.*, **227**, 209.

_____. 1983, *Ap. J.*, **273**, 722.

_____. 1986, *Ap. J.*, **311**, 819.

Torres-Peimbert, S. and Wallerstein, G. 1966, *Ap. J.*, **146**, 724.

Ulrich, R. K. 1973, in *Explosive Nucleosynthesis*, eds. D. N. Schramm and W. D. Arnett (Austin: Univ. of Texas Press), p. 139.

Utsumi, K. 1985, in *Cool Stars with Excesses of Heavy Elements*, ed. M. Jaschek and P. C. Keenan (Dordrecht: Reidel), p. 243.

Wallerstein, G. and Conti, P. S. 1969, *Ann. Rev. Astr. Ap.*, **7**, 99.

Warner, B. 1965, *M.N.R.A.S.*, **129**, 263.

Wood, P. R. 1985, in *Cool Stars with Excesses of Heavy Elements*, ed. M. Jaschek and P. C. Keenan (Dordrecht: Reidel), p. 357.

Yamashita, Y. 1972, *Ann. Tokyo. Astr. Obs.*, **13**, 169.

_____. 1975, *Pub. A. S. J.*, **27**, 325.

Zook, A. C. 1978, *Ap. J. (Letters)*, **221**, 413.

_____. 1985, *Ap. J.*, **289**, 356.