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ON *s*-PROCESS ABUNDANCE EVOLUTION IN THE GALACTIC DISK

H. R. BUTCHER
Steward Observatory, University of Arizona
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ABSTRACT

The *s*-process abundances in C, S, and Ba II stars are examined to investigate whether such stars may have detectably influenced the galactic *s*-process abundance curve over the lifetime of the galactic disk. These peculiar red giants apparently exhibit two characteristic types of abundance curve, one resulting from neutron exposure distributions concentrated at low exposure levels, and the other from exposure distributions restricted to large levels. There is some evidence that both high- and low-mass stars can produce each type of abundance curve, thus probably ruling out the *s*-process as a probe of the stellar initial mass function at early epochs. Although stellar *s*-process abundances do not closely mimic solar/galactic abundances, it remains plausible that abundance evolution due to these stars may be too small to detect. The possible presence of a predisk component to the synthesis pool amplifies this conclusion.

The solar system *s*-process buildup path branches at ^{93}Zr such that $\tau_n \sim 0.3\tau_\beta$. In the Ba II and S stars this branching is characterized by $\tau_n < \tau_\beta$, and probably by $\tau_n \ll \tau_\beta$, leading to speculation that solar system abundances may be composite in nature. Unfortunately, stellar observations appear to require too high an accuracy to be helpful in studying this question. Analyses of the principal branching points in the solar system buildup path indicate that solar abundances are consistent with a single component *s*-process occurring under more or less unique temperature and neutron flux conditions, but that uncertainties in the basic nuclear data prevent any certainty in this conclusion.

Subject headings: galaxies: stellar content — nucleosynthesis — stars: abundances

I. INTRODUCTION

It has recently become evident that the isotopes of carbon, nitrogen, and oxygen can provide valuable probes of the action of stellar synthesis in the Galaxy (see, e.g., Searle 1971; Audouze, Lequeux, and Vigroux 1975). It is clearly also of interest to investigate the effects that the *s*-process synthesis from C, S, and Ba II stars (collectively called peculiar red giants in the present study) may have had on the general evolution of abundances in the Galaxy. The work reported here attempts to provide a preliminary examination of these stars and their contribution to the pool of elements in the solar neighborhood. As with discussions of the CNO isotopes, questions of absolute abundance are skirted, and interest is centered on changes in the morphology of the *s*-process abundance curve and on differences of branching direction in the buildup paths of different *s*-processes. Most peculiar red giants are thought to be low-mass stars (Peery 1970; Eggen 1972*a*), and thus as a class should not have contributed substantially to the initial burst of synthesis in the Galaxy. Questions arise, however, as to whether they may have assumed some importance during later periods, and whether their influence might be detected in some way. It is also of considerable interest to understand if those high-mass peculiar stars which do exist exhibit abundances systematically different from those exhibited by the lower mass stars.

The present study considers these questions in several diverse parts. In § II an attempt is made to assess how large a contribution the low-mass peculiar red giants might have made to the total synthesis pool. Then § III discusses the morphology of the *s*-process abundance curve in peculiar red giants of different types and masses and considers whether these nonstandard abundances might be expected to have detectably influenced the galactic *s*-process curve over the lifetime of the Galaxy. Evolution due to variations in branching direction of different *s*-processes is considered in § IV, where observations of the branch at ^{93}Zr are presented for several red giants, and compared with that branching in the solar buildup curve. Finally, in § V, the possibilities of distinguishing between a multicomponent and a single-component *s*-process from branching point considerations are discussed.

II. CONTRIBUTIONS TO *S*-PROCESS SYNTHESIS

Because most of the peculiar red giants near enough to be easily studied seem to be of low mass ($< 2.5\ M_\odot$), it becomes important to investigate whether such stars can in fact have played any significant role in the general enrichment of *s*-process abundances. This section considers this question for a simple model of galactic evolution.

With present knowledge of the stellar mass spectrum, birthrate over time, and heavy-element synthesis at each stellar mass, any discussion of net element production must necessarily be speculative. The present effort is no exception, and is pursued merely to indicate the order-of-magnitude relative contributions to *s*-process synthesis that one might plausibly expect from low- and high-mass stars.

The procedure adopted is to calculate the total mass of stars to have been born, evolved, and died, which have masses less than, for example, 2.5 $M_\odot$. This figure is then to be compared with the total mass of stars to have lived and died, of all masses. One might hope that with such a procedure the very uncertain mass fraction of each star that actually gets processed and ejected from the star will cancel out, and the final ratio of total masses of dead stars will be a measure of the fractional contribution to synthesis from stars of mass less than the given mass. In the first instance, it will be assumed that the fraction of a star's mass which is processed to new elements and ejected is independent of the stellar mass.

To the present accuracy, an analytical description of stellar evolution similar to that of Tinsley (1973) may be adopted. In this approach, the stellar mass spectrum at birth is taken as $\phi(m)dm \propto m^{-1.35}dm$, where $\phi(m)$ is the total mass of stars at birth with masses between m and $m + dm$; the stellar birthrate is taken as $\psi(t)dt \propto (1 + \alpha t)^{-1}dt$, describing the birthrate with time in the Galaxy through the parameter α; and the lifetime of a star on the main sequence is given by $\tau_{\text{ms}} \approx 10m^{-3}$, with m in solar masses and τ_{ms} in units of 10^9 years. It then follows that the total mass of stars to have evolved and died, of mass less than m^*, at time T after the beginning of star formation, is given by

$$\int_0^T \int_{m(t)}^{m^*} \phi(m)\psi(t)\,dm\,dt \propto \int_0^T \int_{m(t)}^{m^*} m^{-1.35}(1 + \alpha t)^{-1}\,dm\,dt\,, \tag{1}$$

where $m(t) = (10/t)^{1/3}$ when that quantity is less than m^*, and $m(t) = m^*$ when $(10/t)^{1/3} \geq m^*$. To obtain the total mass of stars to have died, including stars of all masses, m^* may simply be set to some large, limiting value.

Before discussing the results of this calculation, a comment is in order. On the basis of a prescription for stellar evolution similar to the above, Tinsley (1974) has suggested that the present stellar birthrate in the solar neighborhood may be several times less than the average past birthrate, implying $\alpha \sim 2$. On the other hand, Salpeter's (1955) derivation of $\phi(m) \sim m^{-1.35}$ from the observed luminosity function near the Sun is based on the assumption of a birthrate constant in time ($\alpha \sim 0$). For the present discussion, the important point is that the value of α is not critical (cf. Fig. 1), so one may point to studies by, e.g., van den Bergh (1957) and Sandage (1957), which indicate $\phi(m) \sim m^{-1.35}$ is not a poor representation of the stellar mass spectrum at birth, at least for Population I.

Figure 1 then displays the results of several integrations of equation (1). Plotted is the ratio R of the total mass of dead stars with mass less than the indicated mass (m^*) to the total mass of dead stars, against the time since the beginning of synthesis in the disk ($T \sim 10$ being "today"). The solid lines are for the indicated m^* values and $\alpha = 2$, while the dashed and dotted lines are respectively for $m^* = 2.5\ M_\odot$ and $\alpha = 2$ with the fractional contribution to synthesis proportional to mass.

It is apparent that low-mass stars ($m^* \sim 2.5\ M_\odot$) can perhaps be expected to contribute a significant if not major fraction of the total processed mass in the galactic disk. Figure 1 also shows that any dependence of synthesis efficiency on stellar mass will

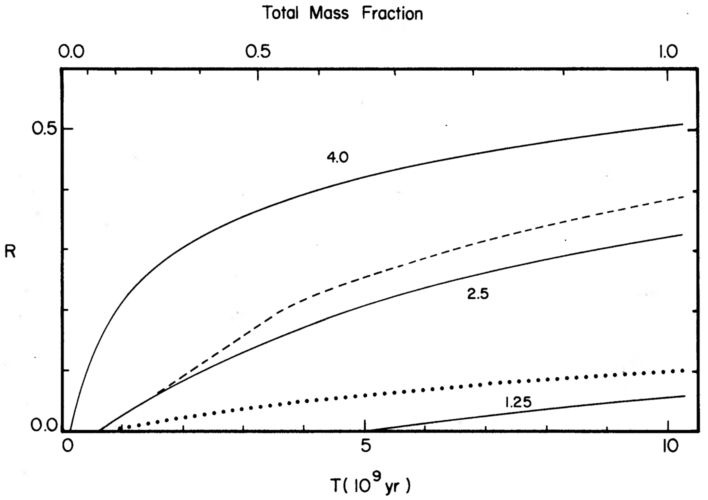

FIG. 1.—Estimated fractional contributions to synthesis, derived using eq. (1), versus the time since the beginning of synthesis R is the ratio of the total mass of stars to have lived and died with masses less than the indicated mass, to the total mass of stars to have lived and died, up until time T. For the particular curves shown, an upper limit of 20 $M_\odot$ has been assumed. The solid curves are for $\alpha = 2$ and the indicated values of m^* (see text); the dashed curve is for $\alpha = 0.4$ and $m^* = 2.5\ M_\odot$; and the dotted curve is for $\alpha = 2$, $m^* = 2.5\ M_\odot$, and each star's fractional contribution to synthesis proportional to the stellar mass (i.e., an extra factor of m has been inserted into eq. [1]). Shown at the top is the fraction of the total mass of stars to have lived and died after 10×10^9 years as a function of time, for the model with $\alpha = 2$ (this gives an estimate of the total fraction of synthesis accomplished up until T for the assumption that the fraction of each star's mass contributing to enrichment is independent of stellar mass).

have drastic effects on the results, but that, as mentioned above, uncertainties in the birthrate function are not so important.

Note that the fractional contribution curves increase only slightly from $T \sim 5$ to $T \sim 10$, indicating that for the present discussion the Sun may be considered a "young" star. Note also that because the model is valid only for synthesis occurring in the disk of the Galaxy, there may be an offset of the actual *s*-process contribution curves due to predisk synthesis, during galactic collapse.

The conclusions to be drawn from these simple calculations then, at least as regards the question of detecting the influence of low-mass *s*-process synthesis in the Galaxy, are that such stars may have contributed a moderate fraction of the local pool of elements over the lifetime of the Galaxy. Should synthesis from low-mass stars then prove to be different in some way from that of high-mass stars, it might be possible to take advantage of this fact to explore the details of stellar evolution in the early Galaxy. This result, although not certain by any means, is sufficiently encouraging to warrant the several studies reported in the remaining sections of this paper.

III. COMPARISON OF σN CURVE MORPHOLOGIES

If the peculiar red giants produce *s*-process abundance distributions markedly different from the one observed in the solar system, it should be possible, independent of problems in explaining the time history of absolute abundances in the Galaxy, to place limits on their contribution to galactic chemical evolution. There exists also, as mentioned, the important possibility of mass-dependent differences in the abundances produced by these stars. In this section, therefore, the morphology of the *s*-process curve in the different peculiar red giants is discussed, and the question of detecting abundance evolution due to the action of these stars is considered.

a) *Observed Abundance Distributions*

Utsumi (1970) has analyzed 22 cool carbon stars, and reports finding two characteristic abundance distributions: one similar to that found in the Ba II and S stars (Warner 1965), with all *s*-process elements heavier than the iron peak overabundant; and the second with only those elements beyond Ba enhanced. This work confirms for *s*-process elements the existence of two subclasses of carbon stars (cf. Bouigue 1954; Gordon 1968). The latter abundance distribution is clearly nonsolar in morphology, while the former, found in the majority of the peculiar red giants, has a characteristic shape qualitatively similar to that of *s*-process elements in the solar system. Whether in reality there exists a continuum of abundance morphologies between these two types is not yet clear.

To determine the extent to which the first category of abundances may or may not mimic in detail the solar *s*-process, analyses of a total of nine fairly extreme Ba II stars have been examined. These analyses, by Tech (1971), Danziger (1965), and especially Warner (1965), are the most accurate available for *s*-process elements in any peculiar red giants.

To characterize the morphology of the *s*-process curves in these stars, $\sigma_n N_s$ products have been calculated for the elements Sr, Y, Zr, Mo, Ru, Ba, La, Ce, Nd, and Sm, these elements having generally the most reliable abundances. The following well-known equation (Burbidge and Burbidge 1957; Warner 1965) has been employed for this purpose:

$$\langle \sigma N_s \rangle^* = (y - 1) N_{\text{tot}}{}^{\odot} \langle \sigma N_s \rangle^{\odot} / N_s{}^{\odot} , \qquad (2)$$

where $\langle \sigma N_s \rangle^{\odot}$ is the neutron-capture cross section, *s*-process abundance product averaged over all isotopes of each element in the Sun; $\langle \sigma N_s \rangle^*$ is that product for the newly synthesized *s*-process elements (only) in the Ba II star; $N_{\text{tot}}{}^{\odot}$ and $N_s{}^{\odot}$ are the total abundance and *s*-process contribution to the total abundance of each element in the Sun; and y is the observed overabundance of the element in question ($\log y =$ [Element/Fe], where the assumption is made that the ratio of unprocessed *s*-process elements to iron in the star is the same as in the Sun). Values for $\langle \sigma N_s \rangle^{\odot}$ and $N_{\text{tot}}{}^{\odot}/N_s{}^{\odot}$ have been taken from the smoothed fit to solar data given by Seeger, Fowler, and Clayton (1965, their Tables 3 and 5), and are displayed, along with the results of the calculation for the ten elements under consideration, in Table 1. Comparison of the results from different authors reveals a considerable scatter. It has therefore been decided to average the results for nearby elements in an attempt to decrease the uncertainties involved, and these averages are also given in Table 1. Here

$$\langle \text{SrYZr} \rangle = (\langle \sigma N_s \rangle_{\text{Sr}} + \langle \sigma N_s \rangle_{\text{Y}} + \langle \sigma N_s \rangle_{\text{Zr}})/3 ,$$

and so forth. Finally, the morphology of the *s*-process abundance curves may be characterized by the ratios $\langle \text{SrYZr} \rangle / \langle \text{BaLaCe} \rangle$ and $\langle \text{MoRu} \rangle / \langle \text{NdSm} \rangle$.

These last quantities are plotted in Figure 2 for the Ba II stars, the Sun, and various theoretical distributions. The theoretical curves have been calculated using neutron-capture cross sections from Allen, Gibbons, and Macklin (1971). The discrete exposure (*solid*) curves rely on an approximation developed by Clayton *et al.* (1961); the exponential exposure distribution (*dashed*) curve relies on an algorithm due to Ulrich (1973). The two positions for the Sun result on one hand from the smooth curve through the data of Seeger *et al.*, and on the other from the best fit exponential exposure distribution curve through that data.

It is evident that there is a bias in the Ba II star points toward flatter σN curves than present in the Sun. There may even be a tendency for the Ba II star points to lie along the discrete neutron exposure curves. Note that in general monotonically decreasing neutron exposure distributions will yield points for which $\langle \text{SrYZr} \rangle / \langle \text{BaLaCe} \rangle$ is less than $\langle \text{MoRu} \rangle / \langle \text{NdSm} \rangle$. Hence the point at (2.9, 8.1) for HD 175674, one of the coolest Ba II stars, if real, appears to require a bimodal neutron exposure distribution. Comparison of points calculated from data from different sources,

TABLE 1

DERIVATION OF STELLAR σN VALUES

Entries are $\log y/\langle\sigma N_s\rangle^{*}$

Element	$\langle\sigma N_s\rangle^{\odot}$	$N_{tot}^{\odot}/N_s^{\odot}$	HD 46408	83548	92626	116713	175674	178717	183915	204075	211594
Sr	130	1.04	+.39 196.	+.19 (+.3) 74. (134.)	+.37 181.	+.46 (+.6) 254. (400.)	+.62 428.	+.45 245.	+.26 111.	+.18 (+1.01) 69. (1246.)	+.74 608.
Y	100	1.21	+.52 280.	+.27 (+.9) 104. (840.)	+.65 420.	+.45 (+.9) 220. (840.)	+.59 350.	+.60 361.	+.29 115.	+.70 (+1.06) 485. (1268.)	+.72 514.
Zr	80	1.16	+.53 222.	+.22 (+.4) 61. (140.)	+.65 322.	+.40 (+.8) 140. (493.)	+.47 181.	+.73 406.	+.60 277.	+.60 (+.86) 277. (579.)	+.89 627.
Mo	58	2.08	+.01 2.42	+.27 (+.6) 104. (361.)	+.37 163.	+.35 (+.7) 150. (485.)	-.09 -23.	- -	+.18 62.	+.47 (+.69) 236. (472.)	+.33 138.
Ru	54	1.95	+.60 313.	+.15 (+.8) 43. (558.)	+.43 178.	+.39 (+.8) 152. (558.)	+.26 86.	+.62 333.	+.06 15.6	+.45 (+.43) 190. (177.)	+.05 12.6
Ba	30	1.18	+1.20 526.	+.31 (+.7) 36.8 (142.)	+1.07 381.	+1.20 (+1.2) 526. (526.)	+.46 67.	+.62 112.	+.79 183.	+1.00 (+1.38) 319. (814.)	+1.10 431.
La	10	1.77	+.68 67.1	+.22 (+.5) 11.7 (38.)	+.87 114.	+.66 (+.9) 63.2 (123.)	+.49 37.	+.77 87.	+.70 71.	+.36 (+.93) 22.8 (133.)	+.68 67.1
Ce	9	1.30	+.59 33.8	+.15 (+.7) 4.80 (47.)	+.65 41.	+.52 (+1.0) 27.0 (105.)	+.34 13.9	+.59 34.	+.81 64.	+.55 (+.98) 29.8 (100.)	+.72 49.7
Nd	7	1.60	+.37 15.0	+.16 (+.4) 5.04 (17.)	+.39 16.3	+.47 (+.8) 21.8 (60.)	+.17 5.37	+.48 22.6	+.64 37.7	+.26 (+.97) 9.18 (93.3)	+.58 31.4
Sm	6.5	3.33	+.69 84.2	+.14 (+.6) 8.21 (64.)	+.73 94.	+.57 (+.7) 58.8 (87.)	+.24 16.	+.70 87.	+.77 106.	+.31 (+.82) 22.5 (121.)	+.75 99.8
<SrYZr>	103		233.	80. (371.)	308.	205. (578.)	320.	337.	168.	277. (1031.)	583.
<MoRu>	56		158.	74. (460.)	171.	151. (522.)	32.:	333.:	39.	213. (325.)	75.
<BaLaCe>	16		209.	17.8 (76.)	179.	205. (251.)	39.3	78.	106.	124. (349.)	183.
<NdSm>	7		50.	6.6 (41.)	55.	40. (74.)	11.	55.	72.	16. (107.)	131.
<SrYZr>/<BaLaCe>	6.4		1.1	4.5 (4.9)	1.7	4.5 (2.3)	8.1	4.3	1.6	2.2 (3.0)	3.2
<MoRu>/<NdSm>	8.0		3.2	11.2 (11.2)	3.1	3.8 (7.0)	2.9	6.0	0.5	13.3 (3.0)	0.6

NOTE.—Entries for $\langle\sigma N_s\rangle^{\odot}$ and $N_{tot}^{\odot}/N_s^{\odot}$ are from Seeger *et al.* (1965). Entries in parentheses are from Danziger (1965) for HD 83548 and HD 116713, and from Tech (1971) for HD 204075 (= ζ Cap). All other entries are from Warner (1965). Note that here $\log y = [N_i/\mathrm{Fe}]$.

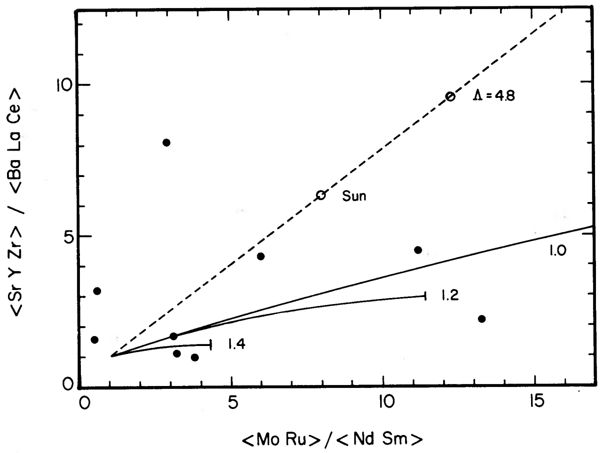

FIG. 2.—Average σN values for 10 elements, combined and plotted in such a way as to provide a measure of the shapes of various observed and theoretical σN curves. The filled dots come from data on nine Ba II stars given by Warner (1965). Points represented by open circles have been calculated from the solar abundances given by Seeger *et al.* (1965) (marked Sun), and from the best fit theoretical curve of Ulrich (1973) (marked $\Lambda = 4.8$, Λ being a parameter used to characterize exponential neutron exposure distributions). The dashed curve is for abundances produced by exponential neutron exposure distributions, flat distributions yielding points toward the lower left, and steep ones points to the upper right. It is fortuitous that the point marked Sun falls exactly on this curve. The solid curves are for discrete neutron exposure distributions centered at the exposure values indicated (in units of 10^{27} neutrons cm^{-2}), of various widths. Infinitely wide distributions give points at (1.0, 1.0); delta function distributions give points at the right-hand limits of the curves. Integrated fluxtime values of 1.0, 1.2, and 1.4 correspond here to average numbers of neutrons captured near 30, 40, and 55, respectively. Note that the positions of the filled circles depend on the assumption that the ratio of primordial *s*-process abundances to Fe in each star is solar.

however, suggests that the point in question may be due simply to observational error.

Without more reliable abundance determinations, it cannot be decided for certain whether a combination of the different kinds of abundance curves will produce a quasi-solar σN curve. If much of the synthesis by peculiar red giants is characterized by rather flat σN curves, as might be inferred from Figure 2, then it may be difficult to support such a possibility. In that case, one may wish to argue for a significant predisk contribution to synthesis, to explain the observed lack of abundance evolution in disk stars.

b) *Abundance Curve Morphology and Stellar Mass*

Convincing arguments are not available on the mass of any individual peculiar red giant star. However, Peery (1975) has presented evidence that certain of the N variables are associated with spiral arms, and therefore are probably young and massive ($> 2\ M_\odot$). Eggen (1972*b*) also has concluded that at least some of the N-type carbon stars are massive, probably with masses ranging up to $\sim 9\ M_\odot$. The theoretical work of Sackmann, Smith, and Despain (1974) is consistent with these observational studies, suggesting that on theoretical grounds one might expect the peculiar red giants to exhibit a considerable range of masses.

Comparison of abundance determinations among the different stars suggests in turn that either type of abundance curve may result from stars of either high or low mass (2.5 $M_\odot$ being an approximate dividing line). For example, among stars with the second type of abundance distribution (with only the elements beyond Ba enhanced), one may point to RY Dra and UV Cam as having abundance curves of this type (Utsumi 1970) and absolute magnitudes ($M_{\rm bol} \sim -5$, Peery 1975) consistent with their being massive, young disk objects; and then perhaps to the CH stars as being low-mass counterparts (Wallerstein and Greenstein 1964). Among stars with the first type of abundance distribution, objects such as W Ori and BL Ori seem clearly to be young and massive (Eggen 1972*b*; Peery 1975), with any of the Ba II and probably also most of the S, stars being their low-mass counterparts (Warner 1965).

It should of course be realized that this rather cavalier classification of masses and abundance types is likely to be too superficial to reflect reality accurately. However, until more is known about the abundances and about stellar evolution through these phases, little else can be done. Suffice it to say that there certainly is no evidence for the confinement of either type of abundance distribution to a restricted range of stellar mass.

c) *Detection of Abundance Evolution*

Representative values of ⟨SrYZr⟩/⟨BsLaCe⟩ for the Ba II stars and the Sun are near 3 and 6, respectively. To the extent that abundances in the Ba II stars characterize the *s*-process products of the peculiar red giants generally, one might therefore expect a gradual evolution of *s*-process abundances in the Galaxy. It seems clear, however, that even if this type of abundance curve were to typify the *only* source of galactic *s*-process elements over the last 5–10 billion years, the expected effects are not large, and the net evolution of the σN curve might still be below presently detectable levels. The facts (1) that the *r*-process contributes somewhat to the abundance of each element, (2) that part of the total mass of heavy elements present today may have come from predisk synthesis, and (3) that stars may exist with somewhat complementary *s*-process abundances (the two categories of abundances of Utsumi), all increase the plausibility of a nearly constant *s*-process curve among disk stars, as is observed. Note that Griffin's (1971) analysis of Procyon has found anomalies in the abundances of the rare earths of a size interesting for the present discussion, but that resolution of the abundances into *r*- and *s*-process components will be necessary before any definite connections can be drawn.

IV. TIME SCALE FOR THE *S*-PROCESS

A second aspect of the *s*-process which merits consideration in the present context is the time scale for neutron capture. It appears likely that there is no one

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group of stars which might be expected to affect dramatically the galactic *s*-process abundance curve. However, it is also possible for *s*-processes to occur with different time scales, but to yield substantially similar overall abundance curves. To explore the possibility that the peculiar red giant *s*-process may occur under different physical conditions in this sense from those of the solar system *s*-process, an analysis has been performed of the ^{93}Zr branching point in three Ba II stars and in the solar system. This particular branching point is chosen as a time scale discriminant because it is the only branching point readily studied in stellar spectra, and because it shows evidence of partial branching in solar material.

Figure 3 depicts the *s*-process buildup path near ^{93}Zr. Clearly, ^{92}Zr and ^{96}Mo are always completely on the buildup path, whereas ^{94}Zr, ^{94}Mo, and ^{93}Nb will have their *s*-process abundances dependent on whether ^{93}Zr captures a neutron or β-decays during neutron irradiation. So for the solar system, where isotopic abundances are available, the analysis proceeds by comparing $\sigma N(^{92}\mathrm{Zr})$ with $\sigma N(^{94}\mathrm{Zr})$, and $\sigma N(^{96}\mathrm{Mo})$ with $\sigma N(^{94}\mathrm{Mo})$, with appropriate (small) corrections for *r*- and *p*-process contributions to the abundances. This solar system analysis has been given by Butcher (1974), Ward, Newman, and Clayton (1976) and others. The result is that some 70–75 percent of the buildup path has gone through ^{94}Zr, the rest going through ^{93}Nb and ^{94}Mo.

In the stellar case, the analysis may proceed in one of two ways. If a star is cool enough to show lines of ZrO, the relative isotopic abundances of Zr may be determined, and ^{92}Zr compared with ^{94}Zr to find the branching ratio at ^{93}Zr. Peery and Beebe (1970) have made such an analysis for the S star R Cyg, and find the buildup path to have gone through ^{94}Zr in that star.

To confirm this result, especially in view of the difficulties involved (cf. Schadee and Davis 1968), and to extend it to other peculiar red giants, a second method of analysis may be pursued: Because Nb has only one stable isotope, ^{93}Nb, its (*s*-process) abundance is a direct indication of the value of the σN curve in its neighborhood. A comparison of $\sigma_n(^{93}\mathrm{Nb})N(^{93}\mathrm{Nb})$ and $\sigma_n(^{93}\mathrm{Zr})N(^{93}\mathrm{Nb})$ with the local σN curve will then determine whether ^{93}Zr captured a neutron or β-decayed during the *s*-process (provided of course the material in question is old enough for all ^{93}Zr to have decayed to ^{93}Nb since the *s*-process). The Ba II stars are good candidates for this type of analysis, both because they are hot enough to show a continuum in the visible region near several Nb lines, and because they show no evidence of Tc, and hence are most likely old enough for all ^{93}Zr to have β-decayed.

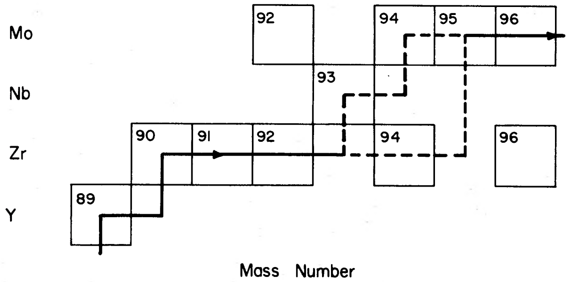

FIG. 3.—The *s*-process buildup path near ^{93}Zr. Stable nuclides are represented by boxes; unstable ones are blank. Neutron capture occurs horizontally toward the right in this plot; β-decay, upward. The two branching paths beginning at ^{93}Zr are shown by the dashed lines.

Allen, Gibbons, and Macklin (1971) give $\tau_n(^{93}\mathrm{Nb}) = 264$ mb at a temperature corresponding to 30 keV; using their procedure for estimating unknown cross sections (cf. their Fig. 9), one may estimate $\sigma_n(^{93}\mathrm{Zr}, 30\ \mathrm{keV}) \approx 90$ mb. There is nearly a factor of 3 between the two cross sections, which should lead to a factor of 3 difference in the abundance of Nb in the extreme cases of total branching one way or the other. This factor is clearly large enough to be detected in a stellar spectrum, but is probably too small to permit discovery of any partial branching, such as is apparent in the solar system.

a) Nb *Observations*

A number of Nb lines have been observed in three bright Ba II stars using the echelle grating system described by Butcher (1971, 1972). Tracings from several 1.5 Å mm^{-1} plates have been averaged digitally to provide as smooth and well-defined a continuum level as possible. The resulting equivalent widths, along with the relevant atomic line parameters, are given in Table 2. The measurements in α Boo have been made by the writer from Griffin's (1968) Arcturus atlas.

The identifications of the lines have been verified by two procedures. First, the central depths of a dozen or so lines of each element in α Boo have been plotted against laboratory intensity estimates from Moore (1959), to yield crude curves of growth. On such plots, blends stand out as being too strong for their laboratory intensities. The Nb I and Mo I lines in Table 2 fall close to the mean relations for unblended lines in these plots; the Zr I lines apparently are so weak that there is considerable scatter in their laboratory intensity estimates, but at least no gross blends are evident. Second, the equivalent weak line strength of each line has been plotted against $\log gf\lambda - \chi\theta_{\mathrm{exc}}{}^{\mathrm{I}}$ for α Boo and the three Ba II stars analyzed. This procedure checks the lines' behavior with temperature and abundance, and should expose any incorrect excitation potential assignments. All the lines in Table 2 are judged by these tests to be satisfactorily identified, as well as being sufficiently isolated to be easily measured in the stellar spectra.

A number of Fe I lines in each star have been measured to provide an empirical saturation curve and a value for [Fe/H]. These saturation curves then yield the desaturated line strengths in Table 3, in the form $-\log W_\lambda(\mathrm{weak})/\lambda$. Also given in Table 3 are $R-I$ colors (on the Johnson system) and the resulting relevant temperature parameters. The differences between $\Delta\theta_{\mathrm{eff}}$ (which is derived using the calibration of Johnson

TABLE 2

MEASURED EQUIVALENT WIDTHS (mÅ)

Line	$\chi_{\rm exc}$ (eV)	I.P. (eV)	α Boo	HD 83548	HD 116713	ζ Cap
Nb I λ5344.17........	0.35	6.88	20	8.5	62	16
5350.74........	0.27		19	9	40	12
5664.71........	0.14		6	8:	20.5	6
Mo I λ5506.49........	1.34	7.13	59	47	91	66
5751.40........	1.42		8	7:	32	12.5
5888.33........	1.47		15	15	65	21
6030.66........	1.53		26	19.5	71	20
Zr I λ5680.90........	0.54	6.84	14	9	49	12
5735.70........	0.00		29	34.5	80	...
6025.36........	0.15		12	...	17	...

NOTE.—A blank (...) entry for the equivalent width signifies substantial plate-to-plate disagreement.

1966), and $\Delta\theta_{\rm exc}$(Fe I) and $\Delta\theta_{\rm exc}$(Zr I, Nb I, Mo I) have been estimated from the Griffins' (1967) comparison of α Boo and ε Vir, ε Vir having a temperature and abundance level similar to those of the Ba II stars.

Finally, the abundance ratios of interest follow from these parameters and the application of curve of growth equations due to Pagel (1965). Presented in Table 4, these results include the factor by which the general level of neutron capture elements are down relative to Fe in α Boo, [s/Fe] ≈ −0.2, as reported by Mackle *et al.* (1975). This value has been checked by the writer by comparing α Boo with α Ind, a normal-abundance giant of similar temperature to the Ba stars; this comparison also yields [s/Fe] ≈ −0.2 for α Boo.

b) The σN Curve through ^{93}Zr *in* Ba II *Stars*

To determine the branching direction at ^{93}Zr in the Ba II stars, the observed abundances have been converted to $\langle\sigma N\rangle^*$ values via equation (2). In this calculation, $N_{\rm tot}$, N_s, and $\langle\sigma N_s\rangle$ have been taken to be their solar values; the assumption is made, therefore, that the abundance curve, and in particular the ratio of r-process to s-process abundances in α Boo, is similar to that in the Sun. The results of Mackle *et al.* suggest this is so, but in any case the step is not a critical one in the analysis. Note especially that $\langle\sigma N_s\rangle^{\odot}/N_s^{\odot}$ for Nb equals either 90 mb or 264 mb (assuming total branching to one of the two available directions), regardless of which direction the buildup has taken in α Boo or the Sun.

Included in Table 4 are the results of this calculation. It is apparent that $\sigma_n(93) \approx 90$ mb best interpolates between Zr and Mo, from which it may be inferred that the neutron-capture path in the Ba II stars has gone from ^{93}Zr on to ^{94}Zr and ^{95}Zr before β-decaying. The value of $\langle\sigma N\rangle^*$ for HD 83548 with $\sigma_n = 90$ mb is slightly low, and might suggest a partial branching in this star. However, while the data here are of very high quality by usual standards, they probably will still admit of the results for HD 83548

TABLE 3

DESATURATED LINE STRENGTHS AND TEMPERATURES

Line	α Boo	HD 83548	HD 116713	ζ Cap
Nb I 5344........	5.43	5.80	4.74	5.52
5350........	5.45	5.77	5.05	5.65
5664........	5.97	5.84:	5.44	5.97
Mo I 5506........	4.80	4.96	4.35	4.70
5751........	5.86	5.91:	5.22	5.66
5888........	5.59	5.59	4.78	5.45
6030........	5.36	5.49	4.72	5.48
Zr I 5680........	5.61	5.80	4.94	5.69
5735........	5.28	5.17	4.68	...
6025........	5.70	...	5.55	...
$R - I$...........	0.65	0.44	0.54	0.43
$\theta_{\rm eff}$..............	1.20	0.98	1.08	0.97
$\Delta\theta_{\rm eff}$............	std	−0.22	−0.12	−0.23
$\Delta\theta_{\rm exc}^{\rm Fe\,I}$..........	std	−0.16	−0.08	−0.17
$\Delta\theta_{\rm exc}^{\rm Nb\,I}$, etc.......	std	−0.19	−0.11	−0.20

NOTE.—Desaturated line strength entries are $-\log\,[W_\lambda({\rm weak})/\lambda]$ with W_λ in mÅ. $R - I$ values are from Westerlund, quoted by Danziger (1965), for α Boo, HD 83548, and HD 116713, and from Johnson *et al.* (1966) for ζ Cap.

TABLE 4

ABUNDANCES AND σN VALUES

Star	Element	[Element/s]	$(y - 1)$	$\langle \sigma N_s \rangle$*
HD 83548........	Zr	+0.57	2.7	250
	Nb	+0.44	1.8	162 or 475
	Mo	+0.54	2.5	260
HD 116713.......	Zr	+0.38	1.4	130
	Nb	+0.45	1.8	162 or 475
	Mo	+0.44	1.8	188
ζ Cap............	Zr	+0.75	4.6	427
	Nb	+0.80	5.3	477 or 1400
	Mo	+0.80	5.3	553
Sun..............	Zr	$N_{\mathrm{tot}}^{\odot} = 16.0$,	$\langle \sigma N_s \rangle^{\odot} = 80$,	$\langle \sigma N_s \rangle^{\odot} / N_s^{\odot} = 5.80$
	Nb	$N_{\mathrm{tot}}^{\odot} = 1.0$,	$\langle \sigma N_s \rangle^{\odot} = \ldots$,	$\langle \sigma N_s \rangle^{\odot} / N_s^{\odot} = 90$ or 264
	Mo	$N_{\mathrm{tot}}^{\odot} = 2.5$,	$\langle \sigma N_s \rangle^{\odot} = 50$,	$\langle \sigma N_s \rangle^{\odot} / N_s^{\odot} = 41.7$

NOTE.—[Element/s] = [Element/Fe] − 0.20, because the general level of the heavier elements in the standard, α Boo, has been found to be down by ~0.2 dex. Two entries are given for Nb in each case: in the first $\sigma_n(^{93}\mathrm{Zr}) = 90$ mb has been used; and in the second, $\sigma_n(^{93}\mathrm{Nb}) = 264$ mb.

being consistent with those for HD 116713 and ζ Cap.

c) *Evolution of the ^{93}Zr Branching in Normal Stars*

The above results, together with the similar findings of Peery and Beebe for R Cyg, suggest that the s-process in Ba II and S stars is characterized by $\tau_n \ll \tau_\beta$ at ^{93}Zr. As mentioned, analyses of solar abundances indicate that $\tau_n \sim 0.3\,\tau_\beta$ characterizes the solar system s-process, implying either a partial branching situation or a mixture of s-processes characterized by different ratios of τ_n to τ_β. It is of considerable interest then to examine a very old star, such as α Boo itself, to see whether the situation has resulted from an evolutionary mixing of different s-processes, as might seem most likely, or whether the galactic s-process is intrinsically characterized by $\tau_n \sim 0.3\,\tau_\beta$.

An attempt has been made to perform this comparison by deriving [Nb/Zr] and [Nb/Mo] between α Boo and the Sun. Unfortunately, it is not possible to use the same lines in both stars for the analysis, and the use of gf-values (in this instance from Corliss and Bozman 1962) to compare the different lines has led to contradictory results: namely, Nb is found to be up a factor of 2 in α Boo, a result which cannot be interpreted on any simple picture of an s-process. Mackle *et al.* (1975) find no evidence for increased r-process abundances in α Boo, so one is led to suspect the available oscillator strengths. The accuracy necessary in comparing any two normal stars can be seen in a simple computation of the maximum difference possible in the Nb abundance: less than a factor of 2, if the r-process contribution to Nb is similar to its contribution in solar material. Thus such a comparison cannot easily be made at the present time, despite its importance.

V. SINGLE-EVENT NATURE OF THE SOLAR SYSTEM s-PROCESS

Ulrich (1973) has suggested that the galactic s-process may result from a single type of event, and has proposed a scheme whereby the solar system s-process abundance curve results naturally from single star events. The scheme has the attraction of producing nearly constant relative abundances in all events, thus predicting the observed near-constancy among normal stars. It is an attractive idea, but as discussed in § III the nearly constant shape of galactic s-process abundances does not necessarily provide a strong argument for single-event production. In the Ba II stars and the other peculiar red giants, no one type of star has clearly produced the solar system abundance curve. However, as indicated in § IV, it does not yet seem possible to distinguish between the two cases of single-component and multicomponent s-processes observationally.

A quite different approach to this question is to examine all the branching points in the solar system buildup path, and ask whether the branching limits so provided point to a single temperature and neutron density. If these various branchings do *not* yield physical parameters consistent with the ^{93}Zr branching, then a multicomponent s-process is indicated; if they do appear consistent, a single process is at least still a possibility.

Such an analysis, for the solar-system branching points with adequate nuclear data, has been given by Butcher (1974) and by Ward, Newman, and Clayton (1976). Both of these studies consider the case of constant temperature and neutron flux, and use mean values for the comparative half-lives of each given type of excited-state β-transition. They both conclude that under these conditions and assumptions nearly all the major branching points in the solar buildup curve are consistent with a temperature in the range $3\text{–}4 \times 10^8$ K and a neutron density somewhat above $10^7\ \mathrm{cm}^{-3}$. The principal exception is at ^{93}Zr, where consistency apparently requires a comparative half-life for the excited-state decay an order of magnitude smaller than the average for its type of transition. If one supposes such an ad hoc adjustment to secure consistency, however, then, as pointed out by Butcher (1974), the consistency result is not a strong one, and it is equally possible for the branches above Ba (at ^{151}Sm and ^{163}Dy) in the end to require different physical conditions from those at the lower masses. This caution is reinforced by the work of Utsumi (1970), which has pointed to the existence of distinct types of stellar *s*-processes, one producing elements mainly above Ba in mass. This much having been said by way of qualification, the consistency result nevertheless remains an impressive one, and may be an important clue to the origin of the solar system *s*-process.

VI. SUMMARY

Preliminary consideration of the role played by the peculiar red giants in galactic *s*-process abundance evolution has led to the following conclusions:

1. If the fraction of a star's mass which is processed to new elements and ejected is approximately independent of the stellar mass, then the readily studied low-mass peculiar red giants can have contributed a moderate fraction of the total pool of *s*-process elements over the lifetime of the galactic disk.

2. Most peculiar red giants exhibit *s*-process abundance curves nonsolar in morphology. There appear to be two principal types of abundance curves produced, one resulting from neutron exposure distributions centered toward low neutron exposures and not grossly different from the solar abundance curve, and the other from exposure distributions restricted to large degrees of exposure. It is not yet clear if there exists a continuum of morphologies between these two abundance types.

3. There is no evidence for any dependence of abundance curve morphology on stellar mass. If this conclusion is borne out by future work, then, as with the ratio ^{12}C/^{13}C, it is unlikely that *s*-process elements can be used to probe details of the initial mass function at earlier epochs.

4. The observed near-constancy of relative *s*-process abundances in the Galaxy may be understood by invoking the presence of a substantial amount of predisk synthesis, or perhaps by supposing that a fortuitous admixture of the different types of stellar abundances has occurred, or both. In any event, the evolution might plausibly be expected to be small.

5. The solar system *s*-process buildup path branches at ^{93}Zr in such a way that $\tau_n \sim 0.3\ \tau_\beta$. In the Ba II and low-mass S peculiar red giants, this branching is characterized by $\tau_n < \tau_\beta$, and probably $\tau_n \ll \tau_\beta$, leading to the speculation that solar system abundances may be composite in nature. That is, solar abundances may have resulted from the mixture of two or more types of *s*-process which branched in different directions, rather than from a single process whose temperature and neutron flux combined to produce a partial branching. Unfortunately, stellar observations would appear to require too high an accuracy to be able to tell whether the branching ratio at ^{93}Zr varies among normal stars in the Galaxy.

6. Analyses of the principal branching points in the solar system buildup path has shown that solar abundances are consistent with, although do not necessarily require, a single-component *s*-process resulting from more or less unique temperature and neutron flux conditions.

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HARVEY BUTCHER: Steward Observatory, University of Arizona, Tucson, AZ 85721