The Astrophysical Journal, **199**:710–717, 1975 August 1

STUDIES OF HEAVY-ELEMENT SYNTHESIS IN THE GALAXY.
II. A SURVEY OF *e*-, *r*-, AND *s*-PROCESS ABUNDANCES

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Received 1974 November 26

ABSTRACT

Results are presented of a survey designed to search for variations in the relative abundances of *e*-, *r*-, and *s*-process elements in G-type dwarfs. Specifically, the abundances of Fe (*e*-process), Eu (*r*-process), and Ba (*s*-process) are examined in some 32 stars with as wide a range of ages, galactic orbits, and compositions as possible. No completely convincing relative abundance variations are found, to a limit of ±25 percent, although a slight enhancement of Eu in certain halo stars may be indicated. Abundances of Eu, Ba, and La are examined in the extreme halo giant HD 122563 and are found to be consistent with, but not as yet to prove, a nuclear (neutron exposure) history for the matter in that star different from the one in the Sun and most other stars.

Subject headings: abundances, stellar — atmospheres, stellar — nucleosynthesis

I. INTRODUCTION

In a previous paper (Butcher 1972, hereinafter called Paper I), the author described a survey of the relative abundances of three elements taken to represent the three main nuclear processes thought responsible for producing the heavy elements, namely the *e*-, *r*-, and *s*-processes of Burbidge *et al.* (1957). The present paper reports the results of that survey, and comments on the problems of their interpretation in terms of the usual picture of stellar nucleosynthesis.

Briefly, as described in Paper I, the idea behind such a survey is to examine elements thought to have been synthesized in radically dissimilar astrophysical environments. Such elements are then supposed to be good candidates for exhibiting relative abundance fluctuations, due to the more or less stochastic processes of production and distribution of elements in the Galaxy. This line of attack on the problem of galactic chemical evolution may be contrasted to the more traditional lines usually undertaken by investigators: instead of first deriving stellar elemental abundances, and then trying to interpret them within the framework of nucleosynthesis theory, the approach is to consider elements with a high likelihood of showing relative abundance variations due to strictly nuclear effects, and determining whether or not they in fact do so. It was initially hoped that this method of attack would be able to throw additional light on the details of galactic nucleosynthesis, and demonstrate perhaps somewhat more convincingly than has been possible to date the essential nuclear nature of galactic chemical evolution.

The choice of the particular elements and production processes considered here has been made primarily for the practical reason of their being easily studied in late-type dwarf stars. Relative abundance variations apparently do exist among the light elements in certain stars, but either these stars are highly evolved (cf. Kodaira, Greenstein, and Oke 1970), thus perhaps exhibiting compositions modified by their own internal nuclear activity, or the abundance analyses are open to at least some doubt. The present discussion has therefore been predicated on elements and stars which are sufficiently well understood that only the most minor question about the method of analysis might arise, and on stars whose atmospheres in all probability really do exhibit a primordial composition.

Specifically, the elements chosen for study are Fe (*e*-process), Eu (*r*-processes), and Ba (*s*-process), and the spectral lines examined are Fe II λ4128.74, Eu II λ4129.73, and Ba II λ4130.66. The identifications and behavior of these lines in late-type dwarf stars, and the advantages of these particular lines, are discussed in Paper I, to which the reader is referred for further details. The present survey, therefore, involves comparing the relative strengths of the three lines in as wide a range of G-type dwarfs as possible. Because the extent to which the age, composition, and orbital parameters of interest can be explored in the Galaxy via G-type dwarfs depends strongly on instrumental capabilities, the performance of the survey spectrograph is first discussed in § II. Following sections then discuss the stars observed (§ III), analysis of the data (§ IV), the final results (§ V), and briefly consider the extreme halo star HD 122563 (§ VI).

II. INSTRUMENTATION

As mentioned in Paper I, when working with a Carnegie RCA C33011 image tube at ~1 Å mm^{-1}, the straight echelle grating system in the Mount Stromlo 74-inch (1.9 m) reflector's coudé can record an 0.6 mm wide spectrum of an $m_\lambda \approx 6$ mag star in ~2 hours. To reach stars fainter than this, the effective focal length of the system has been approximately halved by the introduction of an aplanatic sphere immediately before the focal plane (cf. Bowen 1952; Born and Wolf 1965). This construction provides for the sphere to be inserted completely *inside* the magnet of the image tube, and for the usual 32-inch f.l. camera's field flattener to remain in place (this last component is bonded with optical grease onto the cathode window of the image tube, and is time-consuming and messy to remove). An adequately flat field is provided at the cathode with images nowhere exceeding 16 μ; details of the optical design are given by Butcher (1974).

Installation of the sphere results in a practical speed gain of a factor of 5 or so, while halving the spectral resolution. Thus in two hours, 0.6 mm wide spectra (at $\sim$2 Å mm^{-1}) of $m_\lambda \approx 8.0$ mag stars may be secured with a resolution of 0.15 Å. All spectra, with and without the aplanatic sphere, have been traced to the same final scale for measurement. Even though the spectral resolutions differ, no systematic differences have been detected in equivalent-width measurements from the two sources, and hence all measurements have been treated with equal weight and without regard as to source.

The observational capabilities of the entire instrumental system may be summarized as follows: Stars to $m_\lambda \approx 6.0$ mag can be studied at a resolution of 0.075 Å, and stars to $m_\lambda \approx 8.0$ mag at a resolution of 0.15 Å. Lines of 20–100 mÅ equivalent width in late-type stars can be measured on a single plate with about 10 percent random error (independent of which dispersion is used); for exposures $\gtrsim 2$ hours this error increases to $\sim$20 percent. Finally, lines of $\lesssim 10$ mÅ can only be measured on plates with little or no image-tube background.

The implications of these performance limitations for the study presented here are twofold. For G-type dwarf stars the three survey lines become too weak for accurate measurement at heavy-element abundance levels less than about a tenth solar (i.e., [Metals/H] < -1.0). Although the most extreme halo stars are thus excluded from consideration, it has proven possible to explore a total range in heavy-element abundances of a factor of 30 or so (cf. Table 3). Second, the well-known paucity of dwarfs which both have halo orbits and are brighter than eighth magnitude is reflected in the small number of such stars in Table 1.

III. STARS OBSERVED

Good quality plate material has been secured of some 32 G-type dwarfs. Table 1 lists the stars along with their spectral types, the adopted $R - I$ colors (on the Kron system) with sources, the number of plates secured of the λ4130 region, the approximate dispersions used, and finally the stars' galactic orbital eccentricities and angular momenta (as defined by Eggen, Lynden-Bell, and Sandage 1962) and the source of these. It should be emphasized that these stars are not a random sampling of the stellar population of the Galaxy, but instead include objects with as wide a range in galactic orbital parameters, age, and chemical composition as possible, consistent with unavoidable instrumental limitations and the desire to work mostly with G-type dwarfs.

TABLE 1

THE SURVEY STARS

Name	Sp	R-I	Src	No. of Plates	Disp. Å/mm	e	h	Src
β Hyi	G2IV	.22	2,3,5	4	1	.18	222	2
τ Cet	G8V	.28	3,4	5	1	.3	294	10
κ Cet	G5V	.23	3,4	3	1	.0	260	10
ζ^{1} Ret	G2V	.22	3,4	4	1	.2	225	10
HR1008	G5V	.27	3,5	2	1	.40	170	9
10 Tau	F8V	.21	2,4	2	1	.03	251	2
δ Eri	K0IV	.33	2,3,5	4	1	.23	292	2
o^{2} Eri	K1V	.31	3,4	1	1	.34	253	9
α CMi	F5IV-V	.13	3,5	4	1	<.1	256	10
HR2998	G5IV	.32	2	3	1,2	.16	235	2
HR3018	G0V	.24	2	5	1	.47	209	2
HR3578	F9V	.21	1	4	2	.35	172	9
HR4134	dF6	.18	6	2	1	.2	229	11
HR4523	G5V	.22	2	4	1	.19	227	2
β Vir	F8V	.17	3,4	6	1,2	.2	268	10
HR4587	dG7	.27	1	3	2	.10	248	2
HD114762	F9V	.21	7	3	2	.2	215	12
HD115577	G8IV	.38	1	3	2	.50	145	9
α Cen A	G2V	.22	3	4	1	.1	267	10
ξ Boo A	G8V	.28	8	2	2	.1	266	10
5 Ser	F8IV-V	.17	5	3	1	.3	255	10
ν^{2} Lup	G2V	.28	2	4	2	.41	203	2
γ Ser	F6V	.14	3,4	2	1	.3	221	10
HD148816	F9V	.18	1	4	2	.70	70	9
36 Oph AB	K0V	.30	3,5	5	1,2	.1	233	10
HD157466	---	.18	1	5	2	.2	273	12
70 Oph A	K0V	.26	8	4	1,2	<.1	245	10
31 Aql	G8IV	.21	2	2	1	.35	241	2
HD183877	G5IV	.26	1	4	2	.61	105	9
γ Pav	F8V	.19	3,4	4	1	.4	309	10
ν Ind	G0V	.29	1	5	1,2	.42	173	9
HD215257	---	.22	1	3	2	.4	290	12
SKY	---	---	---	6	1,2	---	---	--

NOTES TO TABLE 1.—(i) One-place values for *e* are estimates from Fig. 1 of Eggen 1964*b*, using the published space velocities. (ii) $h = 250 + 15 + V$ in units of 10 kpc km s^{-1}, where V is the space velocity in the direction of galactic rotation.

SOURCE.—(1) Eggen 1973. (2) Hearnshaw 1972. (3) Kron *et al.* 1957. (4) Johnson *et al.* 1968. (5) Johnson *et al.* 1966. (6) Mendoza 1967. (7) Argue 1967. (8) Breckinridge and Kron 1964. (9) Eggen 1964*b*. (10) Eggen 1962. (11) Eggen 1972. (12) Sandage 1969.

A color-magnitude diagram for many of the stars is available from Eggen (1964*a*), and it is evident that a spread in age of at least from several times 10^9 years to as old as the Galaxy is present in the sample. In addition, the three visual binaries ξ Boo, 36 Oph, and 70 Oph exhibit strong Ca II K-line emission, and have been observed in an attempt to include as young stars as possible in the sample. Comparison of their emission intensities (Wilson 1963; calibrated by Wilson 1968) with those in the Hyades (Wilson 1970) suggests these stars may be as young as several times 10^8 years. It was initially hoped that this considerable age-spread among the stars would allow any systematic relative abundance changes with time in the Galaxy to be revealed.

Table 1 also shows the sample to contain stars with a fairly large range in *e* and *h*: orbits from extreme halo (e.g., HD 148816) to normal disk, with both high (e.g., γ Pav) and low (e.g., ν Ind) angular momenta are represented. Using these parameters, the stars may be separated into halo and disk objects, thus providing some kind of age discrimination during the early, formation period of the Galaxy (Eggen *et al.* 1962).

As will become evident from the analysis in § IV, the range of heavy-element abundance (as characterized by [Fe/H]) among the stars in Table 1, although not extending to extreme metal deficiencies, does cover a factor of 30 or so. The claim is made, therefore, that the sample of stars considered here represents a fair sample of all those parameters thought relevant to element synthesis in the Galaxy, while at the same time being narrow enough in the temperature-gravity plane to preclude any major questions of interpretation in the abundance analysis itself.

IV. ANALYSIS OF THE DATA

Measured equivalent widths with standard errors for the survey lines are given in Table 2. As discussed in Paper I, the analysis of this data has proceeded first by desaturating these measured line strengths.

The Fe II line at λ4128 has been desaturated using the Cowley and Cowley (1964) solar curve of growth, as fitted to measurements of some 15 Fe I lines in each star. The velocity parameter deduced from these fitted curves has for the most part been indistinguishable from its solar value (taken to be 1.7 km s^{-1}). Two of the halo stars (γ Pav and HR 3018) have curves characterized by a velocity parameter of 1.5 km s^{-1}, and α CMi has been shown by Griffin (1971) to exhibit a curve characterized by about 2.5 km s^{-1}, the present data being consistent with that value. It should be noted that the discrimination level for velocity parameter variations here is only about ± 0.2 km^{-1} s, so a certain amount of spread in that quantity may well be present among the stars. In addition, the use of more recent solar curves of growth by Foy (1972) and Yamashita (1972), characterized by somewhat lower microturbulence, are found not to alter significantly the results as presented below.

TABLE 2

MEASURED AND DESATURATED LINE STRENGTHS (mÅ)

Star	FeII λ4128		EuII λ4129		BaII λ4130	
	Meas.	Desat.	Meas.	Desat.	Meas.	Desat.
β Hyi	54±1	98±3	76±2	85±2	57±3	85±7
τ Cet	34 2	43 3	81 2	94 2	38 4	42 6
κ Cet	53 5	95 18	71 6	78 8	56 4	82 10
ζ^1 Ret	48 3	77 9	71 5	78 7	52 5	73 12
HR1008	34 3	43 6	73 1	81 1	38 9	42 15
10 Tau	68 5	178 37	75 4	84 6	48 5	65 11
δ Eri	52 7	91 25	135 8	210 25	76 6	117 19
o^2 Eri	48 -	78 -	110 -	149 -	49 -	59 -
α CMi	85 6	360 100	70 6	77 8	63 3	114 9
HR2998	56 1	107 4	106 3	140 8	60 4	80 9
HR3018	28 2	32 3	54 4	55.5 4	22 2	22 2
HR3578	38 4	51 9	53 3	54 3	27 3	28 3
HR4134	62 5	137 27	80 8	92 12	60 2	96 5
HR4523	47 3	74 9	78 7	89 11	52 5	73 12
β Vir	62 2	137 11	78 4	89 6	58 4	92 9
HR4587	51 1	95 3	88 7	105 12	60 5	87 13
HD114762	36 4	48 8	49 1	49 1	30 4	32 5
HD115577	54 5	99 19	193 5	470 30	79 3	114 9
α Cen A	53 2	95 7	75 2	84 3	49 4	66 8
ξ Boo A	37 3	59 9	61 1	73 9	44 5	88 12
5 Ser	89 5	425 100	98 3	124 6	73 5	145 21
ν^2 Lup	48 4	77 12	68 4	74 5	40 5	45 8
γ Ser	50 8	85 24	50 6	55 5.5	50 6	78 13
HD148816	31 3	38 5	41 4	41 4	21 2	21 2
36 Oph A	28 1	32 2	80 5	91 8	59 5	82 10
36 Oph AB	32 2	39 3	72 6	78 9	41 3	45 4
HD157466	45 1	69 2	46 2	46 2	36 5	42 8
70 Oph A	30 2	35 3	68 1	74 1	38 1	43 1
70 Oph AB	46 2	80 13	81 4	92 6	57 6	70 5
31 Aql	64 3	149 19	115 12	160 25	70 1	126 4
HD183877	46 4	71 12	73 6	81 9	38 5	43 8
γ Pav	34 2	43 3	30 2	30 2	22 2	22 2
ν Ind	28 2	29.5 3	55 4	56 4	21 2	20 2.5
HD215257	41 3	59 7	48 8	48 8	32 5	34 6
SKY	49 4	81 13	61 3	65 3	45 4	57 9
SKY Apl.S.	48 3	78 9	58 1	61 1	44 2	55 4

The Eu II line at λ4129, which has wide hyperfine splitting, has been desaturated by the semiempirical saturation curve described in Paper I, with the exception that the position of this curve is now taken as fixed, instead of varying with the Fe I curve. That this procedure is correct has been suggested by the work of Mihalas and Luebke (1971).

There is sufficient range in effective temperature among the survey stars to provide a check on the behavior of the survey lines with temperature (at constant heavy-element abundance level), thus verifying the line identifications and testing for any blending that might be present. Abundances from both Fe II λ4128 and Eu II λ4129 have been found to show no dependence on temperature; Ba II λ4130, on the other hand, was initially found to exhibit a slight abundance effect with temperature, in the sense of an increasing Ba abundance with decreasing temperature. Careful examination of the tracings suggested that the line Ce II λ4130.70 may in fact have been included in the equivalent width measurements of Ba II λ4130. On the assumption that the raw measurements of Ba II λ4130 in Table 2 do include contributions from both the Ba and Ce lines, a temperature-dependent set of curves relating the measured equivalent width to the weak-line strength of Ba II λ4130.66 has been constructed, taking a constant Ce/Ba ratio, the Ce II line (of 0.56 eV excitation) to be physically unblended and to have a strength of 5 mÅ in the Sun (Moore, Minnaert, and Houtgast 1967), and the Cowley-Cowley solar curve of growth for all stars. The Ba II weak line strength so corrected has in no case resulted in more than a factor of 2 decrease in the final abundance, and typically has been much less. As will become evident, this procedure has eliminated the apparent slight over-deficiency of Ba in λ Pav, HR 3018, and ν Ind reported in Paper I.

The final desaturated survey line strengths are also given in Table 2. The errors quoted in these columns are the standard errors of measurement as magnified by the desaturation process.

Derivation of relative abundances from these desaturated line strengths has been done in a slightly different manner than that described in Paper I. The model calculations of Cayrel and Jugaku (1963) are still judged to be of sufficient accuracy for the present purposes; but instead of employing their detailed line strength curves, the procedure has been to make use of the mean curve-of-growth temperature parameters given in their Table 11, and the curve-of-growth equations due to Pagel (1964):

$$[X] = [N^+/\mathrm{H}] + [\theta_{\mathrm{eff}}] + \Delta\theta_{\mathrm{ion}}\mathrm{I} - \Delta\theta_{\mathrm{exc}}{}^{\mathrm{I}}\chi - 0.75\Delta\theta_{\mathrm{eff}}$$

for lines of neutral species,

$$[X] = [N^+/\mathrm{H}] - \tfrac{3}{2}[\theta_{\mathrm{eff}}] - \Delta\theta_{\mathrm{exc}}{}^{\mathrm{II}}\chi - 0.75\,\Delta\theta_{\mathrm{eff}}$$

for lines of ionized species, and

$$\left[\frac{X_1}{X_2}\right] = \left[\frac{N_1}{N_2}\right] - \Delta\theta_{\rm exc}{}^{\rm II}(\chi_1 - \chi_2) + [x_1] - [x_2]$$

for the relative strengths of two lines from ionized species. In these equations $[Q] = \log\ Q(\text{star}) - \log\ Q(\text{Sun})$, Q being any quantity; X is the weak-line equivalent width (or alternatively the desaturated equivalent width); (N^+/H) is the ratio of the abundance of the ionized species under discussion to the abundance of hydrogen (any slight correction necessary to obtain the total elemental abundance may be made using Saha's equation, as indicated in the last of the above relations by the ionization corrections, x); $\theta = 5040/T$, $\Delta\theta = \theta(\text{star}) - \theta(\text{Sun})$, and the various $\Delta\theta$'s are allowed to be different; I and χ are the ionization potential of the species, and excitation potential of the line, respectively; P_e is the mean electron pressure; and $\Delta\theta$ for the dissociation of H^- is taken to be equal to $\Delta\theta_{\rm eff}$. A comparison of these equations with the exact results given by Cayrel and Jugaku has shown that they reproduce those results well; their advantages are that they may quickly and easily be extended to include stars of lower gravity, such as the subgiants in Table 1, and provide an easy, intuitive way of judging the effects of both systematic and random errors in the various parameters.

Table 3 lists the temperature parameters finally adopted in the present study. The quantity $\Delta\theta_{\rm eff}$ comes directly from the $R - I$ photometry in Table 1 and Johnson's (1966) temperature-color calibration (using transformations to the Johnson system from Eggen 1971 and Argue 1967), taking $\theta_{\rm eff}(\text{Sun}) = 0.87$; the other $\Delta\theta$'s then come from Table 11 of Cayrel and Jugaku.

TABLE 3

ATMOSPHERIC PARAMETERS

Star	$\Delta\theta_{\rm eff}$	$\Delta\theta^{\rm I}_{\rm exc}$	$\Delta\theta^{\rm II}_{\rm exc}$	[Fe/H]	$[P_e]$	$[x_{\rm Fe}]$
β Hyi	.015	.03	.02	−.2	−.3	+.01
τ Cet	.08	.11	.095	−.6	−.6	−.03
κ Cet	.02	.04	.03	.0	−.1	−.01
ζ^1 Ret	.01	.02	.01	−.1	−.1	−.01
HR1008	.07	.10	.07	−.4	−.3	−.05
10 Tau	−.005	.00	.00	−.1	−.3	+.03
δ Eri	.15	.20	.13	−.1	−.7	−.14
o^2 Eri	.12	.16	.11	−.4	−.7	−.06
α CMi	−.09	−.09	−.06	+.1	−.1	+.04
HR2998	.13	.18	.11	−.4	−1.0	−.03
HR3018	.035	.06	.065	−.7	−.4	+.01
HR3578	.00	.01	.03	−.6	−.3	+.03
HR4134	−.03	−.03	−.01	−.3	−.3	+.04
HR4523	.015	.03	.02	−.2	−.1	.00
β Vir	−.05	−.05	−.03	+.2	+.2	+.02
HR4587	.07	.10	.07	+.2	−.1	−.12
HD114762	.00	.01	.03	−.5	−.2	−.12
HD115577	.20	.26	.18	−.6	−1.3	−.10
α Cen A	.015	.03	.02	−.1	−.1	−.01
ξ Boo A	.08	.12	.08	−.4:	−.6	−.02
5 Ser	−.05	−.05	−.03	+.2	−.2	+.04
ν^2 Lup	.08	.11	.095	−.6	−.6	−.01
γ Ser	−.08	−.08	−.05	.0	+.3	+.03
HD148816	−.03	−.03	−.01	−.3	+.1	+.01
36 Oph	.11	.15	.10	−.4:	−.6	−.08
HD157466	−.03	−.03	−.01	−.3	−.1	+.03
70 Oph A	.065	.095	.065	−.1:	−.1	−.11
31 Aql	−.005	.00	.00	+.7	+.4	−.06
HD183877	.065	.095	.065	−.4	−.4	−.02
γ Pav	−.02	−.02	.01	−.5	−.2	+.03
ν Ind	.095	.13	.12	−1.2	−1.0	+.01
HD215257	.01	.03	.04	−.5	−.3	+.02

Values of [Fe/H], $[P_e]$, and [xFe] for each star are also listed in Table 3. These quantities are derived from the first two of the above equations, using 15 Fe I lines measured in each star and the three Fe II lines at λλ4122.67, 4124.79, and 4128.74. The dominant error in these determinations comes from a ±0.02 mag uncertainty in $\theta_{\rm eff}$ (which includes errors of photometry and a roundoff error in converting to $\theta_{\rm eff}$), and is on the order of ±0.1 dex or so for [Fe/H]. This error estimate is corroborated by a comparison of these results with similar determinations for some of the stars by Hearnshaw (1972) and others. Values of $[x_{\rm Eu}]$ and $[x_{\rm Ba}]$ for almost all of the stars are found to be insensibly different from 0.00.

Finally, application of the last equation above to the desaturated survey line strengths in Table 2 yields the abundance ratios given in Table 4 (note that these ratios are *not* logarithmic). The errors quoted here include both the standard error of measurement, as propagated through desaturation, and an error of ±0.02 mag in $\Delta\theta_{\rm eff}$.

Abundance ratios have also been derived using an average of the three Fe II lines mentioned above. The results for all cases agree to within twice the quoted error estimates, and for all but four stars agree to within the estimates themselves.

V. RESULTS AND DISCUSSION OF ERRORS

Before a discussion of the implications of the results in Table 4 can be made, the data for the three

TABLE 4

FINAL ABUNDANCE RATIOS

Star	$\frac{\rm Eu}{\rm Fe}$	± σ	$\frac{\rm Eu}{\rm Ba}$	± σ	$\frac{\rm Ba}{\rm Fe}$	± σ
β Hyi	1.01	± .14	.79	± .13	1.25	± .11
τ Ceti	1.47	.25	1.11	.21	1.34	.11
κ Ceti	.84	.21	.70	.15	1.21	.28
ζ^1 Ret	1.18	.24	.90	.21	1.33	.27
HR 1008	1.40	.27	1.11	.43	1.28	.49
10 Tau	.64	.16	1.16	.26	.57	.15
δ Eri	.97	.32	.70	.17	1.40	.45
o^2 Eri	1.10	.3:	1.14	.3:	.98	.2:
α CMi	.72	.23	1.21	.23	.56	.16
HR 2998	.82	.12	.78	.15	1.07	.13
HR 3018	1.50	.27	1.50	.26	1.01	.13
HR 3578	1.19	.27	1.44	.26	.84	.18
HR 4134	.99	.27	.92	.18	1.09	.22
HR 4523	1.36	.29	.97	.24	1.42	.28
β Vir	1.03	.17	1.06	.19	.99	.13
HR 4587	.70	.13	.70	.16	1.02	.08
HD114762	1.12	.24	1.14	.24	1.00	.23
HD115577	1.62	.39	1.18	.20	1.39	.29
α Cen	.97	.16	1.01	.19	1.01	.14
ξ Boo A	.96	.13	.65	.11	1.48	.21
5 Ser	.48	.13	.94	.19	.52	.15
ν^2 Lup	.67	.14	.81	.19	.83	.20
γ Ser	1.07	.35	.79	.19	1.37	.45
HD148816	1.49	.31	1.87	.36	.80	.13
36 Oph A	1.65	.26	.53	.10	3.14	.44
36 Oph AB	1.16	.19	.83	.16	1.41	.20
HD157466	.97	.16	1.06	.26	.92	.18
70 Oph A	1.41	.21	1.02	.12	1.39	.13
70 Oph AB	.87	.14	.68	.15	1.29	.23
31 Aql	1.19	.28	1.14	.23	1.06	.14
HD183877	.94	.23	1.12	.29	.85	.21
γ Pav	.89	.15	1.15	.20	.78	.09
ν Indi	1.21	.20	1.18	.21	1.03	.17
HD215257	.84	.20	.98	.26	.87	.18
SUN	1.00	--	1.00	--	1.00	--

COMMENT TO TABLE 4.—The errors here have been expressed in terms of the abundance ratios themselves, rather than in log ratios as might be more usual, because the survey lines are nearly weak and because the largest single contributor to the errors comes from simple measurement uncertainty.

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nominally young stars ξ Boo, 36 Oph, and 70 Oph require special discussion. The spectra of the primary components (supposedly) of these binaries have been analyzed using (for ξ Boo and 70 Oph) photometry of the separated components from Breckinridge and Kron (1964), and (for 36 Oph) composite photometry from Kron, Gascoigne, and White (1957), assuming equal components. That there may be certain problems with the results so derived is suggested by two observations. First, spectra of 70 Oph, of both the primary alone and both components together, show quite large differences in equivalent widths of the survey lines (see Table 2). Hence, were there some contamination from the secondary in the spectrum of the primary supposedly alone, it would have fairly gross effects. Similarly, spectra of 36 Oph, of one component alone, and then both together, show a rather different appearance around Ba II λ4130. It can only be concluded, therefore, that the two components are in fact not precisely alike, and the derived results are put into question. Since contamination problems may have been initially underestimated for these two binaries, it follows that the data for ξ Boo should also be regarded with caution. However, even with these suspected problems, the abundance ratios found for the three stars (see Table 4) are sufficiently close to normal that they most likely may be taken as such.

The remaining sample, after exclusion of these three objects, consists of 29 dwarfs or subgiants of near solar temperature, of varying kinematic and composition parameters, for which a set of homogeneous data has been obtained. The final abundance ratios for this sample, given in Table 4, are displayed in Figure 1.

The average standard errors in Table 4 are found to be 22, 21, and 20 percent, for (Eu/Fe), (Eu/Ba), and (Ba/Fe), respectively. Again, these errors include the formal errors of measurement, as propagated through desaturation, and a ± 0.02 mag error in $\Delta\theta_{\text{eff}}$.

Other sources of error undoubtedly include the derived saturation curves, for which, as mentioned, an uncertainty of at least ± 0.2 km s^{-1} must be present. For strong-line stars, errors in the curves of this order may well contribute as much as 10 percent to the scatter of the final results, the effect being strongest for the Eu ratios and smallest for (Ba/Fe). In addition, if there are small atmospheric changes with gravity when going from dwarf to subgiant, there will appear an increase in the final scatter, because all stars are considered together.

These and other effects may tend to increase the dispersion of the final results, but it would seem unlikely that their combined effects should exceed 10–15 percent. If this is so, then the total expected scatter in the final abundance ratios should be about 25 percent. This value (squared) has therefore been taken to be an *a priori* estimate of the variance of the sample due to observational and theoretical uncertainties. In Figure 1 is also shown the normal curve with this variance superimposed on the data.

It is clear that this 25 percent accounts for most, if not all, of the observed dispersion. Of the three ratios, perhaps only (Eu/Fe) may show some small excess width. A χ^2 test on this ratio gives a probability of 14 percent that the dispersion in (Eu/Fe) will be this large or larger; hence no real significance may be attached to this excess width. Chi-square tests on the other two ratios give probabilities of some 35 percent for each, so one may conclude that overall the *a priori* error estimates satisfactorily account for the observed dispersion.

The data may be separated into groups according to the various kinematic and composition parameters of the stars, to see if there are any small effects hidden in these results. In Figure 2 is shown a separation into three groups of different absolute abundance levels. The grouping here is more or less arbitrary, but is done to ensure an adequate number of stars in each group. Immediately evident is the cause of the slight excess width in the (Eu/Fe) distribution, discussed above. That is, there is a small, perhaps 15 percent, systematic variation of (Eu/Fe) with abundance level; there may be some of this effect in (Eu/Ba) as well. Butcher (1974) has suggested that this variation is at least in part due to non-LTE phenomena; perhaps there are also small effects due to the different saturation curves used for Eu and for Ba and Fe, or to systematic problems with the $\Delta\theta_{\text{exc}}{}^{\text{II}}$ derivations. Other than this small, systematic and most likely spurious variation, however, there appear to be no significant changes with abundance level.

Groupings of the data by the other parameters of interest (see § III) likewise show little or no deviations of the data from the expected dispersions. Only when the stars are separated according to galactic orbital eccentricity has any possible effect been found; Figure 3 shows such a grouping. On the picture of galactic collapse of Eggen *et al.* (1962), this division at $e \approx 0.4$ represents an age separation of those stars formed during the actual phase of violent

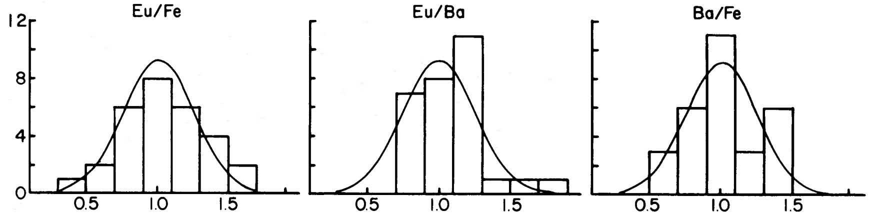

FIG. 1.—Histograms of the survey abundance ratios, normalized to 1.00 in the Sun, for the 29 program stars with reliable data. The grouping bins are ± 10 percent, and the superposed curves are the *a priori* expected normal distributions, with $\sigma = \pm 25$ percent, if there are no real abundance variations.

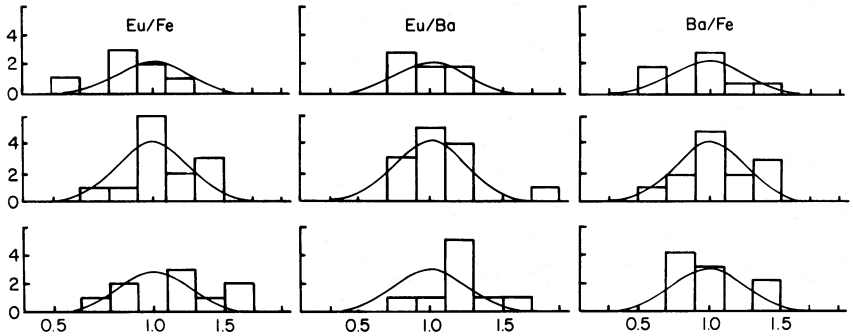

FIG. 2.—Abundance ratio results for three levels of heavy-element abundances. The top graph in each case is for [Fe/H] ≥ 0.0, the middle one for −0.1 ≥ [Fe/H] ≥ −0.4, and the lower one for [Fe/H] < −0.4. Again, the superposed curves are the expected distributions for the case of no relative abundance variations. The gradual, probably spurious, variation in the derived Eu abundance is evident in the plots for (Eu/Fe) and (Eu/Ba).

collapse, and those formed afterward. Note that the division here is *not* the same as one by angular momentum, because included in the sample of high-eccentricity stars are several objects which lead the Sun, i.e., also have fairly high angular momenta.

It is evident that the (Eu/Fe) ratios for stars with $e \geq 0.40$ may possibly be distributed in a nonrandom manner. A χ^2 test on these data (for the scatter around the data's own mean of 1.17) suggests significance at about the 5 percent level, a level which may be marginally significant. That neither (Eu/Ba) nor (Ba/Fe) show any increase in scatter for $e \geq 0.40$ argues against significance for the result, of course; but at least for several stars the data are excellent, and differences are apparently indicated. In particular, the stars, γ Pav and HR 3018 can be singled out as providing the best evidence for variations in the Eu ratios. These stars both have independent temperature estimates in the literature: Hearnshaw (1972) gives a very careful determination of $\Delta\theta_{\text{eff}} = +0.02$ for HR 3018, and Danziger (1966) finds $\Delta\theta_{\text{eff}} = 0.00$ for γ Pav. Both results agree well with the values used here (+0.035 and −0.02, respectively). In spite of such claims of reality, however, the effect is only on the order of the size of the errors (as evidenced especially by the fact that ν Ind is in this analysis no longer considered Eu-rich, as it was in Paper I), and any interpretation relying on it must at present be approached with due regard to its possibly being spurious.

The writer wishes to record at this point a private communication from Wallerstein (1972), in which he describes a visual examination he made of the λ4129 region on a large number of plates of G and K giants, taken by O. C. Wilson. No obviously abnormal Eu abundances were found in that search, a result in complete accord with the present findings.

VI. HD 122563

This star has special importance in the discussion of galactic chemical evolution, because it is one of the most extreme halo stars to have been analyzed in detail, and because it apparently exhibits just the kind of relative abundance anomalies for which the present work has been searching (Pagel 1965; Wolffram 1972). The more or less negative results of searches for anomalies in dwarfs here and elsewhere, however, cast some doubt as to whether the anomalies in HD 122563 are in fact due to nuclear processes. Therefore it is of interest to investigate two points: (1) whether the overdeficiency of Ba in HD 122563 is accompanied by an overdeficiency of *s*-process elements still heavier than Ba. Of special interest in this regard is the size of the ledge in the σN curve following Ba—that is, if the overdeficiency of Ba in the star is due to a neutron exposure distribution concentrated more at low exposures than is the case normally, then *s*-process theory predicts that this ledge should be increased in height (Seeger, Fowler, and Clayton 1965), and *s*-

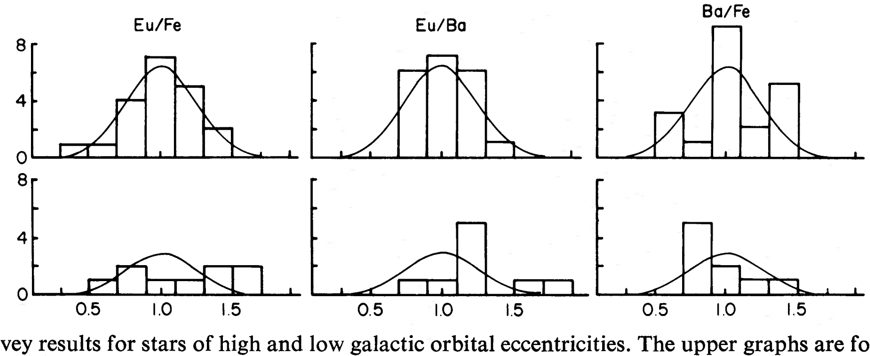

FIG. 3.—The survey results for stars of high and low galactic orbital eccentricities. The upper graphs are for $e < 0.40$; the lower, for $e \geq 0.4$. Note the observed distribution for (Eu/Fe), $e \geq 0.40$.

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TABLE 5

ANALYSIS OF HD 122563

			HD 122563		SUN	
LINE	$\chi_{\rm exc}$(eV)	NO. OF PLATES	Measured (mÅ)	Desaturated (mÅ)	Measured (mÅ)	Desaturated (mÅ)
Eu II λ4129.73.......	0.00	5	11	11	59	62
Fe II λ4128.74.......	2.58	5	18	18	48	79
La II λ3995.75.......	0.17	5	12	12	38*	51
V II λ3997.11........	1.48	5	31	37	50*	83

[Eu/Fe] = −0.58; [La/V] = −0.53; [V/Fe] = −0.50†, so [La/Fe] = −1.03; [Ba/Fe] = −0.95‡. Or (Eu/Fe) = 0.26 ± 0.08:, (Ba/Fe) = 0.11 ± 0.03:, (La/Fe) = 0.09 ± 0.03:.

* From Moore *et al.* 1967.

† This value of [V/Fe] is from Pagel 1965 and from Wolff and Wallerstein 1967, and is apparently well-determined.

‡ From Pagel 1965; Ba II λ4130 is too weak to measure on the writer's plates.

COMMENTS: Both La II λ3995 and VII λ3997 may be slightly affected by hyperfine splitting in the Sun; if both are about equally affected, nearly identical results to the above are obtained. Again, differential atmospheric parameters for this analysis are from Pagel 1965, in particular $\Delta\theta_{\rm exc}{}^{\rm II} = 0.19$.

process elements heavier than Ba should be down in abundance even more than Ba; and (2) whether the *r*-process elements near Ba in HD 122563 are down by exactly the same amount as Ba, or whether they show any evidence of independent behavior. Toward these ends, measurements of several lines in this star have been made and analyzed; the results are displayed in Table 5. Parameters for the analysis, in particular the value of $\Delta\theta_{\rm exc}{}^{\rm II} = 0.19$, have been taken from Pagel (1965), these being at present the best available.

Seeger *et al.* (1965) find La to come almost equally from the *s*- and *r*-processes in the solar system. If one assumed the Eu abundance to be indicative of the *r*-process abundance level in general, and Ba of the *s*-process level, then one would predict $({\rm La/Fe})_*/({\rm La/Fe})_\odot = 0.11/2 + 0.26/2 = 0.19$; instead, a value of 0.09 has been found. Thus the data are indeed consistent with an additional overdeficiency of La, as might be predicted by *s*-process theory. Also, it is evident from Table 5 that Eu may in fact be behaving independently of the *s*-process elements.

A word of caution concerning these seemingly satisfactory results is necessary, however. All these differences are on the order of a factor of 2, and in such an extreme star the unknown factors in the analysis may well be large enough to produce errors of this size. The results should therefore be regarded as tentative, until better analyses can be made, and until data on a number of similar stars become available.

VII. SUMMARY AND DISCUSSION

The relative abundances of Eu, Ba, and Fe have been examined in stars of all ages, and over a range in the (metals/H) ratio of from a tenth to several times solar. No conclusive evidence for relative abundance fluctuations among these elements has been found, to about the 25 percent level, although there may exist a small spread in relative Eu abundances among the halo stars observed.

It is not known at present whether or not this last observation is correct. The situation may be, for example, that stars with $[{\rm Fe/H}] \approx -1.0$ have atmospheric structures, and hence $\Delta\theta_{\rm exc}{}^{\rm II}$'s, which change rapidly with $\theta_{\rm eff}$ or gravity, such as has been suggested for extreme subdwarfs by Travis and Matsushima (1973). On the other hand, HD 122563 apparently does show an overdeficiency of both Ba and Eu (although again, their own relative abundances may or may not be abnormal). Therefore, $[{\rm Fe/H}] \approx -1.0$ may represent an abundance level resulting from few enough synthesis events to show significant relative abundance variations, higher levels having resulted from so many events that all fluctuations have been averaged out. If this latter interpretation is correct, then one would expect the most extreme halo stars to show larger relative abundance variations than those found here, a prediction readily verifiable with only slightly improved spectrographic equipment. Unfortunately, therefore, it seems clear that an unambiguous demonstration of the independent behavior of these elements must await the detailed observation and analysis of more of the most extreme halo stars.

Two comments, however, are in order at this stage. First, Searle (1971) has found large variations in the nitrogen-to-oxygen ratio radially across the disks of Sc-type spiral galaxies, and hence with disk angular momentum. To the extent that nitrogen and oxygen have been synthesized under different and independent conditions (cf. Arnett 1971, where it is suggested that nitrogen comes from hydrostatic CNO-cycle hydrogen burning in stars, while oxygen results from explosive burning in stellar hydrogen or helium zones), one might expect similar, although probably not identical, order-of-magnitude behavior for other "independent" elements. It is curious, therefore, that over a range of a factor of 30 in heavy-element abundances, no significant variations in Eu/Ba or Ba/Fe have been found here, when a factor of less than 2 in O/H (and presumably of 2–4 in Fe/H, Searle 1972) apparently presents N/O ratio variations of nearly a factor of 8.

Second, the well-known and rather large fluctuations in Fe/H among stars of a given age have been shown by Searle (1972), and Talbot and Arnett (1973), to explain in a very natural way (via metal-enhanced star formation) the reason why so few metal poor stars are observed. If in such a picture of star formation in the galaxy, imperfect mixing and nonuniform element production play key roles, then does it not seem strange that relative *e*-, *r*-, and *s*-process abundances should remain so constant?

These questions lie at the foundations of our ideas on the synthesis of the elements, and provide puzzles that must be solved before any claim can be made of understanding the origin of the elements. Future observational work clearly should center on the brightest dozen or so stars as extreme as HD 122563.

The author wishes to thank Drs. M. S. Bessell and A. W. Rodgers for their aid and encouragement during this work, Professor S. C. B. Gascoigne for helpful conversations and the use of his ray-tracing program, leading to the design and construction of the aplanatic sphere, and the Australian National University for the support of a Research Scholarship during 1970–1974.

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