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THIRTEEN-COLOR PHOTOMETRY OF SUBDWARF STARS. III. CHEMICAL COMPOSITIONS, KINEMATICS AND THE (G, 45–63) DIAGRAM

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RESUMEN

Se obtienen fotométricamente la composición química para 116 estrellas, en su mayoría subenanas, y luego se compara la composición con la cinemática galáctica y con los diagramas de gravedad, temperatura. Presentamos evidencia que el enriquecimiento metálico en el halo procedió más lentamente en las estrellas del campo que en los cúmulos globulares. Las subenanas más extremas del halo tienen un [Fe/H] medio de aproximadamente —1.40.

ABSTRACT

Compositions of 116 stars, mostly subdwarfs, have been photometrically obtained and then compared with galactic kinematics and gravity, temperature diagrams. We present evidence that metal enrichment in the halo field stars proceeded more slowly than in the globular clusters. The more extreme halo subdwarfs have an average [Fe/H] of about −1.40.

Key words: **PHOTOMETRY — STARS, SUBDWARFS — CLUSTERS, GLOBULAR.**

I. INTRODUCTION

In papers 1 and 2 (Schuster 1979*a, b*) we showed that the 13-color system, especially the (*37–45, 45–63*) diagram, is both very sensitive and accurate for obtaining [Fe/H] values of metal-poor stars. Recently Hartwick (1976) has studied the chemical evolution of the galactic halo using [Fe/H] values for 60 globular clusters. In this paper we investigate the early history of our galaxy by correlating stellar compositions with kinematic and evolutionary data and by comparing the [Fe/H] frequency functions of high-velocity stars with that of the globular clusters.

II. [Fe/H] DISTRIBUTIONS OF SUBDWARF STARS AND GLOBULAR CLUSTERS

Table 1 lists the 124 stars from paper 1 with photometric [Fe/H] values for 116 of them as derived from the calibration of paper 2. Eight of the stars are much redder than the *45–63* = 1.04 limit of our calibration. Nine others have *45–63* > 1.04, but we have been able to deduce their compositions due to special circumstances. The composition of −15°4041 has been taken equal to that of −15°4042, its common proper motion companion. The stars +19°279, −13°544, G175-39, +37°1312, +42°1922, and +39°2950 have small δ(*37–45*)'s, and so we have estimated that these stars have solar, Hyades, or greater than Hyades metal abundances. For +41°3306 and BS6752D, we have extrapolated the calibration even further for a very rough composition estimate. Finally, the composition given in Table 1 for +34°796 (HD25329), which probably has an unusual nitrogen/iron ratio (Harmer and Pagel 1970), is merely the average of the spectroscopic abundances of Morel *et al.* (1976). The spectroscopic abundances

TABLE 1

PHOTOMETRIC ABUNDANCES FOR SUBDWARFS

Name	37-45	45-63	δ(37-45)	[Fe/H]	Notes
+54°223	0.301	0.920	+0.228	(-0.5)	high vel.
- 9°256	0.160	0.786	+0.138	-0.25	high vel. G2V
+19°279	0.790	1.042	+0.000	(∿+0.25)	
-16°295	0.425	0.958	+0.182	(-0.4)	
-26°828	0.421	0.952	+0.174	(-0.35)	
-17°484	-0.169	0.682	+0.324	-1.79	high vel.
-13°482	-0.148	0.630	+0.258	-1.57	high vel.
-26°957	0.114	0.774	+0.163	-0.39	
G4-37	-0.105	0.699	+0.279	-1.37	high vel.
+33°529	1.401	1.727	....	....	high vel., too red
-13°544	0.848	1.107	+0.067	(∿solar)	
+25°495	-0.147	0.733	+0.360	-1.73	high vel.
G78-26D	1.430	1.620	....	....	high vel., D, too red
+11°468	-0.063	0.805	+0.396	-1.55	high vel.
G5-36	-0.036	0.774	+0.318	-1.28	high vel.
G38-1	1.428	1.739	....	....	high vel., too red
- 7°603	0.178	0.860	+0.241	(-0.6)	
- 3°592	0.023	0.768	+0.243	-0.86	high vel., F9V
+34°796	0.575	1.191	+0.510	-1.81*	high vel., KIV, sp. abun.
+21°607	-0.100	0.674	+0.246	-1.25	high vel.
G175-39	1.023	1.118	-0.087	(>+0.25)	
+45°992	0.128	0.822	+0.230	(-0.6)	
G102-22	1.251	2.127	....	....	high vel., too red
G99-31D	0.152	0.828	+0.219	(-0.5)	high vel., D
+37°1312	0.792	1.048	+0.011	(∿+0.25)	
+19°1185	0.122	0.878	+0.325	(-1.0)	high vel.
- 0°1520	0.114	0.775	+0.165	-0.40	high vel.
+47°1419	0.155	0.785	+0.142	-0.26	
-33°4113	0.057	0.779	+0.229	-0.74	high vel., G0V
+31°1684	0.045	0.895	+0.435	(-1.5)	high vel.
- 1°1883	0.364	0.967	+0.265	(-0.8)	
+29°1664	0.396	0.962	+0.222	(-0.5)	high vel., G8V
G194-22	-0.102	0.710	+0.286	-1.38	high vel.
- 3°2333	0.029	0.669	+0.112	-0.31	
HD 74000	-0.143	0.648	+0.265	-1.52	high vel.
G115-22	0.034	0.825	+0.328	(-1.1)	high vel.
+25°1981	-0.077	0.502	+0.171	-1.41	high vel.
+42°1922	1.077	1.206	+0.035	(∿solar)	
-12°2669D	-0.098	0.479	+0.195	-1.83	high vel., D
G46-5	0.372	0.987	+0.300	(-1.1)	high vel.
G114-26	-0.103	0.747	+0.339	-1.54	high vel.
G115-49	-0.117	0.762	+0.376	-1.68	high vel.
+ 9°2190	-0.132	0.623	+0.238	-1.43	high vel.
G48-29	-0.157	0.593	+0.256	-1.78	high vel.
HD 84937	-0.130	0.617	+0.233	-1.43	high vel.
+44°1910	-0.139	0.688	+0.301	-1.58	high vel.
+23°2207	0.062	0.684	+0.096	-0.20	
G119-32	-0.082	0.724	+0.283	-1.28	high vel.
G196-47	0.030	0.862	+0.392	(-1.35)	high vel.
+21°2247	-0.091	0.704	+0.269	-1.28	high vel.

TABLE 1 (Continued)

Name	37-45	45-63	δ(37-45)	[Fe/H]	Notes
G10-4	0.066	1.040	+0.721	(<-2.0)	high vel., reddened
+36°2165	-0.102	0.626	+0.209	-1.18	high vel.
+26°2251	-0.027	0.711	+0.212	-0.87	high vel.
+51°1696	-0.028	0.840	+0.416	(-1.5)	high vel.
BS4550	0.390	1.003	+0.319	(-1.2)	high vel.
G13-9	-0.127	0.597	+0.227	-1.48	high vel.
G11-44	-0.116	0.706	+0.296	-1.47	high vel.
HD 106038	-0.078	0.722	+0.277	-1.26	high vel.
HD 108177	-0.121	0.698	+0.294	-1.48	high vel.
+40°2570	0.120	0.749	+0.115	-0.20	
G60-48	-0.138	0.738	+0.358	-1.70	high vel.
- 9°3595	0.592	1.028	+0.170	(-0.5)	
+10°2519	0.177	0.867	+0.252	(-0.7)	
G14-45D	1.092	1.274	+0.151	....	high vel., D., too red
+34°2476	-0.135	0.636	+0.247	-1.44	high vel.
G65-22	0.303	0.958	+0.307	(-1.0)	high vel.
G64-37	-0.110	0.598	+0.210	-1.33	high vel.
-13°3834	0.014	0.857	+0.401	(-1.4)	high vel.
+ 1°2920	0.246	0.841	+0.145	(-0.2)	
+30°2536	-0.010	0.537	+0.104	-0.51	
G66-22	0.329	0.974	+0.315	(-1.1)	high vel.
+26°2606	-0.136	0.687	+0.297	-1.55	high vel.
- 8°3858	0.367	0.950	+0.224	(-0.5)	high vel.
-21°4009	-0.038	0.809	+0.378	-1.43	high vel.
+25°2873	0.066	0.618	+0.037	+0.07	
-15°4041	0.648	1.132	+0.321	(-1.8)	abun. from -15°4042
-15°4042	0.417	1.037	+0.363	(-1.8)	high vel.
G15-24	0.033	0.849	+0.372	(-1.3)	high vel.
-10°4149	-0.134	0.793	+0.446	-1.90	high vel.
+42°2667	-0.064	0.725	+0.265	-1.16	high vel.
+39°2947	0.423	0.982	+0.238	(-0.7)	
+39°2950	1.127	1.224	+0.018	(~+0.2)	
G168-42	0.255	1.010	+0.469	(<-2.0)	high vel., reddened?
G180-58	0.074	1.029	+0.691	(<-2.0)	high vel., reddened
- 3°3968	0.350	1.018	+0.390	(-1.8)	high vel.
+37°2804	0.738	1.034	+0.035	(+0.1)	
+43°2659	0.229	0.853	+0.178	(-0.4)	
+17°3154	0.228	0.847	+0.170	(-0.3)	
+ 1°3421	0.116	0.805	+0.217	-0.59	high vel.,G0V
G170-56	-0.043	0.719	+0.238	-1.01	high vel.
+ 2°3375	-0.120	0.719	+0.315	-1.53	high vel.
+37°2926	0.112	0.788	+0.191	-0.50	high vel., G0V
+25°3344	-0.008	0.293	+0.142	(<-2.0)?	high vel., evolved
G20-15	0.030	0.925	+0.507	(-1.9)	high vel., reddened
G183-11D	-0.113	0.654	+0.241	-1.30	high vel., D
G154-36	0.101	0.904	+0.396	(-1.3)	high vel.
+13°3683	-0.002	1.018	+0.742	(<-2.0)	high vel., reddened
G206-34D	-0.127	0.687	+0.288	-1.50	high vel., D
+20°3926	0.081	0.643	+0.037	+0.08	
AC+20°1463-148	1.713	2.074	....	....	too red

TABLE 1 (Continued)

Name	37-45	45-63	δ(37-45)	[Fe/H]	Notes
AC+20°1463-154	1.591	2.102	....	....	too red
+41°3306	0.618	1.059	+0.205	(∼-0.9)	high vel., K0V
+11°3833	0.630	0.960	-0.016	(>+0.25)	high vel., G8IVp
+10°4091	0.032	0.874	+0.409	(-1.4)	high vel.
+ 5°4481	0.100	0.810	+0.239	-0.69	high vel.
-21°5703	-0.055	0.808	+0.391	-1.51	high vel.
+41°3735	0.119	0.895	+0.361	(-1.2)	high vel., evolved
+ 9°4529	-0.062	0.680	+0.216	-1.00	high vel.
- 9°5491	-0.023	0.931	+0.572	(<-2.0)	high vel., evolved
+17°4519	-0.035	0.728	+0.241	-0.99	high vel.
G188-30	0.079	0.964	+0.543	(<-2.0)	high vel., dG2, reddened
G126-62	-0.081	0.691	+0.246	-1.17	high vel.
G18-39	-0.085	0.673	+0.229	-1.13	high vel.
- 8°5980	0.267	0.851	+0.139	(-0.2)	high vel., G6V
G28-43	0.226	0.965	+0.398	(-1.45)	high vel.
G190-15	-0.006	0.977	+0.655	(<-2.0)	high vel., reddened
-14°6437	-0.090	0.733	+0.303	-1.37	high vel.
+26°4734	0.240	0.922	+0.292	(-0.8)	
BS77	0.147	0.806	+0.186	-0.43	
BS219D	0.153	0.795	+0.161	-0.34	D
BS1008	0.391	0.945	+0.189	(-0.4)	
BS6752D	0.793	1.102	+0.113	(∼-0.6)	D
BS6927	0.039	0.714	+0.149	-0.44	
BS8181	-0.003	0.721	+0.200	-0.75	

and ultraviolet excess for this star are not consistent with any logical extrapolation of the calibration.

We have estimated that for *45–63* < 0.81 our calibration gives an [Fe/H] value with a standard deviation of ± 0.1-0.2 for one star, and so in this range the [Fe/H] values have been given to two decimal places. For $0.81 <$ *45–63* < 1.04 the standard error is larger, maybe ± 0.2-0.3, and the values are given to only one decimal place with parentheses to denote greater uncertainty.

Eighty-eight of the stars in Table 1 are found in Eggen's (1964) catalogue of high-velocity stars and so may belong to the halo population of our galaxy. However, four of the 88 stars have contaminated photometry, five are too red for our composition calibration, ten do not have subdwarf classifications, and three, +25°3344, +41°3735, and −9°5491, are greatly evolved being red giants or horizontal branch stars. Six stars with [Fe/H] < -2.0 were also excluded since five of these belong to group 4 of paper 1 (Schuster 1979*a*) which are all reddened stars; G168-42 also has a very large δ(*37–45*) with G (gravity index) and *45–63* values similar to those of group 4, indicating reddening. The least extreme star of group 4, G20-15, has [Fe/H] = (— 1.9), is probably somewhat reddened, but has been left in the sample since it will not greatly bias our final results. All seven of the above stars would have less extreme [Fe/H] values when dereddened; however, we can only roughly estimate the degree of reddening and so have not attempted to correct the [Fe/H] values. We are left with 60 high-velocity stars all of which have subdwarf spectroscopic classifications according to Eggen (1964), Roman (1955), or Eggen and Sandage (1959).

With only 60 subdwarfs in our high-velocity sample we are necessarily limited as to the decisiveness of our arguments. Several of our conclusions will be weaker than we would like due to the possible effects of statistical fluctuation.

In Figure 1*a* we plot a histogram of number versus [Fe/H] for the stars of Table 1 excluding only evolved stars, stars with contaminated photometry, reddened stars, and stars with [Fe/H] $> +0.0$. The

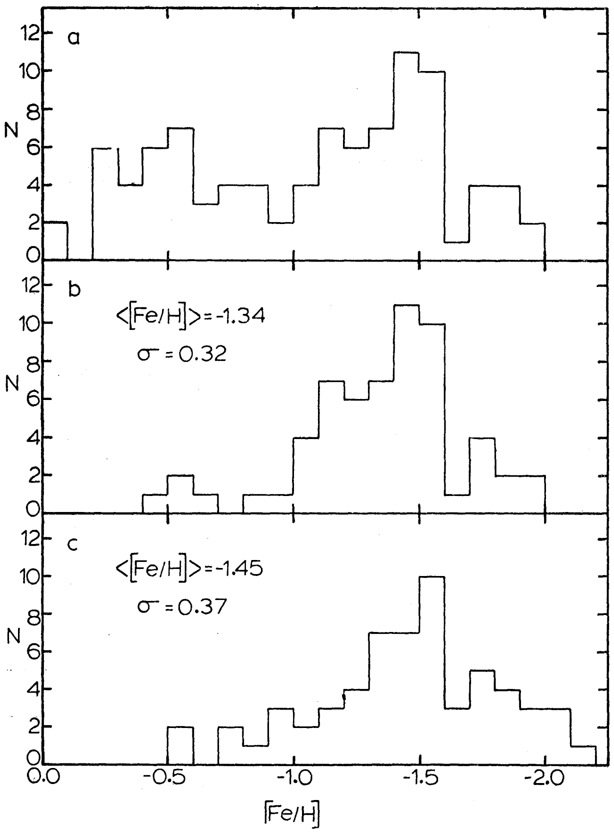

FIG. 1. Frequency-[Fe/H] histograms. (a) For the stars of Table 1 excluding only three evolved stars, six with contaminated photometry, six reddened stars, and eight with [Fe/H] $>$ +0.0. (b) For the final set of 60 high-velocity subdwarfs. (c) For the halo globular clusters as determined by Hartwick (1976).

distribution of Figure 1*b* shows our final sample of high-velocity subdwarfs, and Figure 1*c* gives the distribution for the halo globular clusters (types H and h of Woltjer 1975) as determined by Hartwick (1976). The sample of halo globular clusters is approximately 70% complete and is very representative of the halo, globular-cluster stars. Our sample of high-velocity subdwarfs includes stars from only a limited region around the Sun. Also, since our sampling point for the subdwarfs is located in the galactic disk we would expect that unless we have chosen our kinematic criterion well enough (space motions greater than 100 km/sec with respect to the Sun, Eggen 1964) the average population type for our high-velocity subdwarfs would be somewhat less extreme than for the H- and h-type globular clusters. The distribution of Figure 1*b* does show a less extreme average metal deficiency than the distribution of 1*c*.

We argue that observational selection effects do not bias seriously any of the [Fe/H] distributions for the more extreme high-velocity groups such as Figure 1*b* (or in Table 3). As discussed by Eggen *et al.* (1962) the selection of the vast majority of high-velocity stars depended upon proper motions prior to the existence of accurate photometry for the stars. Ultraviolet excesses did not play a part in the selection of these stars. In Figure 2 we give the histogram of number versus proper motion (Eggen 1964) for our high-velocity sample. We are not surprised to see a sharp drop in the numbers for proper motions less than 0″300/yr. Also, Figures 4 and 6 of Eggen *et al.* (1962) show that for the more extreme high-velocity stars the ultraviolet excess is independent of the kinematics. Hence, if we have overlooked any stars at the less-extreme limits of our kinematic criteria, the [Fe/H] distributions will not be seriously affected. For these reasons we believe that the shapes and dispersions of these distributions for the more extreme high-velocity groups are free from significant observational biases.

We note in Figures 1*b* and 1*c* that the distributions are approximately lognormal and that few subdwarfs or globular clusters are observed to have [Fe/H] < -2.0. This is surprising if we assume that the protogalactic gas was initially metal-free. The distribution of metal abundances for all stars near

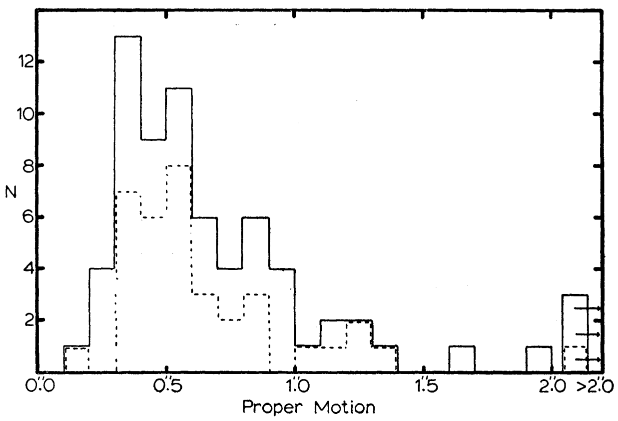

FIG. 2. Frequency-proper motion histograms. The solid line plots the high-velocity stars. The dotted line shows the subset of subdwarfs with $V \leqslant -215$ km/sec.

the Sun is also lognormal but has a much different average abundance (Dixon 1966); very few stars with [Fe/H] < -0.5 have been found. A constant initial mass function (IMF) does not lead to this paucity of metal-poor G and K stars for the solar vicinity; many attempts to resolve this 'G-K dwarf problem' have been made (see Pagel and Patchett 1975; Audouze and Tinsley 1976 and references therein.) Perhaps the very low incidence of extremely metal-poor stars ([Fe/H]) < -2.0) in the halo is analogous to the paucity of metal-poor G and K stars in the solar neighborhood, and both have a similar explanation. For example, arbitrarily few small-mass, metal-poor stars can be produced in a model by requiring that no stars with $M \sim 1M_\odot$ form until the metal abundance reaches some given level (Audouze and Tinsley 1976; Biermann and Tinsley 1974). However, to explain the large difference in mean [Fe/H]'s between the halo and disk distributions, we need some other physical variable. Van den Bergh (1973, 1975) claims that the IMF depends upon the average density of the star forming region with massive stars dominating in high density cases and low-mass stars dominating for low density. Such a mechanism explains the M/L and composition gradients observed in galaxies and the fact that the more massive galaxies have the more metal-rich globular clusters. Hence to explain the [Fe/H] distributions of both the halo and disk we may need a variable IMF that depends both on composition and density. In the halo the critical composition for the formation of low-mass stars was significantly more metal deficient than for the disk since the average density was considerably lower.

TABLE 2

STARS WITH [Fe/H] ⩽ -2.0 ACCORDING TO SPECTROSCOPIC STUDIES

Name	[Fe/H]	Comments	References
Stars whose Spectroscopic [Fe/H]'s have always been ⩽ -2.0			
HD 122563	-2.65 -2.7 -2.7 -2.72 -2.6	Halo red-giant star.	Morel et al. (1976) and references included therein; Wallerstein and Helfer (1966)
HD 128279	-2.05	Subgiant; log g= 3.5.	Spite and Spite (1975)
HD 165195	-2.5	Red-giant star	Wallerstein et al. (1963); Wallerstein and Helfer (1966)
HD 221170	-2.5	Red-giant star.	Wallerstein et al. (1963); Wallerstein and Helfer (1966)
+39°4926	-2.9 -2.14	He-C-N-O rich supergiant.	Kodaira (1973); Kodaira et al. (1970)
M92 III-13	-2.1 -2.3	Globular cluster red-giant star.	Helfer et al. (1959); Wallerstein and Helfer (1966); Pagel (1966, 1970)
Stars whose Spectroscopic [Fe/H]'s have sometimes been ⩽ -2.0			
HD 19445	-1.75 -0.77 -1.75 -2.55	Subdwarf; not greatly evolved.	Morel et al. (1976) and references included therein; Schuster (1979a)
HD 25329	-2.30 -1.32	Subdwarf; unusual [N/Fe].	Heiser (1960); Pagel and Powell (1966); Harmer and Pagel (1970)
HD 140283	-2.00 -2.48 -1.04 -2.03 -1.69	Subdwarf?; probably metal-poor subgiant.	Morel et al. (1976) and references; Schuster (1979a)

In Table 2 we examine further the existence of stars with [Fe/H] < -2.0. The first six stars are all evolved and so span a much larger volume of space than the subdwarfs of Table 1 but smaller than the globular cluster system whose [Fe/H]'s are plotted in Figure 1*c*. The last three stars of Table 2 are much less evolved being unevolved subdwarfs and one metal-poor subgiant. Probably all of the stars of Table 2 have masses of approximately $1M_\odot$; Wallerstein *et al.* (1963) suggest that HD122563, HD165195, and HD221170 have masses of approximately $1.1M_\odot$, similar to the masses of the red giants in globular clusters. The fact that we can find field stars with more extreme metal deficiencies than the most extreme globular clusters agrees with our suggestion that the formation of stars with $M \sim 1M_\odot$ is controlled by a density-dependent threshold. Field densities in the outer halo were lower than the densities in regions of cluster formation.

However, the U-B, B-V diagram of Figure 3 suggests an alternate interpretation. In Figure 3 the lower Hyades line comes from Johnson (1966) and Sandage (1969), the maximum abundance effect (MAE) from Sandage (1969), and the average globular cluster lines from the main sequence photometry of Sandage (1970). Also plotted are the colors of individual main sequence stars from M92 (Sandage 1970) and high-velocity subdwarfs from Table 1 (Eggen 1964). According to the compilation of data

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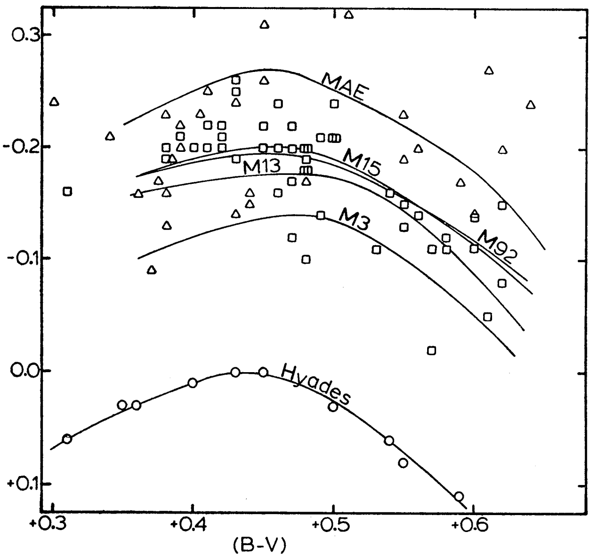

FIG. 3. *U-B* versus *B-V* diagram including average main sequence lines for M3, M13, M15, and M92 (Sandage 1970) and the maximum abundance effect (MAE, Sandage 1969). The squares represent the high-velocity subdwarfs and the triangles individual main sequence stars from M92.

by Hartwick (1976) M3, M13, M15 and M92 have the [Fe/H] values of −1.33, −1.36, −2.04, and −2.11, respectively, while according to our calibration the 25 subdwarfs lying above the M92 line in Figure 3 have the mean [Fe/H] = — 1.47. This result suggests that systematic differences of 0.4 to 0.6 may exist between the spectroscopic [Fe/H]'s obtained for unevolved and evolved metal-poor stars. The globular cluster compositions listed by Hartwick (1976) have all been obtained from spectroscopic or photometric studies of the more evolved cluster members, and in several cases the evolved stars of Table 2 have been used to calibrate the photometric indices. Perhaps due to the weakness of spectral lines in such objects systematic differences in the assignment of excitation temperatures has occurred between the evolved and unevolved objects leading to systematic differences in the [Fe/H]'s. However, in Figure 3 (and Figure 15 of Sandage 1970) the photometry of the individual main sequence stars shows considerable scatter about the mean curves. All of this photoelectric data was obtained with a D. C. amplifier and a strip-chart recorder, and Sandage (1970) suggests that some of the *U-B* values for the main sequence stars may not be precise enough and should be remeasured with pulse counting techniques. Also, for [Fe/H] < −1.5, δ *(U-B)* is less sensitive to changing metallicity than for less extreme compositions (Wallerstein 1962, Figure 9).

III. COMPOSITIONS, KINEMATICS AND THE (G, *45–63*) DIAGRAM

In Figure 4*a* is plotted the (G, *45–63*) diagram for the stars of Table 1 with the same outer envelope as paper 1 (Schuster 1979*a*). In Figure 4*b* we plot only the high-velocity stars (Eggen 1964), distinguishing between those with

$$[\mathrm{Fe/H}] \leqslant -1.0 \text{ and } [\mathrm{Fe/H}] > -1.0.$$

The kinematic parameters which Eggen (1964) gives are based on m-M's derived by force-fitting to the Hyades main sequence after applying the blanketing corrections of Wildey *et al.* (1962, Table 4). The analysis of Eggen and Sandage (1962) shows that this is a good working technique for an average subdwarf at the hotter temperatures. However, the method does not take into account the range of evolution for a given temperature as discussed in paper 1 or as shown here in Figure 4. Also, the method probably breaks down for the cooler subdwarfs (Eggen 1973). We have differentially corrected the m-M's of Eggen (1964) using Figure 4 with the main sequence and subgiant M's of Blaauw (1963). This technique is somewhat crude, but should improve the m-M's. All of the kinematic parameters used in the following analyses are based on the revised m-M's.

In Figure 4b the region 'R' includes stars which may be reddened (Schuster 1979*a*); six of these stars will be excluded from further analysis as discussed above. Region 'T' contains stars which may be in the same age sequence as the turnoff at *45–63* = 0.59, and region 'E' includes evolved stars which are too red to be associated with this turnoff; the eight most-evolved subdwarfs from 'group 3' of paper 1 (Schuster 1979*a,* Figure 14) are all found in region 'E'.

In Figure 5 we plot [Fe/H] distributions obtained by dividing the high-velocity stars at approximately the median values of V and |W|, where V is a star's velocity in the direction of galactic rotation (which is directly related to the angular momentum of a star's galactic orbit) and W is the velocity perpendicular to the galactic plane. Only stars that are reddened, have contaminated photometry, or are greatly evolved have been excluded. We see that the V velocity criterion produces two significantly different [Fe/H] distributions indicating that the high-velocity group contains stars from a range of population types. Greatly differing [Fe/H] distributions are not produced by the |W| criterion. These results could have been anticipated by examining Figures 5 and 6 of Eggen *et al.* (1962).

The subdwarfs +54°223, −0°1520, −8°3858, and +5°4481, as well as the nine high-velocity nonsubdwarfs, are not members of the extreme halo population such as the H-type globular clusters of Woltjer (1975). They probably are members of a transitional population such as the D-type globular clusters or the members of Bingham and Martin's (1974) 'superdisk'. The thirteen stars are all found in the less extreme group of Figure 5*a*, all have [Fe/H] > −1.0, and all remain within 1.5 kpc of the galactic plane (Eggen *et al.* 1962). The H and h clusters have ⟨z⟩ = 5 kpc while the D clusters ⟨z⟩ = 2 kpc (Woltjer 1975). The four subdwarfs are those of Figure 1*b* with [Fe/H] < — 0.7. +54°223 (μ Cas, HD 6582) has been called a subdwarf (or mild subdwarf) by many investigators (Worek and Beardsley 1977; Cohen 1968; Catchpole *et al.* 1967 and others) while Cayrel (1968), Hoffleit (1964), and Sandage and Smith (1963) have given its spectral type as G5Vp, and Eggen (1973) placed it with the old disk stars rather than with the halo stars. Eggen (1964) noted that −0°1520 is unusual having a large eccentricity in its galactic orbit but a small ultraviolet excess. Sandage (1969) found that +5°4481 (G24-13) is a high-angular-momentum star (V + 15 > 0; our results give V + 15 = −34) with a moderately large ultraviolet excess; the collapse theory of Eggen *et al.* (1962) predicts that such

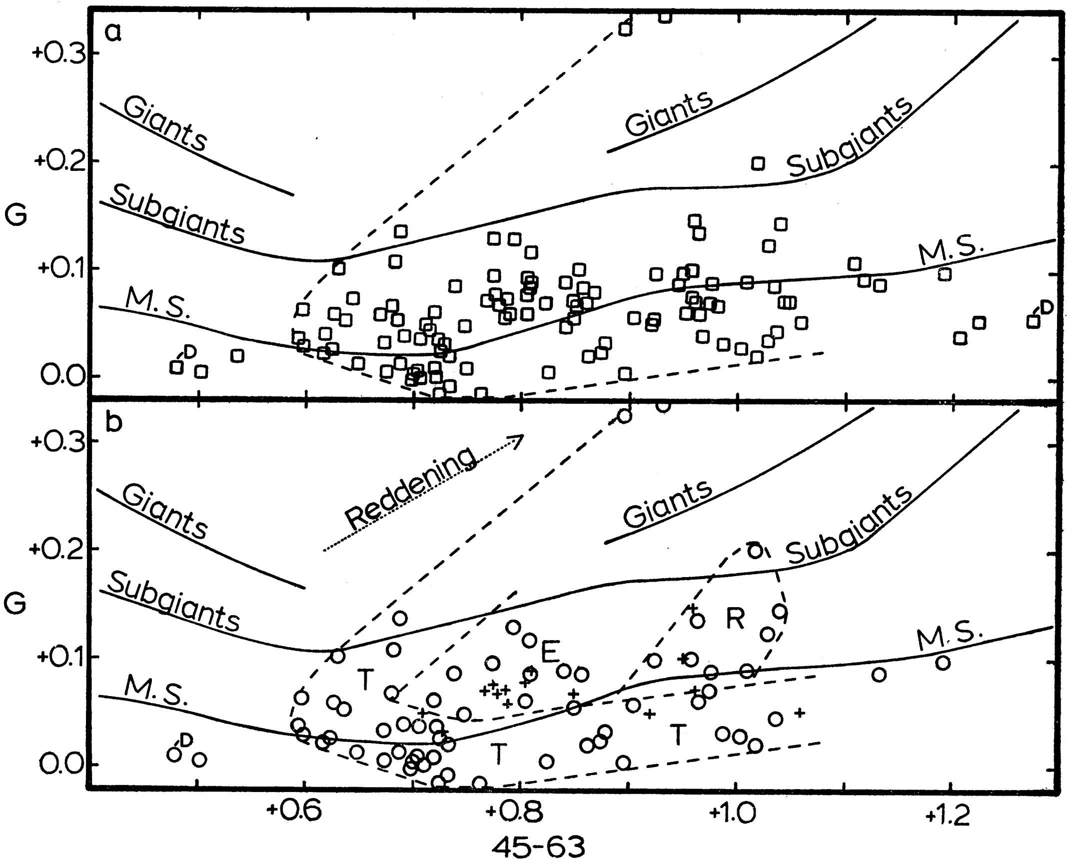

FIG. 4. (G, *(45–63)* diagrams. (a) Includes the stars of Table 1 except those which are too red or which have contaminated photometry. (b) Includes only stars which are found in Eggen's (1964) catalogue of high-velocity stars. Circles are for stars with [Fe/H] ⩽ −1.0 and crosses [Fe/H] > −1.0. The regions T, E, and R. are discussed in the text.

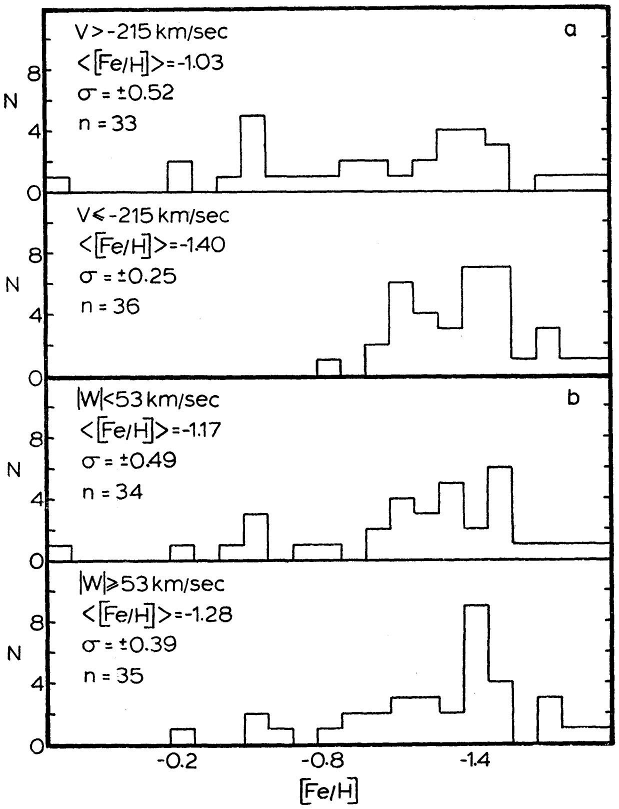

FIG. 5. Frequency-[Fe/H] histograms as a function of kinematic criteria. V is the velocity in the direction of galactic rotation, and W is the velocity perpendicular to the galactic plane.

stars should exist, but few have been found in the solar neighborhood.

In Figure 6 we replot part of Figure 4*b* separating the high velocity stars according to the two kinematic criteria. We see that in both cases a majority of the stars near the turnoff fall in the more extreme kinematic group. Also, the criterion $V \leqslant -215$ km/sec clearly separates the stars of group E between those with [Fe/H] $\leqslant$ — 1.0 and those with [Fe/H] > -1.0. The only exception is G170-56 with [Fe/H] $= -1.01$ and with the bluest *45–63* of group E. According to the discussion of paper 1 (Schuster 1979*a*) the stars of group E with [Fe/H] $\leqslant -1.0$ are at least 2×10^9 years older than those evolving from the turnoff of group T and may be some of the oldest stars of our Galaxy with ages close to that of the universe. However, the group E members with $V > -215$ km/sec are on the average a factor of ten less metal deficient (see Table 3), and so according to the isochrones of Demarque (1967) have approximately the same age as the turnoff stars. Finally, the nine stars of group E with $V \leqslant -215$ km/sec have especially low angular momenta in their galactic orbits. Their average V is approximately 90 km/sec more negative than the average of the group T stars with $V \leqslant -215$; seven of the nine have retrograde orbits in the galaxy. According to the original kinematics of Eggen (1964) only five of these stars had retrograde orbits, and their average V was little different from that of the other stars.

In Table 3 we give the parameters of [Fe/H] distributions for several groups of high-velocity stars. The age sequences were chosen using Figures 4*b* and 6 and the kinematic groups were derived using the two kinematic criteria, $V \leqslant -215$ km/sec and $|W| \geqslant 53$ km/sec. Kinematic group 2 stars satisfy both criteria, group 1 stars only one of the criteria, and group 0 stars neither. The standard deviations show a definite increase from kinematic group 2 to group 0, and the average [Fe/H]'s become less deficient. As discussed above, these changes are caused by the mixing in of stars from a less extreme population, transitional between the halo and old disk.

TABLE 3

COMPOSITION DISTRIBUTIONS AS A FUNCTION OF KINEMATICS AND AGE SEQUENCES.

Group	Comments	Ave[Fe/H]	σ	n
0	Kinematic group	−0.94	±.53	18
1	Kinematic group	−1.29	±.41	31
2	Kinematic group	−1.38	±.24	20
T	Age Sequence	−1.34	±.27	45
E	Age Sequence	−1.06	±.54	18
T	$V \leqslant -215$ Km/sec	−1.36	±.24	26
E	$V \leqslant -215$ Km/sec	−1.53	±.18	9
T	$V > -215$ Km/sec	−1.31	±.31	19
E	$V > -215$ Km/sec	−0.58	±.27	9
T	$\lvert W \rvert \geqslant 53$ Km/sec	−1.37	±.26	23
E	$\lvert W \rvert \geqslant 53$ Km/sec	−1.05	±.52	8
T	$\lvert W \rvert < 53$ Km/sec	−1.31	±.29	22
E	$\lvert W \rvert < 53$ Km/sec	−1.07	±.58	10

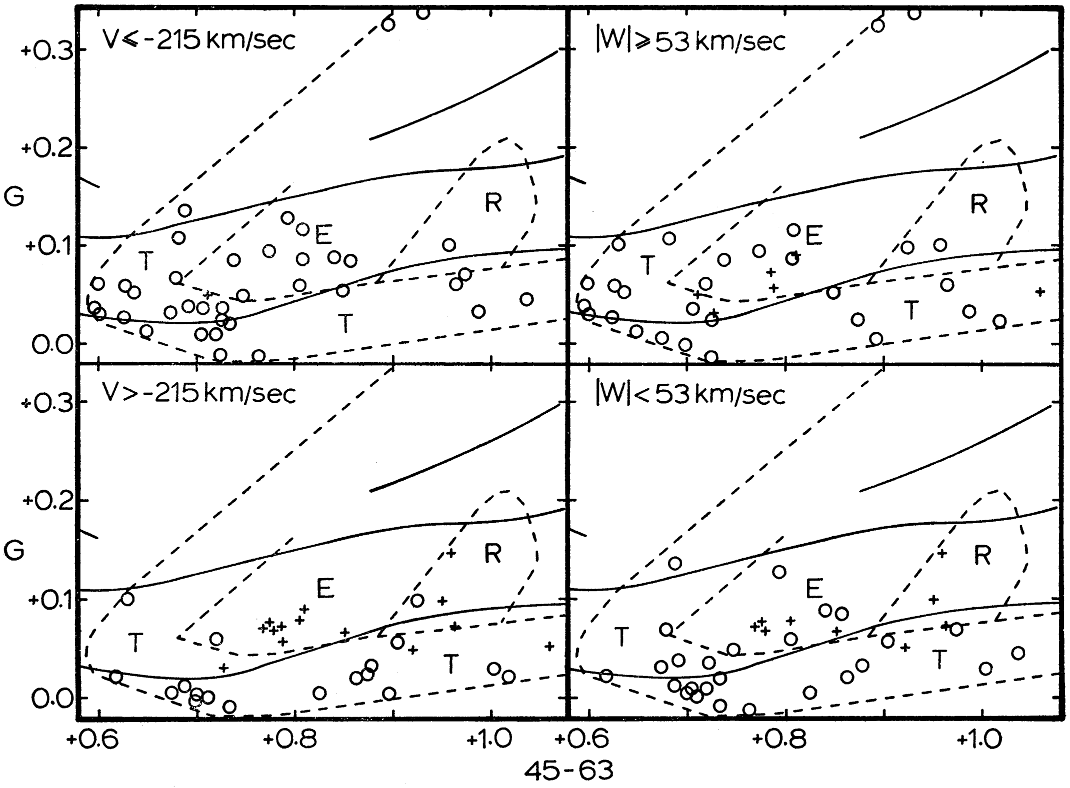

FIG. 6. (G, *45–63*) diagrams as a function of kinematic criteria. Only high-velocity stars are plotted. The symbols are the same as in Figure 4b.

For the age sequence groups of Table 3 the greatest metal deficiency and smallest standard deviation occur for group E with $V \leqslant -215$ km/sec and the smallest deficiency is found for group E with $V > -215$ km/sec. Comparing groups T and E for $V \leqslant -215$ we see only a small but perhaps statistically significant difference between the mean [Fe/H]'s. A t-distribution test shows that such a difference could occur approximately 7% of the time purely by chance.

We note in Table 3 that the standard deviations of the more extreme groups fall in the range ± 0.18 to ± 0.27. In paper 2 (Schuster 1979*b*) we estimated that the observational errors for [Fe/H] would be approximately ± 0.1-0.2 for $45\text{–}63 < 0.81$ and about ± 0.2-0.3 for $45\text{–}63 > 0.81$. These results suggest that the natural plus enrichment dispersion in the [Fe/H] values must be small. For example, if we assume that the lower limit for observational plus natural dispersion is $\sigma = \pm 0.17$ according to the work of Pagel and Patchett (1975), we obtain $\sigma = \pm 0.06$ to ± 0.21 due to enrichment with time. Our value for σ_{en} is significantly less than the values of 0.26 to 0.33 which Hartwick (1976) obtained from the H- and h-type globular clusters. This result suggests either that our kinematic criteria and our age sequences have isolated a more extreme population which formed during a much shorter interval of time than for the cluster sample or that enrichment in the halo occurred much faster in globular clusters than in the field. The first possibility does not agree with the conclusions of paper 1 that the metal-poor subdwarfs formed over a considerable interval of time. The latter possibility does agree well with van den Bergh's (1973, 1975) suggestion that the formation of more massive stars is favored by higher densities.

IV. CONCLUSIONS

We stress again that our comparisons of compositions and kinematics for the subdwarfs carry limited weight due to the small number of stars in our sample.

Many of our conclusions are necessarily provisional. Yet, the [Fe/H] distributions as a function of the kinematic criteria suggest that even our sample of high-velocity subdwarfs includes stars from a range of populations. Most are probably members of the extreme halo population, but several are certainly less extreme being in a transitional population. Probably these should be classified as intermediate Population II stars.

We saw in Figure 1 that the subdwarf and globular cluster numbers drop sharply for $[\mathrm{Fe/H}] < -1.6$, and none are found for $[\mathrm{Fe/H}] < -2.2$. This is perhaps analogous to the absence of metal-poor stars in the solar neighborhood, and both may have been caused by an IMF that varied with composition and density during the formation of the Galaxy's halo and disk. However, a few evolved field stars with $M \sim 1 M_\odot$ and with $[\mathrm{Fe/H}] < -2.2$ have been observed, but from our discussion of Figure 3 we cannot conclude whether such extreme deficiencies are real or whether systematic differences in the [Fe/H] values exist between evolved and unevolved metal-poor stars.

The V velocity separates differing populations much more clearly than $|W|$ as seen in Figure 5, and V also distinguishes more clearly between the differing metallicities of group E. The stars of group E with $V \leqslant -215$ km/sec are some of the oldest in the Galaxy, have on the average the greatest metal deficiencies and the smallest dispersion of such deficiencies, and belong to a galactic component with a very low, even negative, average angular momentum. The stars of group E with $V > -215$ km/sec include six non-subdwarfs, have metal deficiencies which are on the average almost a factor of ten less than the other stars of group E, show kinematics less extreme than for most other high velocity stars, and have ages approximately equal to that of the turnoff of group T. This indicates that some of the intermediate Population II or old disk stars have ages similar to those of the younger halo stars.

Finally, there is evidence that metal enrichment occurred very slowly amongst the halo field stars, more slowly than in the globular clusters. First, for the stars with $V \leqslant -215$ km/sec there is a difference of at least 2×10^9 years between the ages of groups E and T (Schuster 1979*a*), and yet their average [Fe/H]'s differ by less than 0.2. Second, the [Fe/H] standard deviations of the more extreme high-velocity groups, chosen according to kinematics or age sequences, are significantly lower than the standard deviation for the H- and h-type globular clusters of Woltjer (1975). If we assume that the observational and natural deviations are the same for stars and clusters, we obtain significantly different values for σ_{en}, the enrichment dispersion.

However, such comparisons might be biased by physical sampling effects. The globular cluster sample is nearly complete for the entire Galaxy while the subdwarfs are mostly those with orbits having apogalactica of approximately 10 kpc and relatively small $|W|$'s; such stars spend more of their time near the solar orbit. For example, the H- and h-type clusters of Woltjer (1975) have an average distance from the galactic plane of about 5 kpc while the more extreme subdwarfs in our sample have an average *maximum* distance from the plane of only 2 kpc (Eggen *et al.* 1962, Figure 5).

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