1983ApJ...273..187P

THE ASTROPHYSICAL JOURNAL, **273**:187–194, 1983 October 1

THE CHEMICAL COMPOSITION OF DISTANT GLOBULAR CLUSTERS: ARE THERE ANY METAL-POOR CLUSTERS?[1]

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Received 1983 January 3; accepted 1983 March 21

ABSTRACT

We report echelle spectroscopy of giants in the distant globular clusters N4147, M53, N5466, and N6229. Abundances are determined from model atmosphere analyses of the equivalent widths of the metal lines. Our analyses yield [Fe/H] values in the range of -1.3 to -1.9. These values are moderately high for clusters at these galactocentric distances ($R \sim 20$ kpc). In particular, these data argue against the existence of a strong metallicity gradient in the halo. These data may also suggest that the cluster system of the Galaxy predates the formation of the bulge and halo system.

Subject headings: clusters: globular — galaxies: stellar content — stars: abundances

I. INTRODUCTION

An accurate determination of globular cluster metal abundances is important in understanding the early evolutionary history of the Galaxy. The presence or absence of a metallicity gradient in the globular cluster system of the Galaxy can help constrain various formation theories. In addition, accurate abundances are prerequisites for determining reliable cluster ages. This is crucial in helping to resolve the present conflict that exists between recent estimates of the global value of H_0 and suspected globular cluster ages.

Abundances of globular clusters were originally ascertained via analysis of color magnitude diagrams or integrated light properties. Various photometric and spectroscopic systems have more recently been devised to measure the metal abundances of individual stars in globular clusters (cf. Canterna 1975; Butler 1975; Searle and Zinn 1978); each system, however, has limitations on its applications. Zinn (1980*a*) has improved techniques for integrated light measurements using a narrow band photometric index centered on the calcium H and K lines. However, clusters of apparently similar metal abundance often exhibit quite different populations of stars on the horizontal branch (Faulkner 1966; Sandage and Wildey 1967), and the horizontal-branch morphology may affect the integrated light. While the color of the horizontal branch was once thought to be an indicator of metallicity, recent observations cast doubt that metal abundance is even the dominant factor controlling horizontal branch morphology.

The best way of therefore determining cluster abundances is the most direct: Cohen (1978, 1979, 1980), Pilachowski, Wallerstein, and Leep (1980), and Pilachowski, Sneden, and Wallerstein (1983, hereafter PSW) have all determined cluster abundances through high-dispersion spectroscopy of individual stars. Because these observations are time consuming, only a handful of cluster red giants have been observed at present. Here we report MMT echelle observations of giants in the distant globular clusters N4147, M53, N5466, and N6229.

II. SPECTROSCOPY OF GLOBULAR CLUSTER STARS

Observations of giants in the globular clusters N4147, M53, N5466, and N6229 were obtained with the echelle spectrograph on the Multiple Mirror Telescope located at the Fred Whipple Observatory on Mount Hopkins. The high efficiency of the MMT echelle spectrograph allows relatively faint stars to be reached. Typically, the stars that we observed had $m_V \sim 14$, and exposure times were 2 or 3 hr. Under optimum conditions, three spectra can be obtained per night. Excellent observing conditions, avoiding full moonlight, and even partial moonlight with cirrus, are required for these faint stars. Unfortunately, the weather was usually miserable while this program was scheduled on the MMT, so our sample is smaller than we had originally hoped. Thus, although these results are interesting, they should nevertheless be considered preliminary.

Figure 1 presents an example of the quality of the spectrum that we obtained with the MMT echelle

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[1] Research reported here utilized the Multiple Mirror Telescope operated jointly by the Smithsonian Astrophysical Observatory and the University of Arizona.

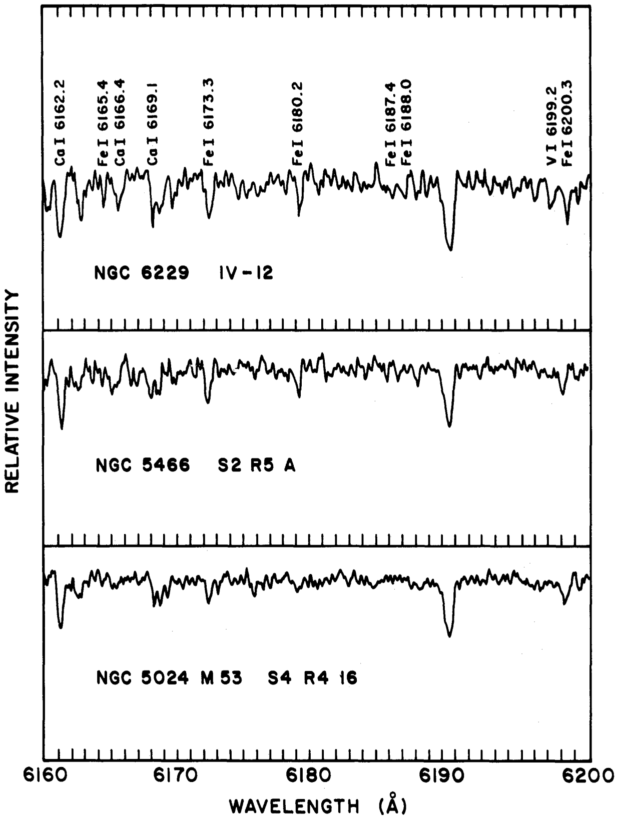

FIG. 1.—Examples of spectra used in this analysis. Spectra have been divided by the spectrum of a continuum lamp to remove the echelle blaze function and have been shifted in wavelength to align spectral features. Some atomic absorption features are indicated.

spectrograph. The spectra have been divided by the spectrum of a continuum lamp to remove both the echelle blaze function and the detector response. Spectra were obtained in three wavelength regions from 6120 Å to 6340 Å, but only two stars were observed in more than one spectral region. Each region gives about 50 Å of spectral coverage. This wavelength range was selected because it contains reasonable numbers of metal lines as well as a variety of species, including oxygen and sodium.

The spectrograph was used with the 79 l mm^{-1} echelle grating, the 300 l mm^{-1} cross disperser, and an intensified Reticon detector (Davis and Latham 1979; Latham 1982; Chaffee and White 1982). This observing configuration yields an effective resolution of 20,000, or ~0.3 Å. A summary of the observations is included as Table 1, which contains the dates of the observations, the central wavelengths of the spectra, the formal signal-to-noise ratio per pixel of the spectra, the measured radial velocities, and the cluster radial velocities as given by Webbink (1981). Note that a resolution element in these spectra is 6 pixels, so that the actual signal-to-noise ratio of the spectra is above 20/1. The echelle blaze function introduces a range of count rates from the edge to the center of the spectrum, and we have estimated the signal-to-noise ratio for an average count rate. The signal-to-noise ratio is better at the center of the spectrum and worse at the edges. We did not measure features in regions of signal-to-noise ratio below 15. Radial velocities were simply measured from the tracings after wavelength calibration and hence are not of high accuracy. They serve only to confirm cluster membership.

The raw data were reduced using software written for the KPNO Cyber computer. Because of the lengthy integration times and low count rates, long dark integrations were taken to allow subtraction of the dark counts. Equivalent widths were measured from the reduced spectra following procedures described in Pilachowski, Wallerstein, and Leep (1980). Equivalent widths are included in Table 2.

During the course of the program, three stars were identified which are not members of their respective clusters, despite the high galactic latitudes and the small scatter of stars in the color-magnitude diagrams. Star S1 R6 5 in the field of M53 and stars S3 R5 N and S1 R2 15 in the field of N5466 are not members of those clusters. Star S1 R2 15 in N5466 was identified as a nonmember from a spectrum obtained with the KPNO 4 m echelle spectrograph.

III. ABUNDANCES OF THE ELEMENTS

To derive the abundances of elements in these globular clusters, we have performed a differential curve of growth analysis using model atmospheres with the Sun as our comparison star. The analysis is based on the grid of model atmospheres published by Bell *et al.* (1976), including their solar parameter model for the Sun.

TABLE 1

SUMMARY OF OBSERVATIONS

Cluster	Star	Date (UT)	λ_c (Å)	Signal-to-Noise Ratio	R.V.$_*$ (km s^{-1})	R.V.$_{cl}$ (km s^{-1})
N4147	IV-30	1982 Apr 11	6140	10	+192	+182
M53	S4 R4 16	1981 May 12	6185	15	−62	−79
N5466	S4 R4 G	1982 Apr 11	6140	15	+111	+120
	S4 R4 G	1982 Apr 12	6305	14	+101	+120
	S2 R5 a	1981 Apr 23	6185	12	+104	+120
	S2 R5 a	1982 Apr 11	6140	12	+109	+120
N6229	IV-12	1981 May 12	6185	10	−139	−154

TABLE 2

EQUIVALENT WIDTH MEASUREMENTS[a]

Wave-length	Atom	Mult. No.	E.P. e.v.	N4147 IV-30	M53 S4R416	N5466 S4R4G	N5466 S2R5a	N6229 IV-12
6300.31	8.0	1	0.00	...	...	51	...	...
6154.23	11.0	5	2.09	...	...	39	61	...
6160.75	11.0	5	2.10	...	...	...	20	32
6122.22	20.0	3	1.88	133	...	143	124	...
6161.29	20.0	20	2.51	33	...	39	23	125
6162.17	20.0	3	1.89	154	131	151	165	...
6166.44	20.0	20	2.51	...	...	...	41	67
6169.06	20.0	20	2.51	...	58	...	83	104
6169.56	20.0	20	2.51	...	56	...	75	95
6193.67	21.0	3	0.00	...	...	...	19	...
6210.68	21.0	2	0.00	...	...	...	17	21
6305.67	21.0	2	0.02	...	...	33	...	...
6309.90	21.1	28	1.49	...	...	28	...	...
6126.22	22.0	69	1.06	22	...	24	...	...
6303.75	22.0	104	1.44	...	...	40	...	...
6119.51	23.0	34	1.06	...	...	25	...	...
6135.07	23.0	60	1.37	...	...	...	42	...
6135.36	23.0	34	1.05	...	...	23	...	...
6150.13	23.0	20	0.30	...	...	...	73	...
6199.20	23.0	19	0.29	...	...	...	...	83
6292.86	23.0	19	0.29	...	...	26	...	...
6330.10	24.0	6	0.94	...	...	34	...	...
6120.25	26.0	14	0.91	18	...	27	42	...
6130.37	26.0	624	3.24	...	...	...	50	...
6136.62	26.0	169	2.44	244	...	172	207	...
6137.00	26.0	62	2.19	131	...	99	104	...
6137.70	26.0	207	2.58	150	...	147	125	...
6147.85	26.0	1016	4.06	77	...	19	...	...
6151.62	26.0	62	2.17	81	...	82	95	...
6157.73	26.0	1015	4.06	81	...	67	37	...
6173.34	26.0	62	2.21	...	61	...	95	128
6180.22	26.0	269	2.72	...	22	...	60	102
6187.41	26.0	342	2.82	...	...	...	...	45
6188.04	26.0	959	3.93	...	...	...	27	39
6200.32	26.0	207	2.60	...	72	...	69	91
6280.63	26.0	13	0.86	...	...	143	...	...
6290.97	26.0	1258	4.71	...	...	46	...	...
6293.92	26.0	1260	4.81	...	...	37	...	...
6297.80	26.0	62	2.21	...	...	33	...	...
6301.52	26.0	816	3.64	...	...	79	...	...
6302.51	26.0	816	3.67	...	...	58	...	...
6311.51	26.0	342	2.82	...	...	53	...	...
6315.81	26.0	1014	4.06	...	...	34	...	...
6318.02	26.0	168	2.44	...	...	91	...	...
6322.69	26.0	207	2.58	...	...	83	...	...
6175.42	28.0	217	4.07	...	...	...	...	50
6186.74	28.0	229	4.09	...	...	...	21	...
6314.67	28.0	67	1.93	...	...	52	...	...
6316.61	28.0	248	4.14	...	...	28	...	...
6327.60	28.0	44	1.67	...	...	35	...	...
6134.58	40.0	2	0.00	68	...	...	...	...
6141.72	56.1	2	0.70	208	...	128	147	...
6320.39	57.1	19	0.17	...	...	22	...	...

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[a] Measurements are given in mÅ.

TABLE 3

DERIVATION OF MODEL ATMOSPHERE PARAMETERS

Cluster	Star	V	$B-V$	Reference	$E(B-V)$	$(m-M)_v$	$T_{\rm eff}$	$\log g$
N4147	II-30	14.65	1.21	1	0.00	16.28	4350	1.1
M53	S4 R4 16	14.08	1.33	2	0.02	16.34	4300	0.8
N5466	S4 R4 G	13.63	1.32	3	0.00	15.96	4250	0.8
	S2 R5 a	13.68	1.23	3	0.00	15.96	4300	0.8
N6229	IV-12	15.15	1.33	4	0.01	17.50	4250	0.7

REFERENCES.—(1) Sandage and Walker 1955. (2) Cuffey 1965. (3) Cuffey 1961. (4) Zinn and Carney 1981.

The procedures employed here closely follow those outlined by PSW, and we will here discuss only the areas in which we differ.

The V magnitudes, $B-V$ colors, interstellar reddenings, distance moduli, and the derived model effective temperatures and surface gravities are listed in Table 3. The interstellar reddenings and distance moduli have been adopted from Zinn (1980*a*). We have transformed the $P-V$ colors of Cuffey (1961) to $B-V$ colors for N5466 following the prescription he gives. The stellar effective temperatures have been chosen as in PSW from the $B-V$ colors, with the caution that, because this analysis is based on such limited wavelength coverage, we are unable to make use of any of the usual spectroscopic checks. We estimate the uncertainty in the temperature to be ±200 K. The surface gravity, derived from the stellar luminosity and distance modulus as in PSW, is by far the least troublesome of the model atmosphere parameters, with an uncertainty of ±0.3 dex. PSW discuss at length the effects of these uncertainties on the derived abundances.

For the microturbulence, we have simply adopted a value of 3 km s^{-1}, since this is the value which, in our experience, is most often appropriate for globular cluster giants. However, the derived abundances are more sensitive to microturbulence than any other model atmosphere parameter, and a more careful derivation of this quantity with the MMT instrumentation would be of great benefit. Unfortunately, such a measurement requires spectra of numerous orders to include sufficient lines, and the data are unavailable.

The abundances we derive for stars in the four globular clusters in our sample are included in Table 4, along with our estimates of the relative uncertainties, and the numbers of lines used in each determination. The lines actually used are a subset of the measurements in Table 2, since lines weaker than $\log W/\lambda = -5.4$ have, in most cases, not been included. Lines weaker than this limit are unreliable given the low signal-to-noise ratios of these spectra. The abundance of barium is noted with a colon to indicate its uncertainty. The analysis for barium uses a solar equivalent width which is outside of our usual line strength limits.

The derivation of the oxygen abundance requires knowledge of the carbon abundance, so that a proper correction for CO molecule formation can be made. We have assumed, following PSW, that [C/Fe] = −0.5; if we had assumed [C/Fe] = 0, the oxygen abundance would be −1.1 for N5466, or even higher if carbon is enhanced. The oxygen abundance in Table 4 is a lower limit.

The sensitivity of the derived abundances on model atmosphere parameters has been reviewed by PSW. In general, the iron abundance changes by 0.1 dex per hundred degree change in the temperature and is almost insensitive to the surface gravity. It is not possible to change the iron abundance significantly (i.e., by more than 0.25 dex) by adjusting the model atmosphere

TABLE 4

DERIVED METAL ABUNDANCES [M/H]

SPECIES	N4147 II-30	M53 S4 R4 16	N5466			N6229 IV-12	UNCERTAINTY
			S4 R4 G	S2 R5 A	Mean		
Oxygen[a]	...	...	−1.3 (1)	...	−1.3	...	0.3
Sodium	...	< −1.9 (1)	−0.8 (1)	−1.0 (2)	−0.9	−1.1 (1)	0.3
Calcium	−1.7 (1)	−1.6 (2)	−1.5 (1)	−1.5 (3)	−1.6	−1.1 (4)	0.2
Scandium	...	...	−1.4 (2)	...	−1.4	...	0.3
Titanium	−2.3 (1)	...	−1.5 (2)	...	−1.5	...	0.3
Vanadium	...	...	−1.8 (2)	−1.3 (1)	−1.6	−1.2	0.3
Iron	−1.3 (4)	−1.9 (3)	−1.6 (11)	−1.6 (7)	−1.6	−1.3 (4)	0.2
Nickel	...	...	−2.2 (2)	...	−2.2	−1.1 (1)	0.3
Zirconium	−1.5 (1)	...	...	...	...	...	0.3
Barium	−1.6: (1)	...	−2.6: (1)	−2.5: (1)	−2.6: (1)	...	0.5

[a] Assumes [C/Fe] = −0.5.

parameters. The uncertainty in the microturbulence, however, does leave room for some change in the derived iron abundance, but fortunately the iron lines we have used are weak (i.e., mostly less than 100 mÅ), and are largely unaffected by small changes in the microturbulent velocity. For a 100 mÅ line, the abundance drops by 0.06 dex if the microturbulence is raised to 4 km s^{-1}, and the abundance increases by 0.3 dex if the microturbulence is lowered to 2 km s^{-1}.

These abundances are compared in Table 5 with metallicities obtained from other techniques applied to the same clusters. Also included in Table 5 are the horizontal branch ratio, $B/(B+R)$, and the galactocentric distances of the clusters (Zinn 1980*a*, *b*). Two clusters are particularly discrepant in Table 5: N4147 and N5466. In both cases the classical methods and the lower resolution techniques give significantly greater deficiencies of metals. For N5466, preliminary analysis of the spectrum we obtained in 1981 indicated a high metal abundance, and in the 1982 season N5466 received a high priority for further observations. We obtained an additional three spectra in 1982, including a second star, all of which independently confirm the high metal abundance. In addition, the several species analyzed in this cluster offer greater confirmation that the cluster is more metal rich than previously thought.

The abundance of metals in N5466 is a particularly critical issue because this cluster is unique among the globulars in containing the anomalous Cepheid variables that are more commonly found in dwarf spheroidal galaxies. The abundances we derive are higher than expected, but the pattern of relative abundances between species is typical for globular clusters. The abundance of oxygen is high, as it usually is in the halo population (Sneden, Lambert, and Whitaker 1979; PSW) and is by no means anomalous. The two elements which might indicate some anomaly are sodium, with an excess of +0.7 relative to iron, and barium, with a deficiency of −1.0 relative to iron. However, as noted earlier, the barium abundances are uncertain. The high abundance of sodium is suggestive, but not definitive, as discussed by PSW.

The case for N4147 is less certain. Our analysis is based on only one spectrum of one star, and only a limited number of lines are available. Furthermore, not all the species agree. Calcium appears deficient relative to iron, which is atypical for Population II stars, and titanium, based on a single very weak line, also appears deficient. However, both the cluster color magnitude diagram and the measurements of Searle and Zinn (1978) are consistent with a somewhat higher metal abundance than Zinn (1980*a*) and Canterna (1975) derive. Also N. Suntzeff (1982, private communication) confirms from his low resolution spectra of individual stars that the metal deficiency of N4147 is intermediate. The metal abundance of N4147 remains uncertain, but it seems likely to be higher than previously thought. Further observations of stars in N4147 are needed to establish the metallicity.

Our results for both M53 and for N6229 are consistent with earlier measurements for these clusters. On the whole, our measurements agree well with the individual star measurements of Searle and Zinn (1978) but not so well with the integrated light measurements of Zinn (1980*a*).

IV. METAL ABUNDANCE GRADIENTS IN THE GLOBULAR CLUSTER SYSTEM

If the metal abundances we derive for giants are representative of the clusters of which they are members, and if our sample of distant halo clusters is representative of the outer halo, then the high dispersion results strongly suggest that distant globular clusters are more metal rich than previous studies have indicated.

To address the question of the completeness of our outer halo sample of clusters we will consider all clusters in the volume defined by galactic latitude $l \geq 40^\circ$, and between 15 and 40 kpc distant from the galactic center. This volume includes all 4 of the clusters we observed, and a total of 7 globular clusters in this volume are listed in the catalog of Philip, Cullen, and White (1976). The three in addition to the four we have observed are N5053, N5634, and Pal 5. N5063 was observed both by Searle and Zinn (1978) and by Zinn (1980*a*), who derived −2.05 and −2.29, respectively, for the metal abundance. Given the typical systematic

TABLE 5

GLOBULAR CLUSTER METAL ABUNDANCE DETERMINATIONS

	[Fe/H]							
CLUSTER	This Paper	Zinn[a]	SZ[b]	CMD[c]	CMT_1T_2[d]	ΔS[e]	$B/(B+R)$[f]	R_{gc}[a] (kpc)
N4147	−1.3	−2.07	−1.64	−1.56	−2.0	...	0.83	20.7
M53	−1.9	−1.99	−1.93	−1.75	−1.6	−1.85	0.93	18.8
N5466	−1.6	−2.17	−1.93	−1.87	...	...	0.82	16.3
N6229	−1.3	−1.49	−1.45	−1.36	...	...	0.56	30.4

[a] Zinn 1980*a*.
[b] Searle and Zinn 1978.
[c] Alcaino 1977; color-magnitude diagram.
[d] Canterna 1975; filters in a photometric system.
[e] Butler 1975.
[f] Zinn 1980*b*.

difference (−0.29 dex) between the metal abundances of Zinn and those of PSW and this paper in this metallicity range, we will adopt a metal abundance of −2.03 for N5053. Both Searle and Zinn (1978) and Zinn (1980*a*) have also observed Pal 5, obtaining −1.1 and −1.48, respectively, for the metal abundance. For Pal 5 we will adopt the average of these values, −1.29. N5634 has been included only by Zinn (1980*a*), who found a metal abundance of −1.92; again, given the systematic difference, we will adopt −1.65 for this cluster. Using these adopted values, and our measurements of the metal abundances of N4147, M53, N5466, and N6229, we obtain an average metallicity, for the clusters in this volume, of −1.58 ± 0.11. This compares closely to the average iron abundance of −1.53 ± 0.14 derived from our measurement of four clusters. The mean is not significantly changed by the addition of three clusters, so we conclude that our sample of four clusters is representative. In this context, we note also that Da Costa, Ortolani, and Mould (1982) have found that the metallicity of another outer halo cluster, Pal 14, is also very high, [Fe/H] = −1.55, from $(B-V)_{0,g}$.

In Figure 2 we plot the combined iron abundance measurements of PSW, Pilachowski and Sneden (1983), and this paper versus galactocentric distance. We have plotted both the individual values and the mean iron abundance for four ranges of galactocentric distance: between 0 and 5 kpc, 6 and 10 kpc, 11 and 15 kpc, and 15 and 40 kpc. The open circles represent the mean in each region, and the error bars are the standard errors derived from each sample. Note that all of the iron abundances plotted in Figure 2 are determined following uniform procedures, and, while the absolute value of the ordinate may contain a systematic error, the relative errors between clusters are small.

The regions from 6 to 15 kpc are reasonably well sampled, as discussed by PSW, but the region near the galactic center, which actually contains the most clusters, is represented by only three. The metallicities of the missing clusters are difficult to estimate, but we suspect that the average metallicity for clusters near the galactic center will shift to higher metal abundance, not lower metal abundance.

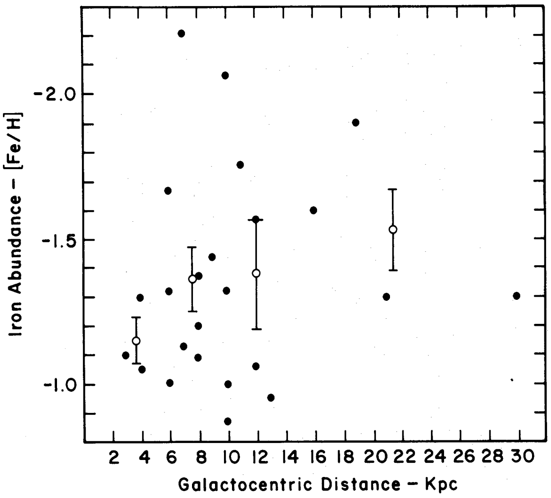

FIG. 2.—[Fe/H] vs. R_{gc}. Points for individual clusters are plotted as filled circles. Zone averages are plotted as open circles with error bars denoting one standard error. The zones are 0–5 kpc, 6–10 kpc, 11–15 kpc, and 16–40 kpc.

The existence of a metallicity gradient in the halo has been the subject of some controversy in the literature (Canterna and Schommer 1978; Searle and Zinn 1978; Harris and Canterna 1979; Zinn 1980*a*, *b*). Figure 1 provides weak evidence for a metal abundance gradient in the 5–40 kpc region of the galactic halo. The existence of a gradient, however, depends on the compositions of a small number of clusters at large galactocentric distances. The addition of even one metal-rich cluster to that sample will raise the average metal abundance enough to eliminate the gradient, except near the galactic center. On the basis of the available spectroscopic data, we can rule out a steep metallicity gradient, but the data are consistent with either a small metallicity gradient in the halo, on the order of −0.015 dex kpc^{-1}, or with no metallicity gradient outside of 5 kpc.

In addition to iron, we also consider, in Figure 3, whether the abundance of the α-process elements is a function of galactocentric distance. Following PSW, we define the abundance of α-process elements as the average of calcium and titanium, giving titanium double weight. When only one of the species is available, we have used that value only. In Figure 3 only the average values for each distance group are plotted, but we include both the logarithmic α-process element to hydrogen and α-process element to iron ratios versus distance. For

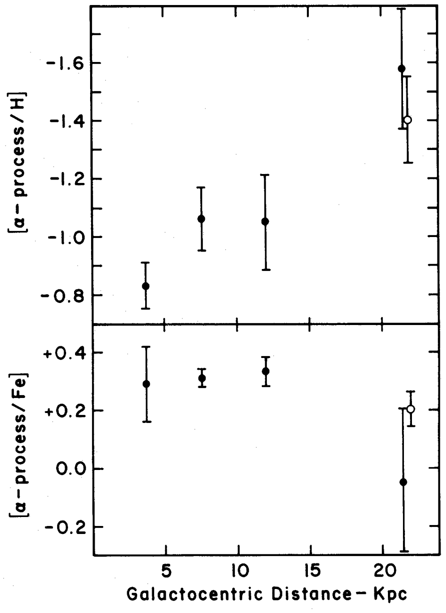

FIG. 3.—[α-process/H] and [α-process/Fe] vs. R_{gc}. Zone averages only are plotted. Zones are defined as in Fig. 2. For the outermost group, a filled circle is used for the average including all four clusters, and an open circle is used for the average omitting N4147.

the outermost group, we have used a filled circle for the average of all four clusters, and an open circle for the average omitting N4147, which we feel is uncertain. For the α-process elements we see more, but still not convincing, evidence for a gradient with galactocentric distance, with a slope of -0.04 dex kpc^{-1}. In the lower panel of Figure 3, we plot the enhancement of the α-process metals with respect to iron. This enhancement seems to be constant throughout the inner 15 kpc but is smaller in more distant clusters. This is especially true when N4147 is included in the outer halo sample and is still marginally evident when N4147 is omitted.

V. DID GLOBULAR CLUSTERS FORM WITH THE GALAXY?

Peebles and Dicke (1968) originally suggested that globular clusters were the first dynamical entities to condense out of the expanding background universe following recombination. Recent evidence on the colors of clusters in M87 (Strom *et al.* 1981), on the distribution of clusters in N4472 (Harris and van den Bergh 1981), and on the orbits of clusters in the Galaxy (Seitzer and Freeman 1981) suggest that globular clusters did, in fact, form somewhat earlier than the visible halos of galaxies. De Young, Lind, and Strom (1982) have considered, in this picture, whether the ejecta from evolved massive stars in young globular clusters could have contributed the metals found in the earliest halo stars. The sparse evidence presented in our study lends further support to the suggestion that the globular clusters formed before the halo.

In the standard model, globular clusters form during the epoch of protogalactic collapse. During this period, the bulge and halo populations of galaxies also form. The wide range in bulge-to-disk ratios presently observed in galaxies presumably reflects the wide range of efficiency of star formation during the epoch of collapse. Large bulge-to-disk galaxies most likely form the majority of their stars during early epochs, whereas spiral galaxies with small bulge-to-disk ratios have only sparse star formation in the initial phases, allowing most of the gas to settle into a disk. The properties and distribution of globular clusters would therefore seem to be especially sensitive to the collapse time and to the efficiency of star formation during the collapse. In particular, if the collapse time is sufficiently slow, then succeeding generations of star formation in the halo should produce a metallicity gradient.

On the other hand, if globular cluster formation proceeds independently of the formation of the halo and bulge populations, then both the formation and the subsequent evolution of clusters might be governed by local processes. The spatial distribution of globulars around galaxies may reflect a dissipationless collapse, and their numbers may reflect only the depth of the potential well in which the parent galaxy eventually forms. Under this scheme, globular clusters cannot derive their metals from stars formed in the halo of the parent galaxy. Two possibilities remain: The enrichment of metals in globular clusters could be either a consequence of a preexisting population of stars (massive Population III?) or the result of *in situ* processes.

In principle, observations of clusters in other galaxies may allow us to choose which of these opposite models is more nearly correct. The detection of globular cluster systems around external galaxies is presently limited by the spatial resolution available from ground-based telescopes, a limitation which the Space Telescope will reduce. Searches for globular clusters systems around galaxies of similar luminosity but dissimilar bulge-to-disk ratio may reveal the most about the formation of globular clusters. For example, do massive galaxies with small bulges have as many globulars as similar mass galaxies which have bigger bulges? The data presently available from ground-based observations are insufficient to adequately address the question.

Demarque and McClure (1977) and Carney (1980) suggest that the ages of globular clusters correlate with metallicity, while Searle and Zinn (1978) suggest that age is the second parameter needed to account for the spread of horizontal-branch morphology in globular clusters. An age-metallicity relationship is best understood in terms of cluster formation occurring during the period of slow protogalactic collapse. Clusters that form first should be located preferentially in the outer, metal-poor regions of the galactic halo, if the orbits are isotropic.

The existence of an age-metallicity relation, however, has been brought into question by high-dispersion abundance analyses of giants stars in the classic metal-rich clusters M71 and 47 Tucanae (Cohen 1980; Pilachowski, Canterna, and Wallerstein 1980). These clusters, which were included among the youngest of the globular clusters, were found to be significantly more metal poor than previously suspected, and hence, somewhat older. The observation that distant clusters are not extremely metal poor further argues against any significant age-metallicity relationship and raises the important question: where are the very metal-poor globular clusters (i.e., $[\mathrm{Fe/H}] < -2.5$)?

The lack of any strong metallicity gradient in our data for the outer halo, coupled with the high average metallicity in this region, favors the suggestion that globulars, while embedded in the same potential well of the parent galaxy, nevertheless formed independently from the halo and bulge populations. Globular clusters may have instead derived their metals from *in situ* enrichment of gas out of which the clusters formed. For instance, if a flat initial mass function is accompanied by an age spread associated with globular cluster formation of a few hundred million years (similar in magnitude to what may be presently observed in galactic open clusters; Stauffer 1982), then the low-mass stars now observed on the main sequence and giant branch are likely to have been enriched by the first generations of star formation. Since the total numbers of stars in globular clusters are small, and the volume of the protocluster is presumably small in comparison to galaxy bulges, the absolute number of supernovae occurring during the period of cluster formation may determine the metallicity of low-mass stars, and therefore the metallicity now observed. In this context, PSW have noted that the abundance ratio

[O/Fe] is not constant between globular clusters, and they attribute the variation to differences in the initial mass function of the protoglobular cluster, leading to a different rate of element enrichment. An interesting further test of this hypothesis will be the comparison of the metallicity gradient for globular clusters to that derived from the field halo star survey of Carney and Latham (1983).

Searle and Zinn (1978) and Zinn (1980*b*) offer the hypothesis that at least the outer halo clusters formed in fragments of the protogalaxy which may have resembled present-day dwarf irregular galaxies. These fragments have since been disrupted by tidal interaction with the Galaxy, forming the globular cluster system. Forte, Martinez, and Muzzio (1982) reach a similar conclusion for the globular rich giant elliptical galaxy M87. They point out that the color differences between the globular and halo populations in M87 (Strom *et al.* 1981) are consistent with the hypothesis that many of these globular clusters have been accreted from less massive galaxies. Harris (1983) notes that the globular clusters of local group dwarf elliptical galaxies are also bluer than the halos of their parent galaxies and suggests that this observation is more easily understood if the clusters and halos were formed in distinct epochs, than if the differences were acquired later by environmental processes.

In summary, we would predict that the collapse of the Galaxy is manifested best in the field halo population, and not in the globular clusters. The lack of substantial metallicity gradient in the outer globular cluster system implies either a rapid collapse of the Galaxy, or, more likely, that globular clusters are coeval and formed independently of the halo and bulge populations, and that local processes associated with individual cluster formation are responsible for determining their metallicity. Since the ratio of the halo volume to the total globular cluster volume is large, these *in situ* processes are unlikely to have spilled over into the field halo population where the truly metal-poor stars are found.

We are grateful to both Steward Observatory and to the Smithsonian Astrophysical Observatory for granting time on the Multiple Mirror Telescope to us for this project, and we want to thank F. Chaffee, J. Beckers, and the Multiple Mirror Telescope Observatory staff for their capable assistance in obtaining these observations. H. Harris, B. Carney, D. De Young, and D. Carbon have all provided much guidance through thought-provoking discussions of the questions we have addressed here. We also want to thank B. Carney and R. Zinn for providing a finding chart and photometry for stars in N6229 in advance of publication. Olszewski acknowledges partial support from NSF grant AST 81-02952.

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