THE ASTROPHYSICAL JOURNAL, 379:157–167, 1991 September 20

EXTRAGALACTIC GLOBULAR CLUSTERS. III. METALLICITY COMPARISONS AND ANOMALIES[1,2]

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Received 1990 August 28; accepted 1991 April 3

ABSTRACT

Using a method based on the strengths of six absorption line indices measured in integrated spectra, we have derived metallicities for 22 globular clusters associated with the Sc galaxy, M33, 10 globular clusters associated with the giant elliptical galaxy, M87, eight globular clusters associated with the Sb(r)I-II galaxy, M81, and three globular clusters associated with the Fornax dwarf elliptical galaxy. In addition, we have derived mean metallicities for 38 bright galaxies, mostly ellipticals, 29 dwarf elliptical galaxies in the Virgo cluster, 10 dwarf elliptical galaxies in the Fornax cluster and four local group dwarf galaxies. Comparing these results with metallicities we previously derived for 149 clusters in M31 and with the Milky Way cluster metallicities, we show that the mean metallicity of a cluster system is linearly related to the luminosity of the parent galaxy. A similar relationship is suggested between galaxy metallicity and luminosity for the bright and dwarf galaxies, although metallicity is not the only parameter differentiating the spectroscopic properties of galaxies. The slope of the relationship between the mean metallicity of a cluster system and parent galaxy luminosity is very similar to the slope of the relationship between galaxy metallicity and luminosity, but there is an offset in the sense that the clusters are more metal poor. Investigation of the distribution of 12 different line strength indices versus metallicity for clusters and galaxies shows a remarkable uniformity in abundance characteristics among these diverse populations. The only apparent abundance anomalies are in the strengths of cyanogen (4170 Å) and the Ca II H and K lines, both of which are enhanced in M31 globular clusters.
Subject headings: clusters: globular — galaxies: stellar content — stars: abundances

1. INTRODUCTION

To what extent are globular cluster properties universal and to what extent do they depend on the characteristics for the parent galaxy? Globular clusters are thought to be among the oldest radiant objects in the universe but there is much debate about their origin and their role in the formation and evolution of galaxies (see Fall & Rees 1987 for a review). It is not even clear whether globulars formed before, during, or after the collapse of the protogalaxy. In addressing this question, we hope to find clues about the formation history of globular clusters and how it relates to our understanding of galaxy formation. In particular, a comparison of the mean metallicities and the abundance distributions among different cluster systems can provide an important test of the enrichment process in collapsing galaxies.

Possible abundance differences among systems have been noted in the past. Van den Bergh (1975) suggested an empirical correlation between a galaxy's luminosity (and presumably mass) and the mean metallicity of its globular clusters. Whether or not the M31 globulars were more metal-rich than Milky Way clusters was debated for many years (e.g., van den Bergh 1969, 1980; Hanes 1979; Frogel, Persson, & Cohen 1980). Spinrad & Schweizer (1972) found a few strong lined M31 clusters which they described as "super metal rich." Burstein et al. (1984, hereafter BFGK) found enhanced cyanogen and Hβ in a sample of 19 M31 clusters. Brodie & Huchra (1990, hereafter Paper I), with a sample of 149 M31 clusters, confirmed the cyanogen anomaly but failed to find a significant Hβ enhancement, although, for objects in common, the Brodie and Huchra measurements were in reasonably good agreement with the BFGK measurements, BFGK suggested that a younger age might explain both the Hβ and CN enhancements in their M31 clusters. Only the brightest M31 clusters were observed by BFGK and, as they themselves pointed out, the brightest clusters may not be representative of the cluster system as a whole. Brodie and Huchra also noted an enhancement of the Ca II H and K lines in M31 clusters compared to Milky Way clusters of the same metallicity. Huchra, Brodie, & Kent (1991, hereafter Paper II) found that the M31 cluster system's dynamics and metallicity distribution were generally remarkably similar to the Milky Way system. However, they found a slightly higher mean metallicity for the M31 clusters which is consistent with M31's slightly higher mass.

Spectroscopic evidence for significantly enhanced metallicity in the M87 cluster system of the giant elliptical galaxy, M87, came from Racine, Oke, & Searle (1978), Brodie (1981), and Hanes & Brodie (1986). Mould, Oke, & Nemec (1987) and Mould et al. (1990) also found the mean metallicity of M87 clusters to be higher than that for the Milky Way clusters but less than that found by earlier workers. Mould et al. also studied the cluster system of another giant elliptical, M49, concluding that it was even more metal-rich than the M87 system.

Dwarf galaxies should have low metallicity clusters if the relationship suggested by van den Bergh is correct. Da Costa

[1] UCO/Lick Observatory Bulletin, No. 1187.

[2] Work reported here based on observations made with the Multiple Mirror Telescope, a joint facility of the Smithsonian Institution and the University of Arizona.

& Mould (1988) obtained metallicities for clusters in the Local Group dwarf galaxies, NGC 147, 185, and 205, which are consistent with such a relationship. There is evidence for low metallicities in Fornax globular clusters from color-magnitude diagrams (Buonanno et al. 1985).

Hesser, Harris, & Harris (1986 and references therein) found that clusters in NGC 5128, a galaxy thought to be affected by a merger, have $(B-V)_0$ colors which are redder than Milky Way clusters. The implication that redder colors imply higher metallicity is supported by the infrared photometry of NGC 5128 clusters by Frogel (1984). Irregular galaxies, the Magellanic Clouds (Searle, Wilkinson, & Bagnuolo 1980; Cohen 1981; Rabin 1982) and the Scd galaxy M33 (Christian & Schommer 1983) contain populous young blue clusters in addition to the normal old red clusters we find in our own Galaxy and M31. In both the Magellanic Clouds and M33 there is an age dependence on metallicity (Smith, Searle, & Manduca 1987; Christian 1987) which complicates comparison with other systems.

Little is known about the metallicities of other cluster systems, largely because of the observational difficulties involved in observing extragalactic clusters. They are usually faint and superposed on background light from their parent galaxy. In most cases there are also problems in distinguishing bonafide clusters from foreground stars and background galaxies.

Over the past several years we have been studying clusters associated with a variety of types of parent galaxy. In addition to the 149 M31 clusters discussed in Paper II, we have integrated spectra of 10 M87 clusters (see Huchra & Brodie 1987, for a dynamical analysis of the M87 cluster system), 22 clusters associated with M33, eight clusters associated with the Sb(r)I-II galaxy M81 and three clusters associated with the Fornax dwarf elliptical galaxy.

A library of comparison objects was also observed, consisting of 39 bright galaxies, mostly ellipticals, 29 dwarf ellipticals in Virgo, 10 dwarf ellipticals in the Fornax cluster, four local group dwarf galaxies and 46 stars, mainly giants in galactic globular clusters and in Draco. Many of these data were originally obtained for other programs involving a variety of workers (Virgo dwarf galaxies: Huchra, Caldwell and Zinnecker; Fornax dwarf galaxies: Caldwell and Huchra; M81 globulars: Huchra, Harris and Schommer; M33 Globulars: Bothun, Schommer, Huchra, Caldwell, and Christian; Bright NGC galaxies: Trinchieri, Kent, and Huchra; M31 globulars: Huchra, Stauffer and Brodie; Fornax globulars: Huchra; M87 globulars: Brodie and Huchra; stars: Brodie and Huchra; Local Group dwarfs: Huchra) and the aims of these other programs, in many cases, dictated the sample selection and the signal-to-noise quality of the data.

In § 2 we describe the observations. In § 3 we derive metallicities for the clusters, galaxies and stars in our sample. In § 4 we discuss abundance anomalies compared to the Milky Way cluster system. In § 5 we summarize our results.

2. OBSERVATIONS

All the observations were made with the MMT and the observational details are identical to those given in Paper I. The majority of the data have been taken with an S20 magnetically focused EMI image tube (Cromwell & Weyman 1982) with a fiber optic reducing boule between the image tube and the Reticon (Latham 1982). This system has a spectral resolution of ~ 8 Å and enhanced blue sensitivity. These observations extend from the atmospheric cutoff at 3200 Å out to at least 6500 Å but second-order overlap becomes a problem longward of 6400 Å. Typical integration times were 5–20 minutes for the M31 clusters, 2–4 hr for the M87 clusters, 0.5–1 hr for the M33 clusters, 1–4 hr for the M81 clusters, and 15–20 minutes for the Fornax clusters.

3. METALLICITY DETERMINATION

We have devised a robust method of metallicity determination, described in detail in Paper I, which uses six absorption line indices measured from integrated cluster spectra to provide metallicity, [Fe/H] estimates good to $\sim 15\%$. The method is designed to be as impervious as possible to observational errors and abundance anomalies. The features found to provide the best estimates of [Fe/H] measure the strengths of the Fraunhofer line-blanketing discontinuity at 4000 Å, the blue cyanogen feature at 3883 Å, the CH G band, magnesium hydride, the magnesium *b* triplet, and Fe λ5270. The calibrations are based on observations of well-studied galactic and M31 clusters and are tied to the metallicity scale of Zinn & West (1984). A weighted mean of the six estimates is used to determine the final [Fe/H] value for each cluster. Throughout this paper we refer to the mean metallicity as [Fe/H], the logarithmic ratio of metal abundance to the solar metal abundance, but we stress the term is applied loosely since some of the indices do not measure the abundance of iron peak elements directly.

3.1. *Globular Clusters*

Table 1 gives the [Fe/H] values we have derived for all the globular clusters in our sample along with their associated errors (see Paper I for a detailed discussion of the errors). The M33 clusters denoted with a Y are the clusters which appear to be young on the basis of the Hβ strengths (Schommer et al. 1991). The indices from which the metallicities were derived may be found in Huchra et al. (1991). There is excellent agreement between the metallicities we derive for the Fornax globulars and the metallicities estimated by Buonanno et al. (1985) from the color-magnitude diagrams of these clusters. Metallicities for individual M31 clusters may be found in Paper II.

A weighted mean metallicity was derived for each cluster system and is given in Table 2. The mean metallicity for the Milky Way is a weighted mean of the individual cluster metallicities in Zinn & West (1984). We have included both the young and the "normal" M33 globulars in calculating the mean for this galaxy. There is a tendency for the young clusters in our sample to be more metal poor than the old clusters (so the inclusion of the young clusters may be causing us to underestimate the mean metallicity for the M33 system). However, Hβ, the only obviously discrepant index, is not one of our primary abundance indicators and was not used in estimating metallicity for these clusters.

The mean metallicity, -0.89 ± 0.16, we have derived for the M87 cluster system is in good agreement with the value of -1.0 ± 0.2 estimated by Mould et al. (1990) and is consistent with the value of -0.5 ± 0.4 found by Hanes & Brodie (1986).

Figure 1 is a plot of mean cluster metallicity versus absolute blue magnitude (on the fully corrected B_T system). Metallicities for the NGC 147 (-2.05) and NGC 185 (-1.65) systems are from Da Costa & Mould (1988) and the metallicity for the M49 (-0.8) system is from Mould et al. (1990) all other metallicities are from this paper. Absolute magnitudes for the parent galaxies are included in Table 2. The absolute magnitude for the Galaxy was estimated relative to that for M31 (using the dis-

TABLE 1

GLOBULAR CLUSTER METALLICITIES

Cluster Name	[Fe/H]
M33	
U 137	−0.12 ± 0.38
CL 32 (Y)	−1.77 ± 1.12
H II 10	−0.91 ± 0.90
CL 3 (Y)	−2.38 ± 0.56
CL 9 (Y)	−2.12 ± 0.51
CL 16 (Y)	−1.06 ± 1.05
CL 17 (Y)	−1.88 ± 1.04
CL 18	−1.98 ± 0.73
CL 20	−1.25 ± 0.79
CL 25	−1.44 ± 0.56
CL 26 (Y)	−2.29 ± 0.66
CL 27 (Y)	−1.92 ± 0.59
CL 29	−0.94 ± 0.33
U49	−1.70 ± 0.53
U77	−1.77 ± 0.77
U78 (Y)	−1.82 ± 1.07
U79 (Y)	−2.48 ± 0.62
U83	−1.69 ± 0.41
U86 (Y)	−2.37 ± 0.57
U87 (Y)	−1.83 ± 0.63
U101 (Y)	−1.66 ± 0.40
U106	−2.18 ± 1.05
M87	
II-134	0.35 ± 0.78
III-137	−1.53 ± 0.80
II-105	−1.28 ± 1.39
III-172	−0.08 ± 1.63
III-171	−0.98 ± 0.91
IV-90	−0.66 ± 0.80
IV-94	−1.10 ± 1.32
IV-67	−1.19 ± 1.32
I-56	−0.93 ± 1.32
I-40	−1.33 ± 0.72
M81	
2	−2.09 ± 0.59
1	−2.10 ± 0.97
6	−1.77 ± 0.83
G18	−1.28 ± 1.21
R12	0.19 ± 1.44
G26	0.40 ± 2.65
G19	−0.99 ± 0.74
G35	−0.98 ± 0.72
Fornax	
2	−2.00 ± 0.78
3	−1.94 ± 0.36
5	−2.00 ± 0.61

NOTE.—M87 cluster designations are from Hanes 1971. (Y) denotes a (presumably young) cluster with strong Hβ absorption.

tance estimate from Freedman 1990) by comparing the estimated mass of the Galaxy with the estimated mass of M31. For the Galaxy, Little & Tremaine (1987) derived a mass of 2.4×10^{11} $M_\odot$ within 50 kpc and, for M31, a mass of 3.1×10^{11} $M_\odot$ within 18 kpc was derived in Paper II. Note that both spiral and elliptical galaxies are included in the figure. Figure 1 confirms the suggestion made by van den Bergh (1975) that there is an empirical correlation between a galaxy's luminosity, or mass, and the mean metallicity of its globular clusters. It appears that the relationship is approximately linear as was indicated by Mould et al. in their comparison of metallicities for three dwarf ellipticals and two luminous ellipticals. Weighted linear regressions were performed on the combined samples of elliptical and spiral cluster systems and separately on the elliptical galaxy cluster systems alone. In performing these regressions, the errors in [Fe/H] were assumed to dominate the errors in the absolute magnitude. The resulting relations are given in Table 3. Adopting the mean for the "old" clusters alone, −1.22, would place M33 very close to the regression line for the elliptical galaxy systems.

TABLE 2

MEAN METALLICITIES FOR CLUSTER SYSTEMS

Parent Galaxy	[Fe/H]	B_T	D (Mpc)	M_{BT}
Fornax	−1.97 ± 0.29	9.04	0.13	−11.5
M87	−0.89 ± 0.16	9.56	15.7	−21.4
M31	−1.21 ± 0.02	4.36	0.76	−20.0
Galaxy	−1.40 ± 0.01	5.52	0.76	−18.9
M81	−1.46 ± 0.31	7.75	3.3	−19.8
M33	−1.55 ± 0.37	6.26	0.79	−18.2
NGC 4472	−0.8 ± 0.3	9.31	15.7	−21.7
NGC 147	−2.05 ± 0.4	10.4	0.67	−13.7
NGC 205	−1.40 ± 0.15	8.85	0.68	−15.3
NGC 185	−1.65 ± 0.25	10.07	0.68	−14.1

NOTE.—Absolute magnitudes are from Freedman 1990 for M31, M33, and M81. Absolute magnitudes for M49 and NGC 147, 185, and 205 were inferred from Mould et al. 1990. The distance to Virgo was assumed to be 15.7 Mpc and the distance to Fornax is from Aaronson et al. 1989. The absolute magnitude of the Galaxy was estimated as described in the text.

M87 is well-known to have an exceptionally high cluster specific frequency (Harris 1986), and it has been argued that galactic cannibalism or the accretion of clusters stripped from neighboring galaxies has resulted in the exceptionally large number of clusters associated with this galaxy (although Muzzio 1987 suggests that cannibalism may result in the loss of clusters from big galaxies). The existence of a galaxy mass-cluster metallicity relationship combined with the high mean metallicity of the M87 cluster system argues against cannibalism or accretion as *major* contributors to the M87 cluster population. Neighboring galaxies are of lower mass and should have lower metallicity clusters. Galaxies which might have been cannibalized in the gravitational field of M87 would,

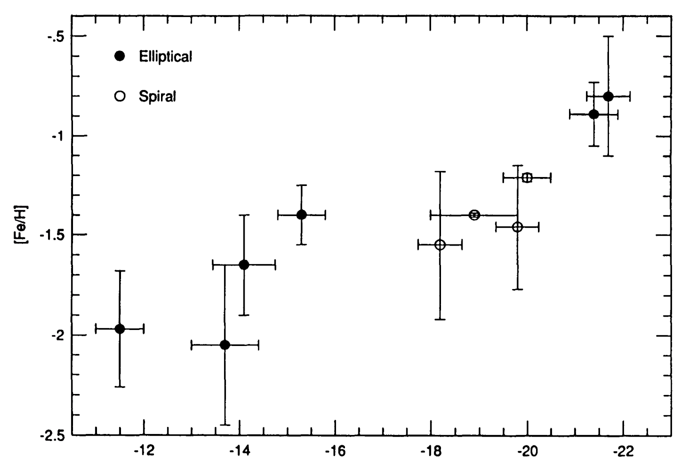

FIG. 1.—Mean metallicity of the cluster system vs. parent galaxy absolute blue magnitude (on the fully corrected B_T system). Metallicities for NGC 147 (−2.05) and NGC 185 (−1.65) are from Da Costa & Mould (1988) and the metallicity for M49 (−0.8) is from Mould et al. (1990).

TABLE 3

MASS-METALLICITY RELATIONS

Sample	Slope (a)	Intercept (b)	χ^2
Globular clusters			
Spirals + ellipticals	-0.13 ± 0.02	-1.20 ± 0.02	2.45
Ellipticals only	-0.11 ± 0.02	-0.96 ± 0.11	0.37
Galaxies			
Complete sample	-0.17 ± 0.03	-0.28 ± 0.09	0.74
High S/N sample	-0.15 ± 0.03	-0.28 ± 0.12	0.86

NOTE.—The equation of the regression line is $[Fe/H] = a(M_{BT} + 20.4) + b$ for the globular clusters and $[Fe/H] = a(M_{B(O)} + 20) + b$ for the galaxies.

by definition, be of lower mass. We also argued against cannibalism in a dynamical study of the M87 cluster system (Huchra & Brodie 1987) in which we found the M87 clusters to have a much lower velocity dispersion than the velocity dispersion of the inner cluster of galaxies. Since one might expect that the globular clusters would partially retain the mean kinematical properties of their parent galaxies, the observed difference in velocity dispersion would be difficult to explain.

3.2. *Galaxies*

In general, when optical colors are considered, the integrated light of elliptical galaxies overlaps and extends the sequence delineated by globular clusters (Brodie 1981; BFGK) leading to an assumption that the clusters and the stars in elliptical galaxies have the same age and differ from each other only in metal abundance. However, infrared colors of elliptical galaxies show little overlap with the colors of globular clusters and appear to define a sequence which cannot be accounted for by any simple extension of the stellar synthesis models for globular clusters to regimes of slightly higher metallicity (Frogel, Persson, & Cohen 1980; Frogel & Whitford 1987; Frogel 1988). This suggests that elliptical galaxies possess a stellar population mix which differs from that which makes up the typical globular cluster. Stars cooler and/or more luminous than those on a globular cluster giant branch seem to be required. Asymptotic giant branch stars with large core mass or extremely metal rich giant stars have been suggested to explain the inconsistency in the IR colors.

Problems with calibrating IR colors at metallicities greater than or equal to solar were apparent in the color metallicity plots of Aaronson et al. (1978). In these plots values at or above solar metallicity were obtained from models of elliptical galaxies and these metal-rich model points did not lie precisely on the extrapolation of the fit to the lower metallicity data points. In the case of the $J-K$ colors, the deviation from the extrapolated fit was slight but in the case of the $V-K$ colors there was a clear steepening in the color-metallicity relation at roughly solar metallicity.

Nonetheless, estimates of the mean metallicities of galaxies are highly desirable in elucidating the processes of galaxy formation and evolution. For this reason we have explored the usefulness of our line-strength indices in predicting [Fe/H] for galaxies. Figure 2 shows index versus metallicity plots for the six line strength indices (Δ, CNB, G-band, Mg2, MgH, Fe λ5270) which, as we showed in Paper I, correlate most strongly with [Fe/H] in M31 and galactic globular clusters. Figure 2 includes not only globular clusters from the various galaxy systems in this study but also the dwarf and bright elliptical galaxies in our library of comparison objects. Six other indices were also studied in Paper I. They were not adopted as primary abundance indicators because of poorer correlations with metallicity (NaI, Hβ), because they showed evidence for abundance anomalies (CNR, H+K), or because they essentially duplicated other more strongly correlated indices (MgB, MgG). Even for those indices which correlate less well with [Fe/H], the galaxies lie close to the extrapolation of the regression line defined by the globular clusters. The situation for the anomalous indices is discussed in § 4 below.

Since the galaxies appear to conform very well to the index-index and index-metallicity relations defined by globular clusters, it is reasonable to use our index-metallicity relations (Table 9 in Paper I) to derive metallicities for the galaxies in our sample. These are given in Table 4. Figure 3 is a plot of the metallicities so derived versus absolute blue magnitude [on the B(O)-Zwicky system; Huchra 1976], for the bright and dwarf ellipticals in our sample. We used B(O) rather than B_T because, for many of the galaxies in our sample, B_T was not available. Although many of the metallicities have been derived from low signal-to-noise data, much of the scatter in the diagram is probably real. Nonetheless, a trend appears to be present. A weighted linear regression through these data produce a relation with a similar slope to the relation between globular cluster mean metallicity and parent galaxy luminosity (Table 3). Since B_T is $\sim$0.4 mag brighter than B(O), we adjusted the zero point of the globular cluster fit by this amount so that a direct comparison can be made with the galaxies. Using only the high signal-to-noise data (with errors in [Fe/H] ≤ 0.6) and removing NGC 3079, which is a well-known Liner/starburst galaxy, and NGC 205, which has an unusually early type spectrum, the slope of the weighted regression is even closer to that found for globular cluster systems. The offset between this relation and the cluster relation for spiral and elliptical galaxy systems is $\sim$0.9 dex, in the sense that clusters are more metal poor, as expected. However, this offset is poorly constrained by our data. The mean difference in [Fe/H] between the globular clusters and the galaxy bulge, for the four systems where we have estimates of both (as before we exclude NGC 205), is $\sim$0.7 dex. This value is consistent with the offset between the fits to the whole sample of cluster systems and the whole sample of galaxies. It would, of course, be desirable to compare the cluster [Fe/H] with the galaxy [Fe/H] at the mean radius of the cluster sample. Unfortunately, since the galaxy light at the typical radius for globular cluster observations is extremely faint, this comparison will be difficult to make. The slope of the relation connecting the metallicity and luminosity of H II regions also appears to be the same as the slopes we have derived for the clusters and the galaxies (N. Panagia, private communication). Skillman, Kennicutt, & Hodge (1989) find a similar, although marginally steeper, relation between H II region metallicity and parent galaxy luminosity in a sample of irregular and dwarf elliptical galaxies.

The fact that the relationship for clusters and for galaxies has almost the same slope indicates that globular clusters are good tracers of the formation history of galaxies: the same physical processes probably were involved in enriching both clusters and galaxies. Faber et al. (1991) find a similar trend of increasing metallicity with increasing galaxy mass, again with substantial scatter, in their sample of predominantly brighter elliptical galaxies. Taken together these samples show a trend over a range of 11 mag in intrinsic luminosity.

These results are suggestive of the kind of universal mass-metallicity relation first proposed by Faber (1973) and dis-

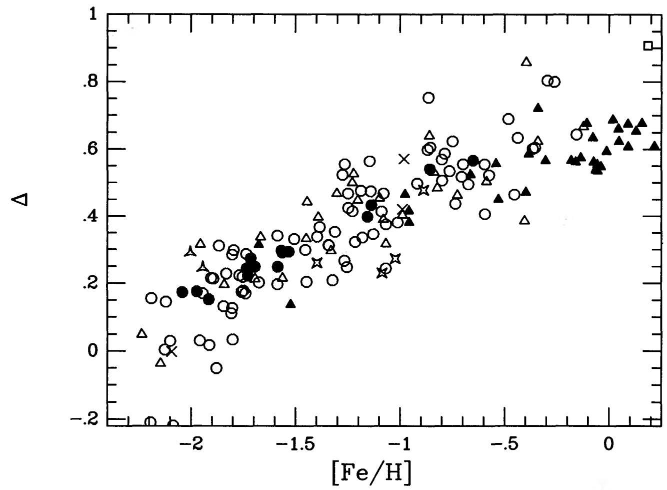

FIG. 2*a*

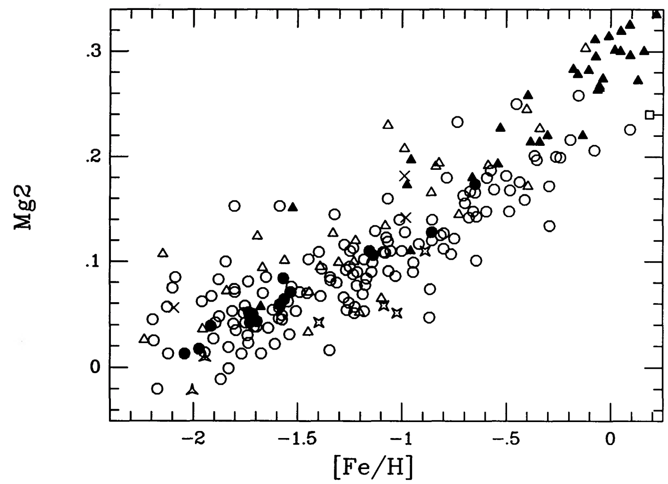

FIG. 2*b*

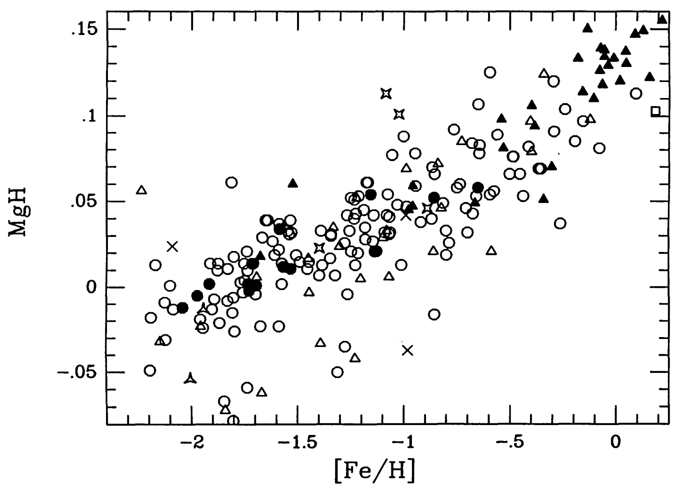

FIG. 2*c*

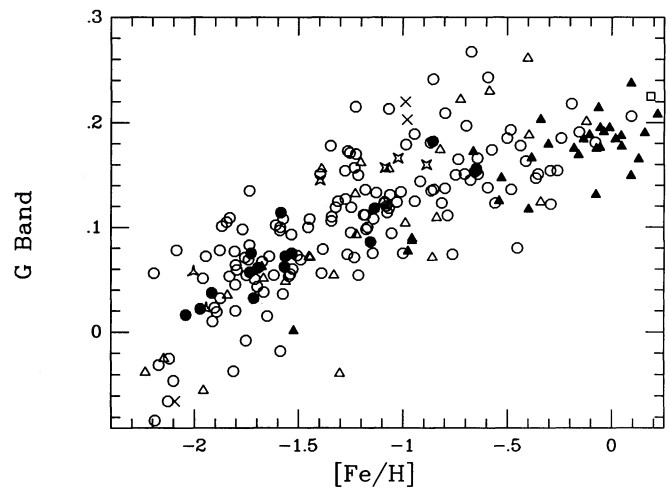

FIG. 2*d*

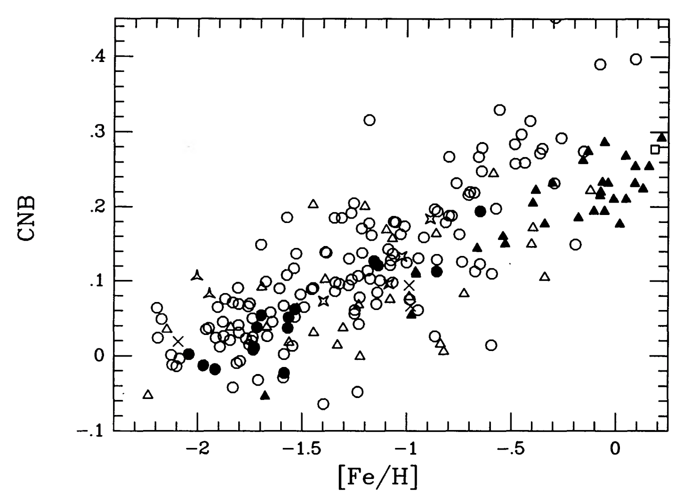

FIG. 2*e*

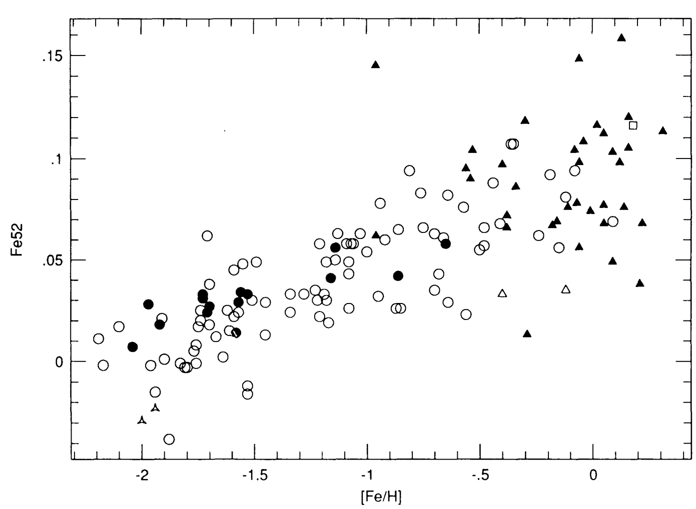

FIG. 2*f*

FIG. 2.—Index vs. index-derived mean metallicity, [Fe/H], for Galactic globular clusters (*filled circles*), Andromeda globular clusters (*open circles*), the mean of 6 NGC 188 giants (*square*), bright galaxies (*filled triangles*), dwarf galaxies (*open triangles*), M81 globulars (*crosses*), Fornax globulars (*three pointed stars*). For the low S/N spectra of the M87, M33 and M81 globular clusters and the Virgo and Fornax dwarf galaxies we have also derived mean, S/N weighted, indices. These are plotted as four-pointed stars. (*a*) Δ, (*b*) Mg2, (*c*) MgH, (*d*) G-band, (*e*) CNB, (*f*) Fe λ5270. Only points with [Fe/H] errors <0.75 are plotted. Error bars have been omitted to avoid confusion. For (*f*) Fe λ5270, data with index errors >0.03 (>20% of the range of the index) have been excluded.

TABLE 4

GALAXY METALLICITIES

Name	V (km s^{-1})	[Fe/H]	$M_{B(O)}$ (mag)	Other Names
NGC 221	-200 ± 6	-0.56 ± 0.25	-16.4	M32, Arp 168
NGC 224	-297 ± 1	0.16 ± 0.57	-19.6	M31, Andromeda
NGC 1097	1275 ± 10	-0.29 ± 1.00	-20.5	
NGC 1373	1385 ± 13	-0.34 ± 0.30	-16.4	
NGC 1399	1422 ± 10	0.21 ± 0.93	-20.0	
NGC 2859	1685 ± 14	-0.06 ± 0.59	-20.3	
NGC 2974	1924 ± 24	-0.07 ± 0.65	-20.1	
NGC 3079	1114 ± 25	-0.98 ± 0.48	-20.2	Liner
NGC 3377	689 ± 19	-0.06 ± 0.45	-17.3	
NGC 3379	922 ± 181	-0.18 ± 0.64	-20.3	
NGC 3489	693 ± 18	-0.96 ± 0.43	-17.7	
NGC 3585	1373 ± 11	-0.08 ± 0.69	-20.2	
NGC 3607	951 ± 21	-0.16 ± 0.50	-18.3	TG 39
NGC 3818	1732 ± 22	0.16 ± 0.79	-19.0	
NGC 3923	1649 ± 15	0.09 ± 0.74	-20.6	
NGC 4073	5952 ± 12	0.22 ± 0.74	-21.5	MKW4
NGC 4104	8220 ± 37	-0.06 ± 0.68	-21.5	
NGC 4251	1067 ± 21	-0.30 ± 0.28	-19.5	
NGC 4382	758 ± 13	-0.53 ± 0.45	-20.7	M85, HO 397A
NGC 4459	1215 ± 16	-0.40 ± 0.59	-19.5	
NGC 4486B	1586 ± 10	0.05 ± 0.58	-16.6	IZw 38
NGC 4486	1292 ± 10	-0.38 ± 0.89	-21.0	Liner
NGC 4636	937 ± 15	0.05 ± 0.90	-20.1	
NGC 4638	1148 ± 18	-0.04 ± 0.52	-18.6	
NGC 4641	2012 ± 30	-1.52 ± 0.64	-16.2	12-99
NGC 4649	1095 ± 17	0.12 ± 0.88	-20.8	M60, VV 206, Arp 116
NGC 46973	1210 ± 13	0.05 ± 0.64	-20.3	
NGC 5532	7367 ± 39	-0.01 ± 0.66	-21.7	
NGC 5864A	2240 ± 11	-0.11 ± 0.47	-18.2	
NGC 5846	1709 ± 8	0.09 ± 0.69	-20.5	TG 95
NGC 5850	2527 ± 13	0.13 ± 0.69	-20.6	
NGC 5866	672 ± 9	-0.54 ± 0.40	-19.6	
NGC 5898	2103 ± 20	0.02 ± 0.57	$-19.$	
NGC 5920	13584 ± 24	0.31 ± 0.93	-20.8	MKW 3S
NGC 6051	9588 ± 20	0.14 ± 0.76	-20.7	AWM 4-1
NGC 6166	9293 ± 20	-0.13 ± 0.59	-21.7	A2199
NGC 7331	819 ± 10	-0.38 ± 0.27	-20.7	HO 795A
NGC 7743	1658 ± 25	-0.96 ± 0.63	-19.3	Liner
NGC 147	-188 ± 45	-1.45 ± 0.49	-13.3	DDO 3
NGC 185	-227 ± 22	-1.39 ± 0.57	-13.7	
NGC 205	-271 ± 30	-2.15 ± 0.60	-14.9	
DN 3115	698 ± 42	-0.99 ± 0.58	-13.9	
0336−3727	1220 ± 74	-0.99 ± 1.63	-14.2	NG 2
0324−3304	1415 ± 50	-1.07 ± 0.76	-17.1	G14
0324−3553	1545 ± 32	-0.40 ± 0.51	-18.0	G103
0334−3532	1823 ± 90	-0.10 ± 1.58	-16.5	G79
0337−3532	912 ± 60	-1.48 ± 0.84	-14.3	G72
0348−3603	1596 ± 100	-1.30 ± 0.71	-16.9	G91
0333−3237	1625 ± 62	-1.84 ± 0.62	-17.5	G8
0338−3554	1277 ± 109	-0.86 ± 0.54	-14.6	NG 4
0340−3404	2019 ± 124	-1.69 ± 0.70	-17.7	G23
0343−3705	2015 ± 54	-1.23 ± 0.63	-16.5	NG 47
1157+14	1564 ± 28	-2.24 ± 0.63	-16.1	
I3118	1733 ± 63	-1.51 ± 1.54	-15.9	+9-9
I3167	2024 ± 45	-2.12 ± 1.19	-16.0	
1218+0552	2120 ± 23	-0.12 ± 0.61	-16.9	VCC 344
1219+0726	848 ± 37	-0.73 ± 0.49	-13.9	VCC 538
1224+1301	1330 ± 40	-0.34 ± 0.62	-15.4	VCC 916
I3349	1471 ± 46	-1.44 ± 0.32	-15.8	+12-44
I794	1934 ± 22	-0.84 ± 0.51	-16.0	
NGC 4472D8	1350 ± 29	-1.10 ± 0.30	-15.2	NGC 4472-D8
I3443	1814 ± 42	-1.22 ± 0.53	-15.5	M87-DW 6
I3442	1332 ± 63	-0.47 ± 0.85	-15.7	+14-48
I3457	1469 ± 51	-0.94 ± 1.06	-15.7	M87-DW 11, +12-64
1229+1220	1022 ± 87	-1.96 ± 0.62	-14.7	M87-DW 3
I3470	1500 ± 38	-0.52 ± 0.92	-16.1	
I3602	1279 ± 51	-1.07 ± 0.68	-15.6	+10-53
I3612	1313 ± 45	-1.56 ± 0.32	-15.7	I3621
I3652	470 ± 39	-0.40 ± 0.68	-16.0	
1240+1057	1672 ± 98	-2.44 ± 0.93	-15.7	VCC 194
1241+1313	940 ± 40	-0.82 ± 0.55	-15.5	VCC 199

TABLE 4—*Continued*

Name	V (km s^{-1})	[Fe/H]	$M_{B(O)}$ (mag)	Other Names
I2782	999 ± 56	-1.67 ± 0.54	-15.9	
I2787	742 ± 39	-1.55 ± 0.92	-13.5	
I783	1312 ± 34	-0.84 ± 0.85	-16.1	+16-13
1223+1308	1265 ± 64	-1.76 ± 1.17	-13.7	+13-50
NGC 4406B	1101 ± 55	-0.59 ± 0.42	-14.0	VCC 882
1226+1243	538 ± 80	-121 ± 1.40	-15.2	M87-DW 7
1229+1245	723 ± 60	-1.20 ± 0.50	-15.1	M87-DW 8
D10..................	609 ± 82	-1.60 ± 1.23	-15.8	NGC 4472-D10
4472-D6.............	688 ± 53	-1.08 ± 0.29	-16.5	U7580
D1	1691 ± 54	-1.33 ± 0.50	-15.6	NGC 4472-D1

cussed in detail by Mould (1984), who showed how such a relation might be consistent with theoretical models, even if mergers played an important role in galaxy formation. However, the scatter in the galaxy relation points to the existence of one or more parameters, in addition to mean metallicity, which govern the relative characteristics of galaxies in their integrated light and which operate over a wide range of luminosities. The central velocity dispersion has already been suggested as a second parameter in the mass-metallicity relation (Terlevich et al. 1981; Efstathiou & Fall 1984). There are hints that the dispersion in metallicity may be smaller at the high-luminosity end of the metallicity-luminosity relation for galaxies. If confirmed, this would be consistent with a scenario in which the upper limit of metallicity is determined by the IMF. The galaxies closest to the upper limit would be those in which star formation had progressed to the greatest degree of completion, or in which the IMF was the flattest. Those galaxies with lower metallicities at a given luminosity might be those where star formation had ceased prematurely, perhaps due to loss of gas or disruption due to stripping, mergers, etc. The more massive galaxies would be less likely to suffer disruption and so a smaller dispersion in metallicity might be expected among high-mass, high-luminosity galaxies. A fall-off in the upper limit of metallicity at the low-luminosity end might be due to the ease with which low-mass systems could lose their gas through common events such as supernova explosions. These ideas must remain at the level of speculations until more high signal-to-noise data are available, particularly since lower luminosity objects generally have lower signal-to-noise spectra and this tends to increase the scatter at the low-luminosity end of the relation.

The weighted mean of the metallicity estimates for the 29 Virgo dwarf galaxies in the sample is -1.15 ± 0.10. This result does not confirm the suggestion of Bothun et al. (1985, 1986), based on $J-K$ colors, that Virgo dwarfs generally have metallicities in excess of -0.7. Thuan (1985) also deduced high metallicities for the Virgo dwarfs, again based on near-IR photometry. Our sample of Virgo dwarfs is essentially the same as that observed by Bothun et al. One of the clusters in common with the sample of Bothun et al. (1985), specifically mentioned by these authors as being particularly metal rich for its mass, is M87–DW 8. Bothun et al. have measured the Ca K line and Balmer line strengths for this object and, referring to the age-metallicity diagnostic diagram of Rabin (1982), suggest that this cluster is old but even more metal rich than 47 Tuc (which has a metallicity of -0.71 ± 0.08 according to Zinn & West 1984). However, our method of metallicity determination yields a metallicity of -1.20 ± 0.50 for this cluster and, although the two values are marginally consistent with each other, our value is more consistent with the average dE metal-

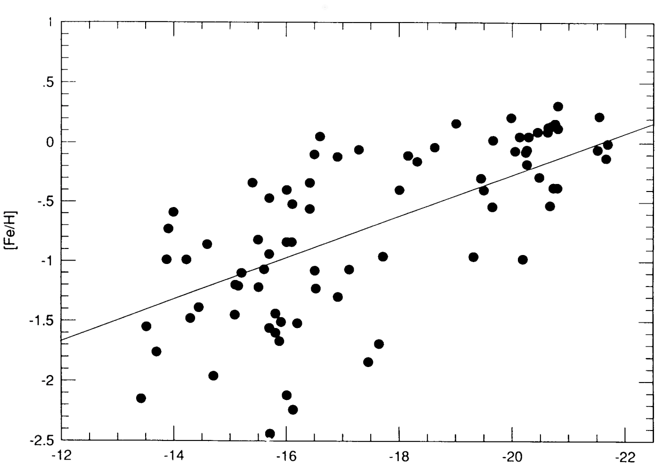

FIG. 3*a*

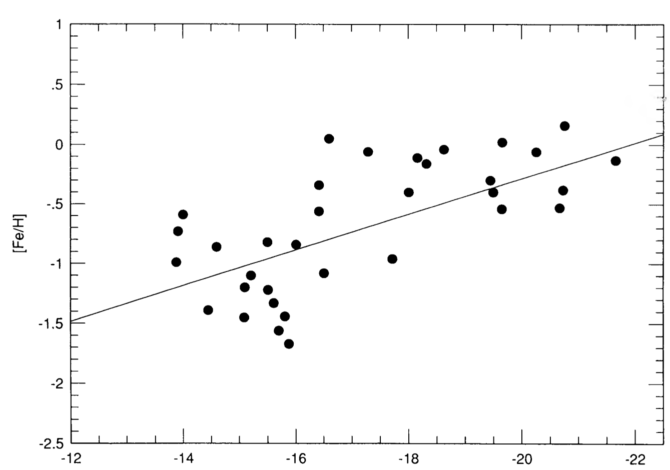

FIG. 3*b*

FIG. 3.—Metallicity, [Fe/H], vs. absolute blue magnitude [on the B(O) system] for bright and dwarf galaxies. The errors on the absolute magnitudes are typically ~ 0.3 mag and reflect our estimates of the uncertainties in the distances to the galaxies, generally $\sim 15\%$. The errors on the magnitude themselves are only ~ 0.1 mag. The fitted lines are weighted linear regressions with errors in [Fe/H] assumed to dominate the errors in absolute magnitude. (*a*) The entire sample of galaxies, (*b*) Galaxies with metallicity errors ≤ 0.6.

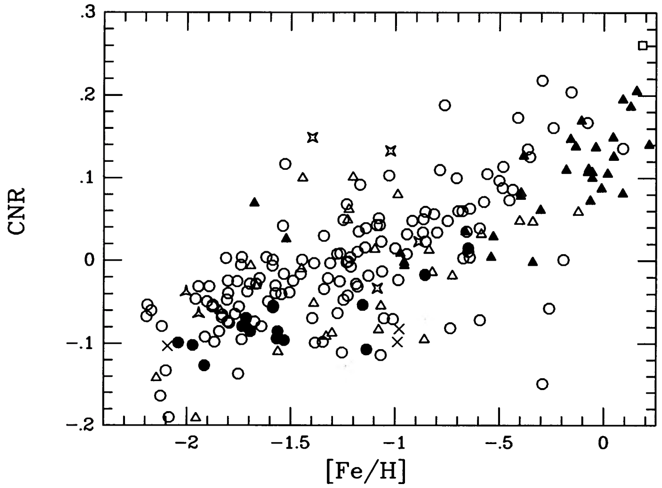

FIG. 4*a*

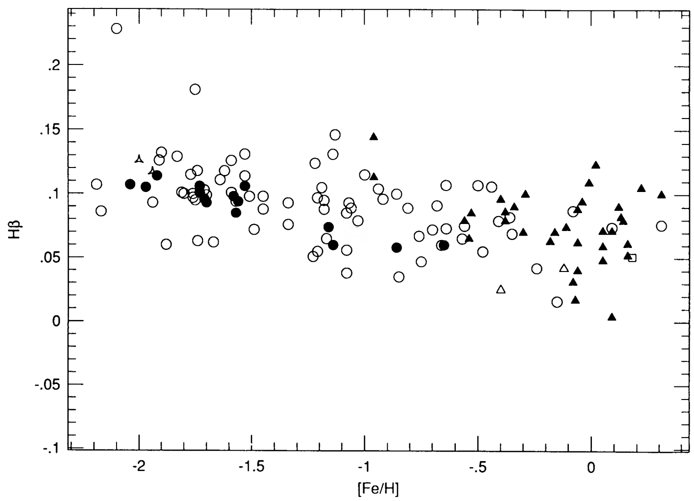

FIG. 4*b*

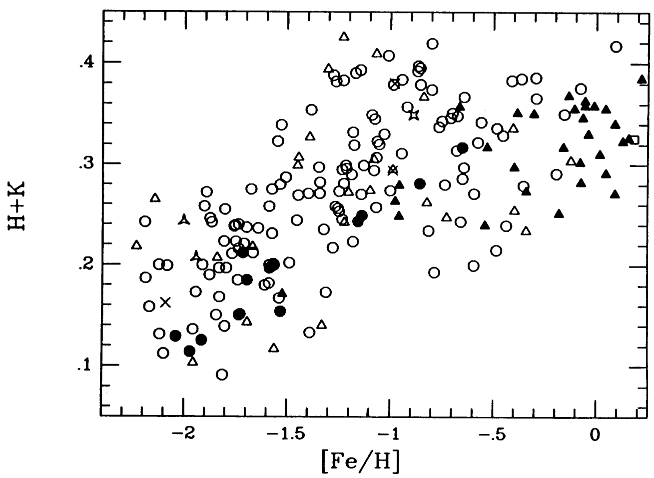

FIG. 4*c*

FIG. 4.—Index vs. metallicity, [Fe/H], for the clusters and galaxies in our sample. Symbols as for Figure 2. (*a*) CNR, (*b*) Hβ, and (*c*) H+K. Data with index errors >0.03 ($>20\%$ of the range of the index) were excluded from (*b*). When the low signal-to-noise data are excluded, the slight tendency for Hβ enhancement in M31 clusters disappears.

licity. Another cluster in common, M87–DW 6, has an even redder $J-K$ color than M87–DW 8 but we find its metallicity to be -1.22 ± 0.53. For comparison we derived [Fe/H] for these two galaxies using only the strength of the H+K features we had measured in their integrated spectra. We found values of -107 and -1.3 for M87–DW 8 and M87–DW 6, respectively. It should be stressed, however, that the error on a metallicity derived from a single index is substantial in low S/N spectra. Considering the sample of Virgo dwarfs as a whole, we find no offset between metallicities derived from our six primary indicators and metallicities derived from H+K.

Since the samples are essentially the same, a possible explanation for the discrepancy may lie in the calibration. Bothun et al. and Thuan calibrate their colors by comparison with galactic globular clusters. If the population mix is significantly different in the dwarf galaxies compared to the globulars, such a comparison may not be valid. Indeed, the IR color-metallicity plots of Aaronson et al. (1978) suggest that the IR color-metallicity relation for clusters may not be valid at metallicities near solar and beyond. However, below solar metallicity the cluster data agree well with the Aaronson et al. galaxy models, especially in $J-K$.

A population of asymptotic giant branch stars could be responsible for the vey red $J-K$ colors seen by Bothun et al. in the sample of Virgo dwarfs, although as Bothun et al. (1985) point out, the $H-K$ colors of the dEs are more consistent with those of globular clusters than with systems with significant contributions from AGB stars. It is perhaps significant that the infrared colors of bright ellipticals are also not consistent with the infrared colors of globular clusters if the two populations differ only in metallicity. As we discussed in § 3.2, AGB stars have been suggested to explain the inconsistency in the case of the bright ellipticals. The data in Figure 2 support the use of our primary abundance indicators in establishing metallicities for galaxies. In view of the inconsistency of these results with the IR observations, the use of IR colors as metallicity indicators for galaxies should perhaps be viewed with caution. We derive a similarly low mean metallicity, -1.11 ± 0.22, for the 10 Fornax dwarf galaxies.

4. ABUNDANCE ANOMALIES

BFGK suggested that galaxies and Milky Way globulars formed a continuous sequence in the CNR-Mg2 plane and that the M31 clusters lay above that sequence. In Figure 4 we show CNR, Hβ, and H+K versus metallicity for the clusters and galaxies in the sample for which we have high signal-to-noise spectra. It is not clear from our data whether the M31 clusters or the Milky Way clusters form a sequence with the galaxies in the CNR-[Fe/H] plane. What *is* clear is that the CNR enhancement requires CN band strengths equal to or exceeding the strengths found in the most extreme CN-rich giants in Galactic globulars (Hesser, Hartwick, & McClure 1977; Norris and Freeman 1979; Burstein 1987).

The Hβ plot shows that the galaxies lie on an extrapolation of the relationship defined by the Milky Way and M31 globulars. The data here are quite noisy (as noted in Paper I) due at least in part to the difficulty of measuring this narrow-band index. Some of the scatter may be intrinsic. Spinrad & Schweizer (1972) and Rabin (1981) found excess Balmer line absorption in some M31 clusters. Rabin attributed this to contamination of the Hβ wings by metal lines in the strong-lined M31 clusters.

In the plot of H + K versus [Fe/H] the tendency of this index to roll over or flatten at metallicities above about -1.0 is readily apparent. This effect is due to the saturation of the Ca II H and K lines in red giants at high metallicities (Suntzeff et al. 1986; Friel 1987). Despite this flattening, the offset between the Milky Way globulars and the M31 globulars is quite apparent, although any comparison with the galaxies is clearly meaningless.

Both CNR and H + K are significantly enhanced in the M31 clusters compared to Milky Way clusters of the same metallicity. Offsets in CNB and Hβ are not apparent in our data. Explaining *both* the CNR and the H + K anomalies simultaneously presents quite a challenge and will probably require detailed modeling with synthetic spectra before a wholly satisfactory explanation can be found. However, we discuss here some alternative explanations, pointing out potential problems with each of the possibilities considered.

The cyanogen enhancement in M31 globulars is now very well established. BFGK were the first to discover the effect in a sample of 19 M31 clusters studied at resolutions comparable to our own. Noting that CN is essentially absent in main-sequence stars, BFGK sought an explanation for the CN enhancement from giant stars. Subsequently, Tripicco (1989) obtained higher (~ 2.1 Å) resolution integrated spectra of nine metal-rich M31 clusters, six of which were in the BFGK sample and all of which were in our sample, and confirmed that both the $\lambda 3883$ and $\lambda 4216$ CN bands are exceptionally strong. He also deduced that the 4000 Å light of M31 clusters is heavily dominated by dwarfs which contribute $\sim 80\%$–85% of the light at this wavelength. A roughly even giant/dwarf split is expected in metal-rich Milky Way globulars. The CN band strengths would then require an order of magnitude CN excess in both the giants and the dwarfs. BFGK did not measure the blue cyanogen index, CNB, but our data (Fig. 3) show little or no offset between the M31 and the Milky Way clusters. This is to be expected because the blue cyanogen feature saturates quickly with increasing metallicity (Tripicco 1989; Tripicco & Bell 1990). In addition, the CNB bandpass (like the CNR bandpass) includes contributions from other strong metallic lines, including Mg and Fe, which may be dominating the response of the index to changes in [Fe/H], especially at the low-metallicity end where CN should be virtually undetectable (Smith 1987).

Increasing nitrogen, and/or carbon, will enhance CN. The strongest argument in favor of nitrogen rather than carbon as the cause of the CN enhancement is the lack of an enhancement in the G-band strengths in the M31 clusters we have observed. In addition, since CN is so strong, a nitrogen enhancement might be preferred over a carbon enhancement because N affects the CN strength more directly than C. This is true at least for stars cool enough for CO to be produced. Whether the postulated N enhancement would be more likely to have a primordial origin or be due to mixing is an open question. Again, given the size of the CN enhancement, a primordial origin might be more likely. Arguments for and against mixing and primordial abundance variations as explanations of the CN variations found in galactic globular cluster stars are summarized by, for example, Smith (1987) and Kraft (1988).

Can a nitrogen enhancement affect the H + K index? Suntzeff (1980) pointed out that the nucleosynthetic production of calcium is different from that of nitrogen and calcium anomalies and cannot be caused by envelope mixing. Therefore, we might conclude that the calcium abundance anomaly must be due to a primordial abundance variation. However, increasing N also affects the strengths of Al and Na (Norris & Pilachowski 1985 and references therein) and there are Al I resonance lines (at 3944 and 3961 Å) in the wings of the Ca II H + K lines. If Al is enhanced because N is enhanced, then the H and K lines might, at least to some extent, be expected to appear stronger.

Although a correlation between N and Ca II H and K line strengths has not generally been observed in galactic globulars (Kraft 1988), such an effect has been observed in NGC 6752 in moderate resolution (3.7 Å) stellar spectra and in ω Cen (Norris et al. 1981). There is also weak evidence for a Ca H and K line strength correlation with CN in horizontal branch stars in 47 Tuc (Norris & Freeman 1982). If Al and Na are overabundant in the M31 clusters it is unlikely to be due to internal mixing in the clusters stars since it is difficult to manufacture Al and Na in low-mass stars (Norris & Pilachowski 1985). It is conceivable, although Norris and Pilachowski argue unlikely, that it could result from some atmospheric phenomenon.

It seems most likely that Al and Na enhancements, *if* they are present, are due to an overabundance of N. Unfortunately, the night sky contamination of our Na I index would tend to mask any enhancement of Na in our low-resolution spectra, as discussed in Paper I. A slight enhancement of our Na I index may indeed be present in Figure 4(l) of Paper I but, because of the scatter due to contamination, we are unable to infer anything more about Al from our current observations. One obvious problem with this scenario is the size of the effect we see in H + K. In order to produce this much of an offset, Al would have to be extremely overabundant. A detailed model would have to be constructed to determine whether the required amount of Al could be produced without overproducing CN.

An overabundance of N, possibly primordial, appears then to offer a plausible explanation for the CN enhancement that we observe and, to some extent, for a correlated Ca H and K enhancement. A primordial change in N would be expected to have a widespread effect on the H-R diagram so detailed spectrum synthesis modeling of the behavior of the entire cluster is required to fully assess the viability of this suggestion. An observational test which might be applied more readily is to observe the NH band at 3360 Å which, in moderate metallicity clusters ([Fe/H] $\leq \sim -1.5$) should show up strongly if N is enhanced. It may be that more than one mechanism will be required to explain both anomalies.

Surface gravity is another factor which can affect both CN and H + K. As pointed out by BFGK, lowering the surface gravity in giants will increase CN. It will also increase the strength of the Ca II K line (O'Connell 1973) which would at first seem to be consistent with the H + K enhancement we observe. However, lowering gravity will simultaneously decrease Mg2 (Mould 1978), and we see no offset in Mg2 between M31 and Milky Way globulars (Fig. 3). BFGK plotted all their indices against Mg2 so they were sensitive only to relative changes and not to the behavior of Mg2 by itself. BFGK suggested that the mechanism for lowering the surface gravity might be to make the M31 clusters younger than the Milky Way clusters. This was also consistent with the enhanced Hβ they found in their sample of M31 clusters. However, since we do not find a general Hβ enhancement, lowering the surface gravity through an age effect would appear to be ruled out.

Unfortunately, the signal-to-noise quality of the data for the globular clusters associated with M87, M33, M81, and Fornax is too poor to permit an investigation of individual abundance anomalies in these systems.

5. SUMMARY AND CONCLUSIONS

There is at least one property of globular clusters which is not a universal number. We have shown that the mean metallicity of a globular cluster system depends on the luminosity, and presumably mass, of its parent galaxy and the dependence of metallicity on absolute magnitudes is approximately linear. Since it is generally believed that clusters are not massive enough to support self-enrichment, this relationship implies that the material from which the clusters formed was enriched to a greater extent in bright galaxies than in dwarfs. Mould et al. (1990) suggest that this is consistent with the formation of giant ellipticals by mergers of gas-rich dwarfs.

Moreover, abundance anomalies exist. There are significant enhancements in the strengths of features measuring CN and Ca II H and K line strengths in M31 clusters compared to Milky Way clusters of the same metallicity. There are hints that these differences may, at least in part, be primordial in origin, resulting from an overabundance of nitrogen. In comparing CN strength in globulars with that in bright elliptical galaxies, it is not clear whether the Milky Way globulars or the M31 globulars are anomalous. The Ca II H and K line feature saturates at metallicities lower than those typical for such galaxies and so a comparison between globulars and galaxies is not possible for this feature.

The high mean metallicity found for the M87 cluster system combined with the mass-metallicity relationship argues against galactic cannibalism, or the stripping and accretion of clusters from neighboring galaxies, as major contributors to the high cluster specific frequency which characterizes M87.

The abundance characteristics of the dwarf and bright elliptical galaxies are remarkably similar to those of the globular clusters in the sense that the galaxies conform to the index-metallicity relationships defined by the globular clusters. This fact allows us to apply the method of metallicity ([Fe/H]) determination we developed for globular clusters to the determination of metallicities for the galaxies themselves. Using this method we find that the Virgo dwarf galaxies are more metal poor than was previously supposed based on IR colors. The inconsistency between metallicities derived from optical line strength indices and metallicities derived from the IR colors may perhaps be indicative of differences in stellar population mix between globular clusters and dwarf ellipticals.

It appears that a mass-metallicity relation exists for the galaxies, analogous to the one connecting cluster mean metallicity with parent galaxy mass. This lends support to the idea of a universal mass-metallicity relation as discussed by Mould (1984). However, the scatter in this relation implies that additional parameters are required to explain the spectroscopic differences between galaxies. If the upper envelope of metallicity is set by a universal IMF then the location of a galaxy in the metallicity-luminosity plane might be strongly influenced by gas loss or disruption due to such effects as stripping or mergers.

The slope of the relationship between the mean metallicity of a globular cluster system and the luminosity of the parent galaxy is very similar to the slope of the relation connecting galaxy metallicity and luminosity. This suggests that the physical processes responsible for enriching galaxies were the same as those operating in globular clusters. Globular clusters should therefore be considered as excellent tracers of the formation history of galaxies. There is an offset in the relations, in the sense that clusters are more metal poor than the galaxies at a given luminosity.

We gratefully acknowledge enlightening discussions with Mike Briley, Dave Burstein, Carol Christian, Tim Davidge, Sandy Faber, Eileen Friel, Jay Gallagher, Gretchen Harris, Jim Hesser, David Koo, Bob Kraft, and Mike Tripicco. We have particularly benefitted from stimulating discussions with Graeme Smith. We are grateful to Sandy Faber for showing us her data in advance of publication, to Hank Donnelly for help with Mongo, to Susan Tokarz and Kathy Clemens for help with data entry, to the staff of the MMTO for keeping things running, and to Pat Shand for her excellent editorial work. This work was supported by the Guggenheim Foundation, the Smithsonian Institution and Faculty Research funds from the University of California, Santa Cruz.

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