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# THE METALLICITY OF GLOBULAR CLUSTERS ASSOCIATED WITH THE GIANT ELLIPTICAL GALAXY NGC 4486 (M87)

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## ABSTRACT

We have derived cluster metallicities from measurements of absorption features in low-dispersion spectra acquired at the Anglo-Australian Telescope for five globular clusters associated with the giant elliptical galaxy M87, a member of the Virgo Cluster. We have augmented our sample to six through the recalibration and inclusion of the results presented by Racine, Oke, and Searle (1978) for three clusters, two of which are common to both studies. We confirm their conclusion that the mean metallicity in their sample of three is about one-fifth solar (a conclusion which is not strongly sensitive to recent revisions in the globular cluster abundance scale, given the uncertainties), but all three of the clusters newly observed by us are as metal-rich or richer. Thus the mean metallicity in our total sample is $[Fe/H] = -0.5 \pm 0.4$, considerably more metal-rich than the average ($\sim -1.2$) for clusters in our own Galaxy. Moreover, it appears that a significant fraction of the globular clusters in M87 are more metal-rich than any known in the Galaxy; however, the most metal-poor cluster in our sample has a metallicity near the lower bound observed for globular clusters in our own Galaxy. We see no correlation of cluster metallicity with projected galactocentric distance, but there is some evidence suggesting that the less-luminous clusters are more metal-poor, a result which is consistent with some form of self-enrichment in the most massive clusters.

*Subject headings:* clusters: globular — galaxies: individual — stars: abundances

## I. INTRODUCTION

Globular clusters are highly luminous stellar aggregates which seem likely to date from the earliest epochs of star formation. Their chemical and dynamical properties may thus shed light upon early collapse and enrichment processes within galaxies. Extragalactic cluster systems have been identified in many galaxies (see, for example, Harris and Hanes 1985) but have been spectroscopically analyzed only within the Local Group (e.g., by van den Bergh 1969) and for the nearby peculiar galaxy NGC 5128 (Hesser *et al.* 1984). More remote systems, such as the Virgo galaxies, contain vast numbers of clusters (Hanes 1977*a*), but at magnitude levels which make the spectroscopic observations very difficult. Yet the Virgo Cluster contains the nearest giant elliptical galaxies, which are of special interest in the question of galaxy formation.

In this paper we report the results of a spectroscopic study of several of the brightest globular clusters in the field of NGC 4486 (M87), the central giant elliptical galaxy in the Virgo Cluster. The paper will take the following form: in § II we describe our choice of candidates and justify their identification as extragalactic globular clusters. In § III we summarize our observing methods. In § IV we introduce two (of 16) indices used by Brodie and Hanes (1986, hereafter Paper I) in quantitative determinations of metallicity from the spectra of the integrated light of globular clusters in our own Galaxy. We demonstrate in § V how we compensate the measurements described in § IV for the nonnegligible effects of differential refraction. In § VI we present the spectra and tabulate the metallicity-indicative indices. Before a final determination of metallicities, we reconsider in § VII the observations by Racine, Oke, and Searle (1978, hereafter ROS) of three clusters in the M87 field, comparing and combining their results with ours to yield an enlarged sample. In § VIII we derive metallicities, discussing the distribution of observed values in § IX. Finally, in § X we discuss possible astrophysical interpretations of the observed range and distribution of metallicities.

## II. OBSERVATIONS: SELECTION OF CANDIDATES

Five candidate clusters were studied from a list of objects selected from Hanes's (1971) broad-band photometry of unresolved objects in the M87 field. In Table 1 we summarize the properties of these objects (and a sixth, III 156, which is included for reasons to be discussed later). The positions were derived from $x$-$y$ measurements made on the Coradograph at the Institute of Astronomy, Cambridge, on a large-scale finder reproduced from a plate taken at the prime focus of the 5-m telescope at Mount Palomar. The measurements were tied into a local astrometric sequence defined by SAO stars on Palomar Sky Survey glass plates. The positions are probably good to $\pm 3''$ in each coordinate.

Inspection of Hanes's (1971, 1980) color-magnitude diagram for several hundred objects in the M87 field reveals that the observed objects are five of the eight brightest likely globular clusters associated with that galaxy. The proper motions in Table 1 come from Prociuk's (1976) measurements and analysis. His standard errors of measurement are $\pm 0''.0027$ $yr^{-1}$ in each coordinate, so the tabulated values are consistent with negligible proper motions in each case.

It is important to assess the probability that the objects observed are indeed extragalactic globular clusters. Their negligible proper motions are important, although this provides evidence of only a negative sort: objects with measurable

TABLE 1

CANDIDATE CLUSTERS

| Name[a] | α(1950) | δ(1950) | $V^a$ | $B-V^a$ | Proper Motion[b] (arcsec yr$^{-1}$) |
|---|---|---|---|---|---|
| I 40 ............ | 12ʰ28ᵐ31ˢ.4 | +12°39′39″ | 19.50 | 0.80 | 0.0040 |
| II 105 ......... | 12 28 05.6 | +12 35 52 | 19.73 | 0.79 | 0.0040 |
| III 122 ........ | 12 27 56.3 | +12 41 27 | 19.76 | 0.80 | 0.0056 |
| III 156 ........ | 12 28 08.4 | +12 44 11 | 20.35 | 0.80 | 0.0015 |
| III 172 ........ | 12 28 11.4 | +12 44 36 | 19.75 | 0.82 | 0.0034 |
| IV 94 .......... | 12 28 19.6 | +12 43 20 | 19.99 | 0.74 | 0.0023 |

[a] Hanes 1971.
[b] Prociuk 1976.

proper motions cannot be globular clusters in Virgo, but this does not mean that every apparently stationary object is a cluster. Indeed, halo dwarfs of late G to early K spectral type would have detectable proper motions at the 2 $\sigma$ level only with transverse velocities of $>160$ km s$^{-1}$ and would be photometrically similar to the objects studied here.

A second consideration arises from our finding of strong magnesium hydride features (see § VIII) in some of the spectra. Clark and McClure (1979) have demonstrated the strong luminosity dependence of a photometrically measured magnesium feature in single stars: near $B-V=1.2$, it is considerably stronger in dwarfs than in giants. If our program objects had been this red, the strong MgH features observed might lead one to suspect the contamination of the sample by an interloping dwarf. However, at $B-V=0.8$ (the color of the program objects observed here) the magnesium-feature strengths are comparable in giants and dwarfs and we have no reasons on those grounds alone to suspect our sample of contamination.

In the last analysis, the strongest evidence in favor of their identification as globular clusters comes from the excess of such objects in the immediate environs of M87, where there are twice as many objects at the $19.5 < V < 20.0$ level as in the fields of 12 other Virgo galaxies at that latitude (Hanes 1977*a*). Moreover, some of these objects have red colors and measurable proper motions which are consistent with their identification as halo dwarfs. Since we expect such stars to be randomly found in the fields of Virgo galaxies, the contrast in numbers of objects in the color range appropriate to globular clusters must be very striking indeed. (Unfortunately, deep *BV* photometry has been carried out only in the M87 field). On these grounds we expect at most one and more likely none of the candidates to be an interloping field star rather than a globular cluster associated with M87.

## III. OBSERVATIONS: METHODS

The observations described here were acquired in successive observing seasons with the 3.9 m Anglo-Australian Telescope (AAT). We summarize the observational methods in Table 2, but some additional comments are in order.

We used the Robinson-Wampler image dissector scanner (IDS) in 1978; as it happened, that run was all but lost to bad weather, with a spectrum of only one candidate cluster being acquired. In the 1979 run, we used the higher resolution image photon counting system (IPCS) at somewhat higher dispersion. The 1978 observations were made through a pair of rectangular dekkers, 2″.5 × 1″.6 in size with 20″ edge-to-edge separations; in the 1979 observations we employed a pair of circular dekkers, 3″ in diameter with 20″ separation. The usual techniques were employed, alternative integrations being made through different holes, with frequent reference to wavelength-calibrating emission lamps and to the standard stars customarily used at the AAT (Oke 1974), and so forth. The data reduction was accomplished through use of the Anglo-Australian Observatory's SDRSYS reduction package for spectroscopic data. The spectra were wavelength-calibrated, corrected for the effects of atmospheric extinction, and referred to standard stars in an attempt to define correct continuum shapes (but see § V). For the observations of the faint cluster candidates in M87, individual integrations were added in order of increasing air mass until no net gain in detected signal-to-noise ratio was achieved. The total integration time per object ranged from 3000 to 9000 s.

Also observed for calibration purposes were a number of globular clusters in our own Galaxy, chosen to span a wide range of metallicities. Those observations (including an important continuation of the program in the 1982 observing season) and their subsequent interpretation in terms of metallicity-

TABLE 2

OBSERVING LOG

| Observing Feature | Session 1 | Session 2 |
|---|---|---|
| Date .......................... | 1978 May 8/9–10/11 | 1979 Mar 22/23, 25/26, 26/27 |
| Telescope ..................... | 3.9 m AAT | 3.9 m AAT |
| Detector ...................... | Robinson-Wampler IDS | IPCS |
| Spectrograph ................. | Boller & Chivens | RGO, 25 cm camera |
| Focus .......................... | f/15 Cassegrain | f/8 Cassegrain |
| Dispersion .................... | 390 Å mm$^{-1}$ | 156 Å mm$^{-1}$ |
| Central wavelength .......... | 5200 Å | 5200 Å |
| Objects ....................... | IV 94 | I 40, II 105, III 122, III 172 |

indicative indices derived from absorption-line strengths are described in detail in Paper I and are summarized in the next section. An important point is that the observations of globular clusters in the Galaxy were made with the telescope moving in a raster over the face of each cluster to provide a spectrum which is truly representative of the integrated light.

## IV. SPECTROPHOTOMETRIC FEATURES INDICATIVE OF METALLICITY

In Paper I we demonstrated that low-dispersion spectra of the integrated light of globular clusters may be quantitatively interpreted to yield precise estimates of metallicity. In that paper we examined 16 spectral features, but here we restrict our attention to two in particular because the spectra for the candidate clusters are of too poor signal-to-noise ratio to warrant finer analysis.

The features of interest are the following:

1. The $\Delta$ parameter, a measure of the continuum break at 4000 Å which reflects the line blanketing shortward of that wavelength. It is defined by

$$\Delta = 2.5 \log \left[\frac{F(4000, 4200)}{F(3800, 4000)}\right], \qquad (1)$$

where $F(\lambda_1, \lambda_2)$ represents the integrated flux in the wavelength interval $(\lambda_1, \lambda_2)$.

2. The MH index, a measure of the magnesium hydride band (plus Mg *b* triplet) strength. It is defined by

$$\mathrm{MH} = 1.0 - \frac{2F(\lambda_2, \lambda_3)/(\lambda_3 - \lambda_2)}{F(\lambda_1, \lambda_2)/(\lambda_2 - \lambda_1) + F(\lambda_3, \lambda_4)/(\lambda_4 - \lambda_3)}, \qquad (2)$$

where $(\lambda_1, \lambda_2, \lambda_3, \lambda_4) = (4740, 4940, 5350, 5550$ Å). The index is a measure of the flux per unit wavelength within the band, compared with the average flux per unit wavelength in two adjacent proportions of the spectrum.

We have measured these indices for the M87 clusters but defer their presentation to § VI because of our recognition of a potential source of systematic error: the effects of differential refraction. NGC 4486 lies at a moderately northern declination (+12°), and the unresolved candidate globular clusters are therefore seen at minimum zenith distances of $\sim$43° at the AAT. Despite the restricted wavelength baseline over which the $\Delta$ parameter and the MH index are defined, differential refraction may cause problems because of the small dekkers employed, with consequent distortions of the continua in the observed spectra. We now model the expected effect.

## V. EFFECTS OF DIFFERENTIAL REFRACTION

We assume that the television guiding system of the AAT will yield an effective peak of $\sim$5500 Å for the guided image of a candidate cluster. Although the S20 photocathode response itself peaks at $\sim$4100 Å, the candidate clusters are moderately red ($B-V = 0.8$) and are seen through large air masses. A consequence of our assumption is that atmospheric refraction will lead to the differential loss of blue light so that the candidate clusters will appear too red as a function of air mass even after the usual extinction corrections have been applied. Indeed, examination of the spectra from individual integrations, typically of 1000 s duration, confirms this expectation (within very large uncertainties for these faint objects). Systematic overestimates of $\Delta$ will arise, although the effect upon MH will be negligible.

We now quantify the effect in the following simple fashion. In 1979 the seeing was measured at 1″.8–2″.0 (FWHM) during the time that the M87 clusters were observed through a 3″ circular aperture. For ease of calculation, we approximate the aperture by a square, 3″ on a side, and the seeing profile by a two-component square top-hat function, with 50% of the light contained in a central flat peak 1″.5 square and 100% of the light within a 3″ square. Figure 1 compares a central cut through the adopted profile with a central cut through a bivariate normal profile (FWHM = 2″) of equivalent peak intensity.

Using this model, it is straightforward to calculate the losses caused by atmospheric dispersion as a function of zenith distance, using the wavelength dependences for refraction which are summarized in Allen (1973). For the 1978 session, better seeing permitted the use of smaller apertures (2″.5 × 1″.6, with 1″.4 seeing), and we model those observations in the same approximate fashion, adopting a square aperture 2″.0 on a side and a seeing profile like that in Figure 1 but with a central width of 1″.0 and full width of 2″.0. This exercise yields a second set of corrections. During the data reduction, then, each separate integration was corrected for the effects of differential refraction according to our model.

Fortunately, there is a direct test of the adequacy of our crude corrections. Two of the candidate clusters studied here were also observed by ROS. Their observations, which will be discussed in § VII, were through larger (5″) apertures and at smaller zenith distances (from Mount Palomar) than were ours. We may thus take their continua to be of the correct shape, if not zero point, an assumption which is borne out by the fact that ROS found their spectra to reproduce the observed broad-band colors of the clusters (Hanes 1971) to within the expected random errors. Thus in Figure 2 we compare their spectra with our corrected versions for objects I 40 and III 172. (In the figure we do not show their error bars, which are comparable in size to our own except in the $\lambda < 3800$ Å region. There, theirs are smaller by a factor of 2 or so, principally because of the increased efficiency of working through smaller air masses.)

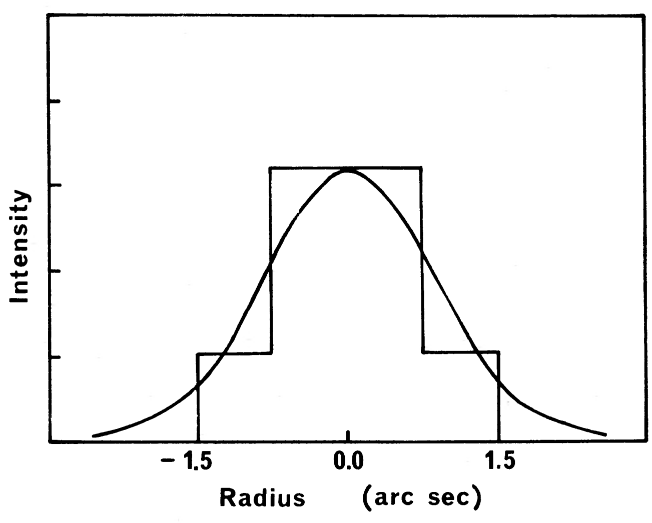


FIG. 1.—A central cut through our adopted model image profile, a two-dimensional square top-hat function with 50% of the light within the central peak (which extends to ±0″.75 from the center along each axis) and 100% of the light within the whole profile. The superposed curve shows a central cut through a bivariate Gaussian of 2″ full width at half-maximum and equivalent peak intensity.

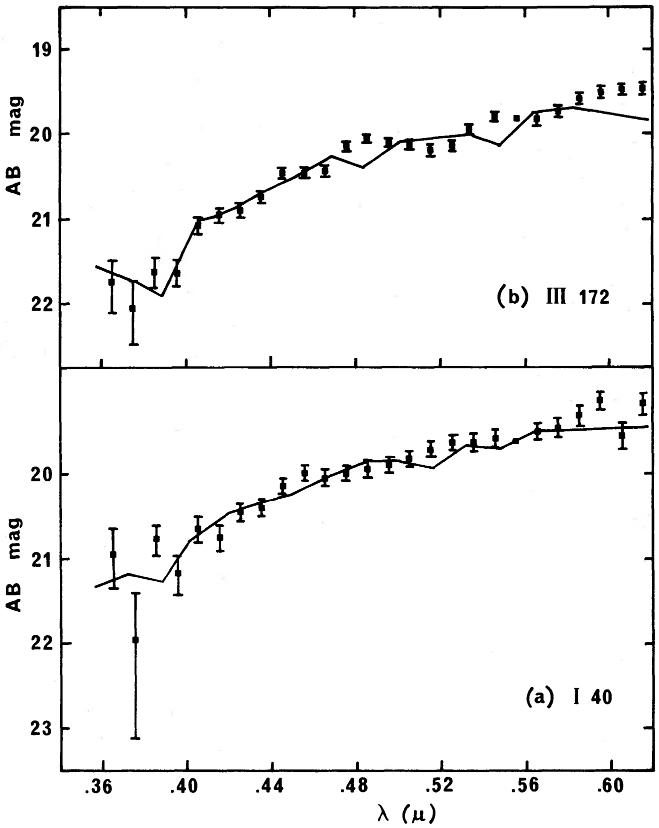


FIG. 2.—Comparison of the spectra of objects I 40 and III 172 as observed by ROS (*solid lines*) with those observed by us (*points*, in 100 Å bins with photon-statistical error bars). Our spectra have been corrected for differential refraction as described in the text. The ordinate scale is in *AB* magnitudes ($= -2.5 \log f_\nu - 48.60$) on the ROS scale: our data have been vertically shifted to cross the ROS spectra at ~5000 Å in each case.

The figure makes clear the adequacy of our adopted method of correcting for the effects of differential refraction. We note that a failure to correct would lead to overestimates of Δ by 0.17 at a mean zenith distance of 50°; the MH index is not significantly changed. We will show in § IX that the principal conclusions of the paper are not significantly affected by the uncertainties introduced by our necessarily approximate corrections.

### VI. OBSERVATIONS: THE DATA

In Figure 3 we present the spectra acquired for the five candidate clusters. The data have been binned to 100 Å intervals to smooth the spectra somewhat, and the photon-statistical error bars are shown where the uncertainty is greater than ±0.05. For M87 IV 94 the observations were made with the Robinson-Wampler image dissector scanner, the output of which is not readily interpreted statistically because of the unknown multiplicity of the counting of incident photons. Experiments at the AAT have shown that the combined efficiency of the Boller & Chivens spectrograph plus IDS is not dramatically different from that of the Royal Greenwich Observatory (RGO) spectrograph plus IPCS; thus we have assigned to the scan of IV 94 the error bars appropriate to it, as judged by the other spectra.

Also shown are the reddening-corrected spectra acquired by Brodie and Hanes (Paper I) for two globular clusters in our Galaxy: NGC 5927, which is the most metal-rich cluster we observed, at [Fe/H] = −0.65; and NGC 6809, for which [Fe/H] < −2.0. Inspection of the spectrum of NGC 5927 reveals the pronounced 4000 Å continuum break and the MH absorption feature. However, it is apparent that these features are also strong in four of the five M87 clusters studied; they seem to be rather metal-rich.

These subjective impressions are quantified in Table 3A, where we present values of Δ and the MH index derived from the scans of the M87 clusters. Comparison with the tabulations presented in Paper I reveals that in general these values are numerically larger than those measured in the spectra of globular clusters in our own Galaxy and reflective, therefore, of higher metallicities. (In Table 3A we present the measurements of Δ and the MH index for NGC 5927 and NGC 6809 from Paper I for a direct comparison.) However, before interpreting the measurements in terms of cluster metallicities, we first reconsider the study by ROS of three clusters in the M87 field, partly as an external check upon our results and partly to allow us to augment our sample and to refine our estimates through the inclusion of their results.

### VII. A RECALIBRATION OF RACINE, OKE, AND SEARLE'S OBSERVATIONS

ROS concluded from their study of three clusters in the M87 field that the average metallicity was about one-fifth solar ([Fe/H] ~ −0.7). However, their calibration was indirect and warrants reconsideration. They estimated relative cluster metallicities in two ways: by using the color in the line-free part of the spectrum, and by measuring the blanketing in the violet through a parameter *K* which is analogous to our Δ. Their absolute calibration was indirect: it was provided by a comparison with similar quantities measured in Searle's unpublished spectrophotometry of globular clusters in M31 and related thereby to a subjectively estimated line-strength index *L* (van den Bergh 1969) for those clusters. The precise calibration of this index in terms of [Fe/H] is imperfectly known, and the calibration is also sensitive to uncertainties in the reddening of clusters in M31, as ROS recognized. There is also the danger that the reddening laws in M31 may be different from those in our own Galaxy (van den Bergh 1969; Martin and Shawl 1979). Finally, we note that ROS assumed a metallicity scale for globular clusters which predated the recent important revisions summarized by Pilachowski (1984) and adopted in Paper I; for this reason, a recalibration of the results of ROS is doubly required.

Because our Paper I provides an analytic method of determining metallicities from objectively measured indices in cluster spectra, we need not rely upon the ROS calibration procedures. Of course, it is important to compare their results with our own, especially for the clusters in common. In fact, however, we cannot even apply their calibration to our data: the first method is subject to residual uncertainties in our continuum shapes, and we cannot exactly reproduce their parameter *K*, which is defined with reference to a continuum slope reaching to 7400 Å, a region where overlapping second-order light contaminates our spectra.

Instead we use their published data to measure two indices Δ′ and MH′ from the spectra of their candidate clusters, where the indices are defined to match as closely as possible our own Δ and MH; we subsequently interpret Δ′ and MH′ in terms of metallicity. Fortunately the task is straightforward because the spectra of the Galactic globular clusters studied in Paper I can be rebinned to mimic data produced by the Oke multi-

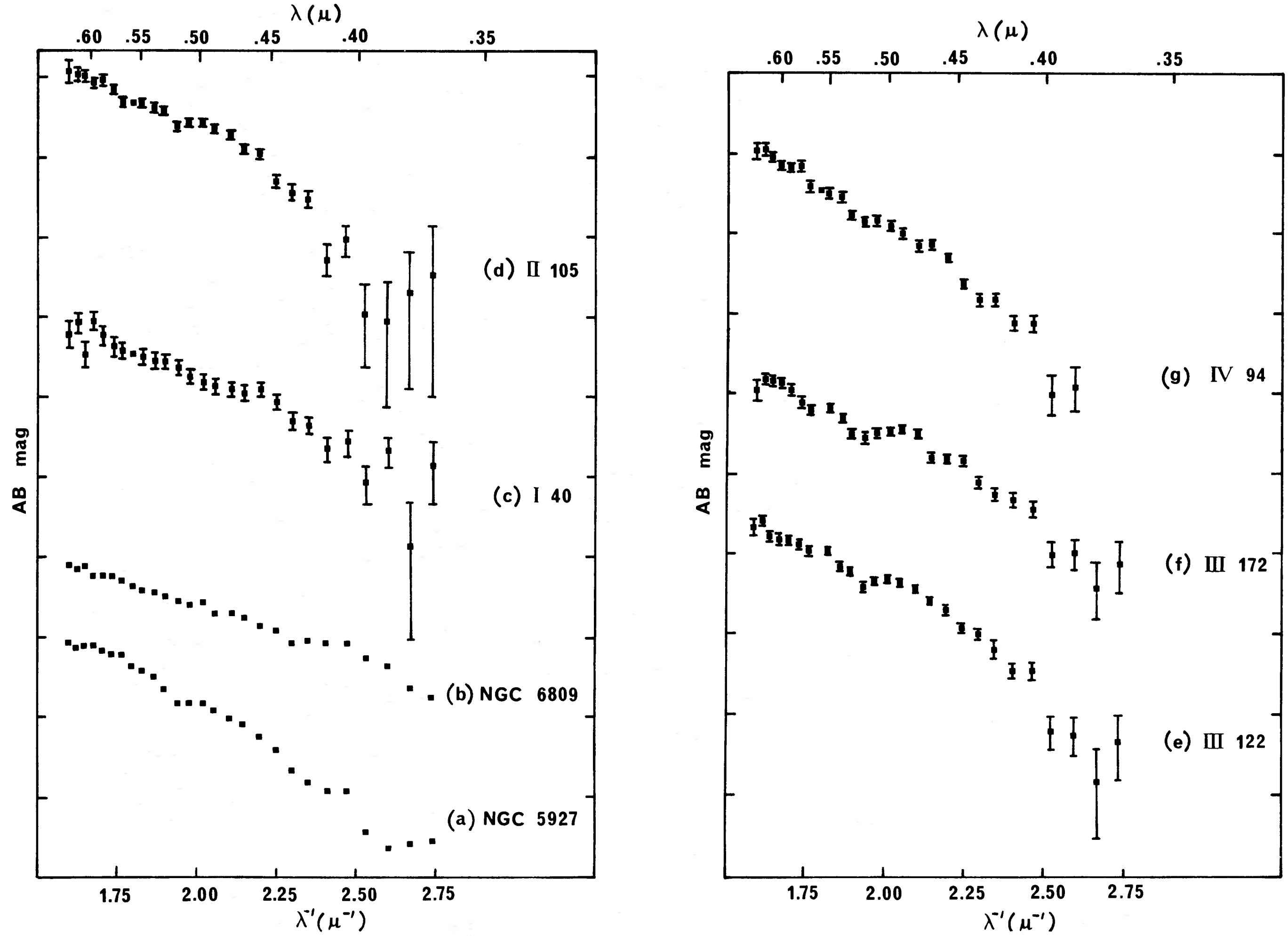


FIG. 3.—Our spectra for the five candidate clusters and, for comparison, for two globular clusters representing the extremes of metallicity in our own Galaxy (Paper I). The data have been binned in 100 Å intervals. The error bars are those arising from photon-statistical considerations only; no error bar is given for the bin containing the strong 5577 Å night-sky line, at which point the spectrum was artificially smoothed if a large residual signal was observed after sky subtraction. The ordinate scale is in magnitudes ($= -2.5 \log f_\nu$) with an arbitrary zero point; the tick marks are at intervals of 1 mag.

channel scanner used by ROS. Thus, for example, we present in Figure 4 the unsmoothed data of ROS and, for comparison, the spectrum of NGC 5927 in the same bins. We now define the parameter

$$\Delta' = 2.5 \log \left[\frac{F(3960, 4120)}{F(3800, 3960)}\right] , \quad (3)$$

where the wavelength limits are those of the two Oke scanner bins just shortward and just longward of the discontinuity. We have derived values of $\Delta'$ for the globular clusters studied at the AAT in 1979 and 1982 (Paper I); as Figure 5 shows, $\Delta'$ is related to our original $\Delta$ by

$$\Delta' = 1.093\Delta - 0.087 , \quad (4)$$

with a scatter of 0.011. Application of this relationship to $\Delta'$ as measured from the spectra of ROS (and given here in Table 3B) then yields the estimates of $\Delta$ which we present in the column labeled "$\Delta$(inferred)" in that table.

We treat the MH′ index similarly, defining it as in equation (2) (§ IV), except that now $(\lambda_1, \lambda_2, \lambda_3, \lambda_4) = (4920, 5080, 5240, 5400$ Å). We find from the globular clusters studied in Paper I that

$$\mathrm{MH}' = 1.463\mathrm{MH} + 0.001 , \quad (5)$$

with a scatter of 0.007. Application of this transformation to the ROS data then yields the estimates of MH which are given in Table 3B.

Comparison of the entries of Tables 3A and 3B reveals that there is no significant difference between our measurements and those of ROS for the two clusters in common. (The quoted errors come from our photon-statistical uncertainties and from the tabulated measurement errors given by ROS.) Thus in Table 3C we present the final estimates of $\Delta$ and MH for all clusters studied; for two clusters in common, the values were averaged, weighted as the inverse squares of the errors. In Figure 6 we plot the final values of $\Delta$ and MH for the six globular cluster candidates observed. Also plotted in the figure are the same quantities measured in the reddening-corrected spectra of the integrated light of globular clusters in our own Galaxy observed at the AAT with identical instrumentation (Paper I). Finally, the open circle represents the light of the central regions of M87 itself. Examination of the figure reveals

TABLE 3

METALLICITY-INDICATIVE FEATURE STRENGTHS

A. PRESENT MEASUREMENTS

| Cluster | Δ | MH |
|---|---|---|
| I 40 | 0.11(+0.23, −0.29) | −0.04(±0.09) |
| II 105 | 0.78(+0.44, −0.76) | 0.01(±0.05) |
| III 122 | 0.67(+0.21, −0.26) | 0.12(±0.04) |
| III 172 | 0.50(+0.17, −0.20) | 0.12(±0.04) |
| IV 94 | 0.70(±0.20) | 0.05(±0.04) |
| NGC 5927, Paper I | 0.577(±0.010) | 0.066(±0.003) |
| NGC 6809, Paper I | 0.131(±0.008) | 0.004(±0.007) |

B. ROS MEASUREMENTS

| Cluster | Δ′ | Δ(inferred) | MH′ | MH(inferred) |
|---|---|---|---|---|
| I 40 | 0.44(+0.15, −0.17) | 0.48(+0.14, −0.15) | 0.15(±0.05) | 0.10(±0.04) |
| III 156 | 0.13(+0.17, −0.21) | 0.20(+0.15, −0.19) | 0.00(±0.07) | 0.00(±0.05) |
| III 172 | 0.80(+0.09, −0.10) | 0.81(+0.08, −0.09) | 0.02(±0.11) | 0.01(±0.08) |

C. FINALLY ADOPTED VALUES

| Cluster | Δ | MH |
|---|---|---|
| I 40 | 0.36(±0.14) | 0.08(±0.05) |
| II 105 | 0.78(+0.44, −0.76) | 0.01(±0.05) |
| III 122 | 0.67(+0.21, −0.26) | 0.12(±0.04) |
| III 156 | 0.20(+0.15, −0.19) | 0.00(±0.05) |
| III 172 | 0.76(±0.12) | 0.10(±0.04) |
| IV 94 | 0.72(±0.20) | 0.05(±0.04) |

that the globular clusters associated with M87 generally lie on the metal-rich extrapolation of the sequence defined by Galactic globular clusters, albeit with large individual uncertainties.

## VIII. METALLICITY CALIBRATION

For calibration of the cluster metallicities, we follow the arguments given in Paper I, considering the data in two non-disjoint subsets.

### *a) More Metal-rich (MR) Objects (I 40, II 105, III 122, III 172, IV 94)*

In Paper I we determined the abundances of metal-rich clusters and galaxies using a slightly modified version of Burstein's (1979) calibration of the $(Mg)_0$ index introduced by Faber (1973); this index is similar to our own MH. We repeat those steps here, as follows:

1. We first improve our estimate of MH by averaging with it a value inferred from Δ (since MH and Δ are strongly correlated; the transformation used, $MH = 0.141\Delta - 0.022$, comes from Paper I). The direct and implied estimates of MH are weighted in the averaging according to the inverse squares of the formal errors, yielding $\overline{MH}$.

2. We convert $\overline{MH}$ to $(Mg)_0$ according to

$$(Mg)_0 = -2.65\overline{MH} + 0.006 \tag{6}$$

(Paper I).

3. Finally, we determine the cluster metallicity according to our modified version of Burstein's (1979) calibration:

$$(Mg)_0 = -0.18[Fe/H] - 0.206 . \tag{7}$$

The final estimates for these more metal-rich clusters are to be found in column (2) of Table 4.

### *b) More Metal-poor (MP) Objects (I 40, II 105, III 156)*

For these clusters we follow the procedures of Paper I in reducing the MH observations to an equivalent Δ. That value is averaged with the directly measured Δ to yield a weighted average $\bar{\Delta}$, which then yields a metallicity estimate via reference to Figure 8 of Paper I. The estimates formed in this way for the more metal-poor clusters are to be found in column (3) of Table 4.

The first of the calibration procedures is to be preferred for clusters which are more metal-rich than $[Fe/H] \sim -0.8$. Because there is some uncertainty over the exact regime of applicability of the calibrations, we have treated two clusters in the intermediate region (I 40 and II 105) in both ways. Inspection of Table 4 reveals that there is not a large difference in the inferred metallicities, considering the purely random errors of the determinations. In the fourth column in Table 4 we present the final metallicities which we adopt for all the clusters studied.

## IX. DISCUSSION

In their analysis, ROS concluded that the average metallicity of a globular cluster in M87 was $[Fe/H] \sim -0.7$. This conclusion was based upon a composite spectrum from the three objects observed and is of course sensitive to the abundance scale for globular clusters in our own Galaxy, since these are the ultimate calibrators. That scale has lately been revised (see Pilachowski 1984 for a summary), principally in the sense that the most metal-rich clusters are now recognized as being somewhat more metal-poor than was once thought. Ignoring this effect for the moment, we may simply put the individual line strength indices $L$ given in Table 2 of ROS into their calibration to yield individual metallicity estimates of $-0.6 \pm 0.3$,

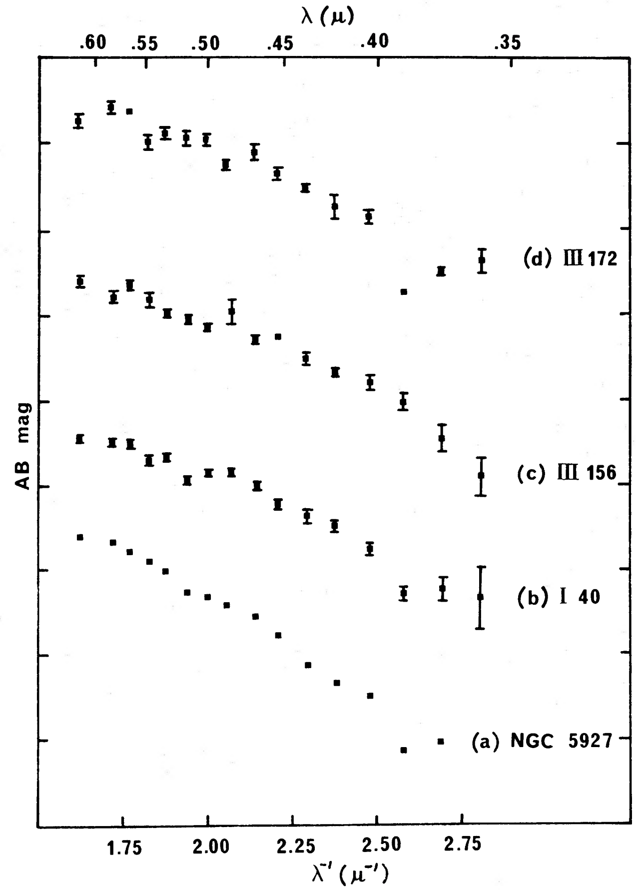


FIG. 4

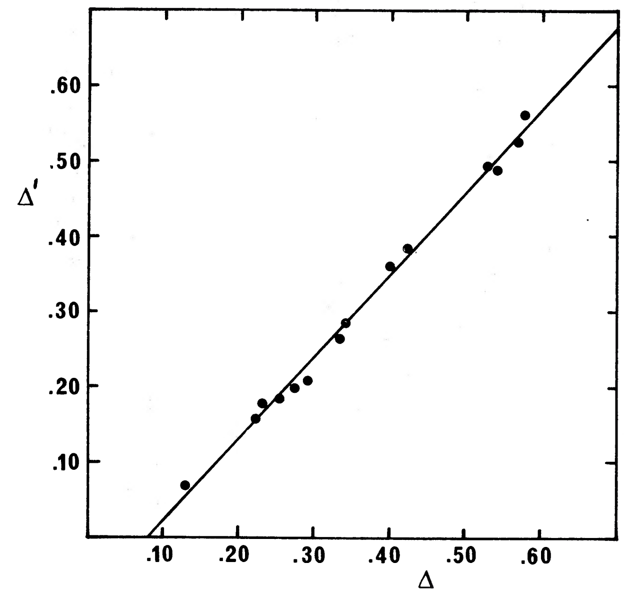


FIG. 5

FIG. 4.—Spectra observed by ROS for three candidate clusters in M87, plotted directly from their tabulations. The ordinate scale is in magnitudes, with arbitrary zero points; the tick marks are at 1 mag intervals. Also shown is the reddening-corrected spectrum of the metal-rich ([Fe/H] = −0.65) Galactic globular cluster NGC 5927 (from Paper I) rebinned to the wavelength intervals used by ROS.

FIG. 5.—Relationship between the indices $\Delta'$ and $\Delta$, defined in the text, as measured in the reddening-corrected spectra of Galactic globular clusters observed at the Anglo-Australian Telescope in 1979 and 1982 (and further described in Paper I). The fitted line is a least-squares regression with the equation $\Delta' = 1.093\Delta - 0.087$.

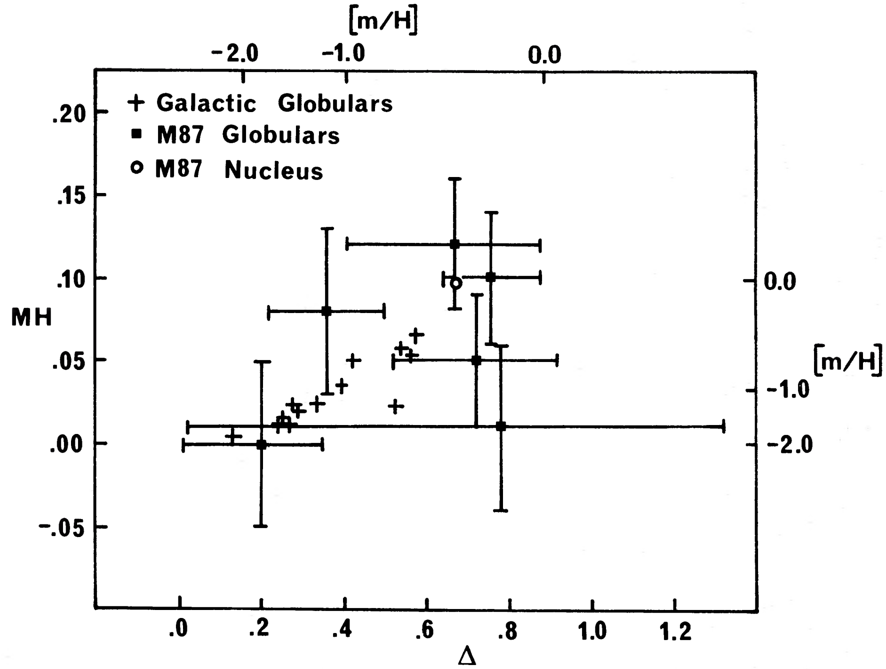


FIG. 6.—Observed values of the MH index and Δ for globular clusters in the Galaxy (from Paper I), for the globular clusters associated with M87, and for the nuclear light of M87 itself. The metallicity scales indicated are those implied by the calibrations derived in Paper I.

TABLE 4

DERIVED CLUSTER METALLICITIES

| Cluster | [Fe/H]$_{MR}$ | [Fe/H]$_{MP}$ | [Fe/H] | $r$ (arcmin) | $r$ (kpc) | $V$ |
|---|---|---|---|---|---|---|
| I 40 ............ | $-0.6 \pm 0.3$ | $-0.9 \pm 0.5$ | $-0.7 \pm 0.3$ | 3.3 | 13 | 19.50 |
| II 105 .......... | $-0.8 \pm 0.4$ | $-0.9 \pm 1.1$ | $-0.8 \pm 0.3$ | 5.2 | 21 | 19.73 |
| III 122 ......... | $+0.3 \pm 0.3$ | | $+0.3 \pm 0.3$ | 5.4 | 22 | 19.76 |
| III 156 ......... | | $-1.7 \pm 0.7$ | $-1.7 \pm 0.7$ | 4.8 | 19 | 20.35 |
| III 172 ......... | $+0.3 \pm 0.3$ | | $+0.3 \pm 0.3$ | 4.9 | 20 | 19.75 |
| IV 94 ........... | $-0.1 \pm 0.3$ | | $-0.1 \pm 0.3$ | 3.4 | 14 | 19.99 |

NOTE.—In cols. (2) and (3) the subscripts MR and MP refer respectively to the more metal-rich and the more metal-poor subsets of objects (see text); col. (4) lists the final, adopted metallicities.

$-1.3 \pm 0.3$, and $-0.3 \pm 0.3$ for clusters I 40, III 156, and III 172, respectively. These estimates are in quite good agreement with the results given in our Table 4, except that their scale appears to be somewhat compressed. (On the "new" abundance scale, this compression will be somewhat more pronounced.) In general, their conclusion regarding the metallicity of the composite or average spectrum seems to have been fairly well founded.

The findings of the present paper differ from those of ROS in some important ways. First, of the three clusters newly studied here, only one (II 105) is more metal-poor than the average cluster discussed by ROS, and that one only insignificantly; the other two are considerably more metal-rich. A simple mean of all the metallicities yields a new estimate of [Fe/H] = $-0.5 \pm 0.4$ for an average cluster. One indisputable conclusion is that the mean metallicity in this small sample is considerably higher than the mean for the globular clusters in our Galaxy, where [Fe/H] = $-1.2$ on the old scale (Harris and Racine 1979); the mean metallicity will be somewhat lower still on the new scale. Of course, until a much larger sample is available, it is unknown how this average compares with a truly representative average for the thousands of clusters in M87.

A second difference is that individual globular clusters in M87 attain metallicities which are higher than the highest seen in our Galaxy, although this statement cannot be made with the same confidence as that concerning the mean metallicity because of the large random errors of measurement. It is also important to be certain that our corrections for differential refraction, described in § V, do not introduce systematic errors. We are confident that this is so, for the following reasons:

1. The metallicity determinations depend in large part upon the measurements of the MH index. The wavelength dependence of atmospheric refraction is such that the index will be essentially unaffected by dispersion, given our aperture sizes. In any event, MH is an index measured symmetrically with respect to two regions of nearby continuum, and to first order

small differential losses will have no effect.

2. Our corrected continua agree well with those of ROS, who did not experience the same problem and who were able to judge the correctness of their continua on the basis of inferred broad-band colors.

3. Perhaps most important, the most likely error in our adopted correction would be such as to lead to underestimates of cluster metallicity in any event. The corrections described in § V assumed that the guided image corresponded to a 5500 Å image. Given the relatively blue response of the S20 photocathode, we are perhaps more likely to guide upon a bluer image, which means that we will have overcompensated for atmospheric dispersion: Δ, and thus [Fe/H], will have been underestimated.

For these reasons we are confident of the reliability of our principal conclusions: that in this small sample of clusters the mean metallicity is higher than in the Galaxy; that a full range of metallicities comparable to that in the Galaxy is seen; but that individual clusters making up a large fraction of the sample are more metal-rich than the most metal-rich seen in our own Galaxy.

## X. INTERPRETATION

In Table 4 we presented the final metallicities adopted for the globular clusters in the M87 field. There we also tabulated two parameters of interest: the position of the cluster relative to the center of M87, expressed both as an angular offset in minutes of arc and as a projected separation in kiloparsecs (assuming a true distance modulus of 30.7 for M87; Hanes 1979), and the $V$-magnitudes of the clusters (Hanes 1971). We now consider possible interpretations of the observed distribution of metallicities.

1. Van den Bergh (1980) and Alcaino (1979) have pointed out that there is no obvious correlation of cluster metallicity with intrinsic luminosity for the globular clusters in our Galaxy. However, van den Bergh presents some weak evidence demonstrating that such a correlation may be present in the globular cluster system of M31, suggesting that the few most luminous clusters found in this populous sample may be sufficiently massive to retain some of the enriched gas ejected by the first generation of stars. He points out that the very luminous globular cluster $\omega$ Cen, for which $M_V = -10.3$ (Harris and Racine 1979), has a range of heavy-element abundance (Freeman 1980) which may be a manifestation of such a process. If the effect is important, then it will surely occur in the M87 globular clusters studied here: they have integrated absolute visual magnitudes in the range $-10.4$ to $-11.2$ (at a distance modulus of $30.7 \pm 0.3$; Hanes 1979). It may be significant that the most metal-poor cluster in the sample, III 156, is the least luminous studied (see Table 1). This accords with our expectation that self-pollution should be less important in the intrinsically fainter clusters. On the other hand, Strom *et al.* (1981) find that the average broad-band $(B-R)$ colors of the globular clusters in the field of M87 are independent of luminosity, which would seem to suggest that there is no strong correlation, if the colors are sensitively enough dependent upon metallicity to justify this interpretation. A clarification of this question will require spectroscopic analysis of many of the fainter clusters in the field.

2. Strom *et al.* (1981) have demonstrated that there is a radial trend of the mean color of globular clusters surrounding M87 in the sense that those nearer the center are redder and, by inference, more metal-rich; this trend was also apparent in the data of Hanes (1971). A similar correlation between galactocentric distance and cluster metallicity is well established for the clusters in our own Galaxy (Harris 1976). However, inspection of our Table 4 reveals that there is no particular correlation between inferred metallicity and position for the small sample studied here. In particular, the most metal-poor cluster (III 156) lies at a projected distance of about 19 kpc, as do clusters II 105, II 122, and III 172, all of which are considerably more metal-rich. The two clusters nearest the center of M87, I 40 and IV 94, are not the most metal-rich examples. Of course the statistics are poor, and the projection factors are unknown; moreover, nothing is known of the orbital elements for the clusters around M87, so the mix of metallicities to be expected at a given galactocentric distance is entirely unpredictable. The strongest conclusion one can draw is that the evidence does not strongly support the existence of a metallicity gradient. It must be remembered that the clusters are seen at projected distances of $>13$ kpc (or larger, if the distance modulus for M87 is greater than 30.7); in our own Galaxy these would be considered halo clusters, and the absence of a pronounced gradient would be no surprise (although the high mean metallicity would be).

3. It has been suggested by van den Bergh (1969, 1980) and Racine (1980) that the metallicities of globular clusters associated with more massive galaxies are higher on average than those of globular clusters in less massive systems, independent of any correlation between metallicity and cluster luminosity within a population. Generally these speculations have been based upon broad-band photometry, the interpretation of which may be subject to subtle random errors and reddening effects (Hanes 1977*b*, 1980; van den Bergh 1980). It is certainly true that the low-mass Fornax dwarf spheroidal galaxy has no globular cluster more metal-rich than $[Fe/H] = -1.2$ (Zinn and Persson 1981), in an admittedly small population of five, of which four have been spectroscopically analyzed. The M87 globular clusters seem to fit into this general picture, although the validity of the suggestion will have to await the study of many more clusters at fainter levels to clarify the status of alternative explanations such as the two discussed above.

## XI. CONCLUSIONS

The globular clusters associated with the giant elliptical galaxy M87 are on average considerably more metal-rich (at $[Fe/H] \sim -0.5$) than the average cluster ($[Fe/H] \sim -1.2$) in our own Galaxy, although the full range of observed metallicities may not be very different. A substantial fraction of the M87 clusters seem to be more metal-rich than the most metal-rich known globular clusters in the Galaxy. In this small sample, there is no evidence for a dependence of cluster metallicity upon projected galactocentric distance, although such a gradient has been inferred on photometric grounds (Strom *et al.* 1981). There is a suggestion that cluster metallicity depends upon luminosity, with fainter clusters being more metal-poor; such a relationship may be the manifestation of a self-enrichment process which is most important in extremely massive clusters. If this is the case, one prediction is that the average metallicity defined by a large number of clusters in the M87 field will be more like that seen in the globular clusters in our Galaxy.

Further observations are needed at considerably fainter levels to test various hypotheses but may need to await the Space Telescope. It would be especially important to measure cluster velocities to permit the identification of any dynamical subsystems and correlate these with cluster metallicities.

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