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THE GIANT BRANCH OF FORNAX

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ABSTRACT

The color-magnitude diagram of the giant branch of the Fornax system is presented. The photographic observations secured at Cerro Tololo and at Las Campanas are calibrated with a photoelectric sequence to $V = 19.70$. A wide giant branch comparable to the giant branch of ω Cen is observed. The dispersion suggests the existence of a range of abundances among the Fornax stars. A newly defined parameter measuring the slope of the upper giant branch, $\Delta V_{0,1.6-1.2}$, is used to compare the giant branch of Fornax to those of Population II systems.

Subject headings: galaxies: individual — galaxies: stellar content

I. INTRODUCTION

The Fornax dwarf elliptical galaxy (A0237 − 34, R.A. (1950) = $2^h37^m.8$, decl. = $-34°44'$) occupies an important position in understanding the makeup and evolution of the Local Group. Its mass lies midway between that of globular clusters and nearby dwarf irregulars such as IC 1613 (Hodge 1961, 1971). In the more-massive systems, young stellar components have generally been found (Hodge 1971) while a unique age seems most consistent with the diagrams of less-massive systems. Some of the companions of M31 have globular clusters as well as a young stellar component (Hodge 1973, 1974). The fact that Fornax is the only galaxy of its class in the Local Group containing globular clusters suggests the possibility that this galaxy might be closer from a population point of view to a dwarf elliptical such as NGC 205, than to other systems of lower mass such as Draco or Sculptor.

The present investigation reports a color-magnitude (C-M) diagram of Fornax to about $V = 20.0$; observations are based on plate material obtained with the 1.5 m reflector and the Yale 1 m telescope of CTIO and the du Pont 2.5 m telescope.

II. OBSERVATIONS

A photoelectric sequence (Table 1, Fig. 1) was observed south of the main body of Fornax. Bright standards *A–Q* were measured in 1968 using a photometer attached to the CTIO 1.5 m telescope and equipped with a 1P21 photomultiplier and integrators, following precepts described by Demers (1969). From the dispersion of two measures, we estimate the internal errors on the mean values listed to be on the average $0^m.02$ for $V < 18$ and $B < 17$; and $0^m.06$ for $18 < B < 19$.

The fainter standards (R–X) were observed in 1972 with the three-channel photometer attached to the CTIO 1.5 m reflector. This photometer employs a dichroic beam splitter followed by standards filters to separate the V and B bands. The procedure as well as the precision of this type of photoelectric photometry has been described previously (Demers and Kunkel 1976). A larger group of stars observed once was preferred to a shorter list of stars observed more than once. Stars used in this extension of the earlier p.e. sequence were selected with sky-limited 60 inch plates to be free of background contamination.

A third group of standards (numbers) were measured in 1978 with the two-channel photometer attached to the 0.9 m telescope of CTIO. Some of the fainter stars were measured with the 4 m telescope using the temporary photometer fitted to the cassegrain spectrograph. As mentioned above, the precision of this type of photometry has been described by Demers and Kunkel (1976). Star N appears nonstellar and star 6737 shows large residuals; they were not used in the final reduction.

The photographic material consists of two series of plates. Series A consists of a pair of IIa-D + Schott RG 495 and one IIa-O + Schott GG 385 (CTIO 1 m telescope) plus two 103a-D + W16 and two 103a-O + W2C (du Pont 2.5 m telescope). For series B we combined the four du Pont plates with four plates taken with the CTIO 1.5 m telescope; two 103a-D + RG 495 and two 103a-O + GG 385.

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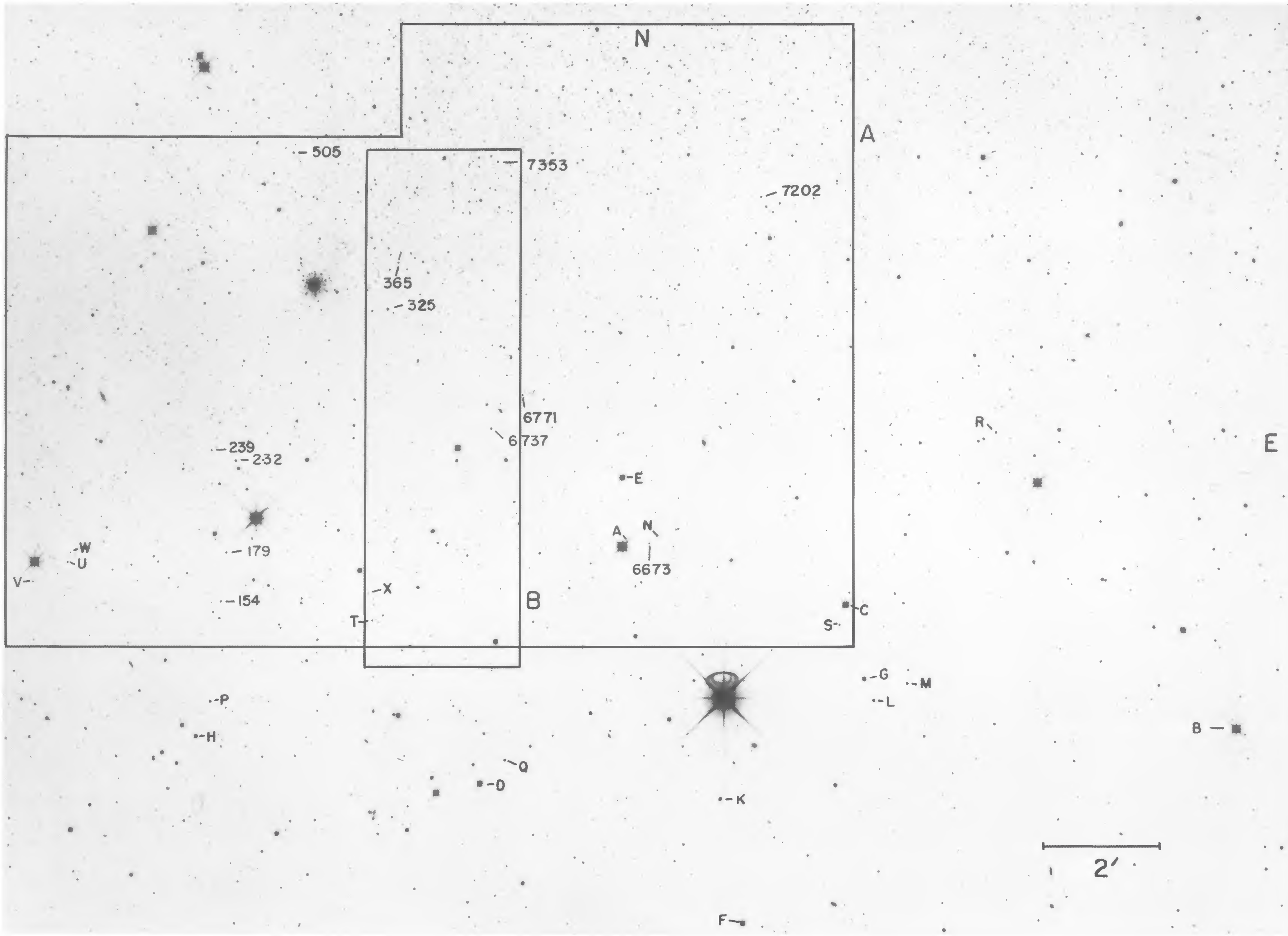

FIG. 1.—Southern part of Fornax (visual plate). The p.e. sequence stars are identified as well as the very red star No. 11365. Areas of series A and series B are outlined.

TABLE 1

PHOTOELECTRIC SEQUENCE

Star	V	$B-V$	n	V_{pg}	B_{pb}
A	10.67	0.58	2	...	...
B	11.35	1.14	2	...	...
C	12.15	0.51	2	...	...
D	12.76	0.57	2	...	...
E	12.80	0.61	3	...	...
F	13.58	0.92	2	...	...
G	13.88	0.53	3	...	...
H	14.44	0.97	2	...	...
K	14.97	0.65	2	...	...
L	15.65	0.51	2	15.52	16.11
M	16.30	0.86	2	16.34	17.26
N	16.30	0.65	2	...	...
P	17.17	1.58	2	17.16	18.66
Q	17.23	1.34	2	17.20	18.54
R	17.02	0.93	1	17.04	17.97
S	18.24	1.68	1	18.46	19.87
T	18.53	1.63	2	18.50	20.19
U	18.85	1.51	1	18.83	20.45
V	19.41	1.31	1	19.40	20.70
W	19.63	1.07	1	19.67	20.81
X	19.70	1.28	1	19.82	20.99
6673	18.93	1.55	1	18.86	20.36
6737	18.02	1.88	1	variable?	...
6771	18.24	1.55	1	18.29	19.82
7202	18.33	1.19	1	18.27	19.55
7353	18.26	1.26	1	18.37	19.76
11154	18.82	1.49	1	18.66	20.28
11179	18.56	1.66	1	18.42	20.22
11232	17.90	1.38	1	17.81	19.29
11239	18.93	1.40	1	18.86	20.43
11325	17.68	1.94	1	17.68	19.55
11505	17.98	1.70	1	18.16	19.59

The instrumental magnitudes (b_{aO}, v_{aD}) from the iris photometer measures were reduced to the B, V system by means of the transformations

$$B_{aO} = b_{aO} - 0.09(B - V)\,,$$

$$V_{aD} = v_{aD} + 0.09(B - V)\,.$$

Two hundred and fifty stars were iris-measured on plates of series A. They represent all stars brighter than $B = 20.5$ mag in an area of 470 arcmin^2 located in the south part of Fornax (Fig. 1). The C-M diagram of these stars is shown in Figure 2 and serves to define the top of the giant branch.

All stars visible in an area of 100 arcmin^2 on plates of series B were also iris-measured. This second sample of 180 stars is limited to $B \lesssim 21.2$ mag and forms an unbiased sample of the giant branch.

III. COLOR-MAGNITUDE ARRAYS

The C-M diagram for Series A is shown in Figure 2. Foreground contamination by field stars is not negligible, even though the sample region lies well within the tidal radius of Fornax determined by Hodge and Smith (1974). However, a comparison of stellar frequency functions in the color range $1.2 < (B - V) < 2.0$ with that for the color range $0.6 < (B - V) < 1.0$ indicates a marked increase in the red group at $V = 18.2$ mag, suggesting that the top of the giant branch sets in at about this magnitude. Photometry toward the north galactic pole by Prociuk and Racine (1979) shows that the number of stars in the two color intervals considered here is approximately the same to $V = 20.0$ mag. Thus the surplus of red stars observed in the direction of Fornax at $V \gtrsim 18.2$ mag must be red giants in Fornax and not red dwarfs in the Galaxy.

Because of the large angular size of Fornax, a test of the membership of the observed giant branch by comparing an area outside the tidal radius with the central regions is not feasible with the present plate material. Rather, we tested the radial dependence of the number of stars brighter than $V = 19.0$ mag in the two color groups by comparing a small northern region, closer to the center, with a region on the south side of Figure 1. We found that the number of stars with $(B - V) > 1.2$ is 3 times higher in the area closer to the center while the number of stars with $(B - V) < 1.0$ is the same in both areas. This confirms the Fornax membership of the red group.

The series B data extend uniformly to a faint limit of $B = 21.2$ mag. The calibration curves established from the iris measures were simply extrapolated beyond the limits of the p.e. sequence ($V = 19.7$ mag, $B = 21.0$ mag). Because of the observed run of the residuals with magnitudes, we feel confident of our slight extrapolation to $V = 20.0$ mag and $B = 21.2$ mag. Magnitudes fainter than $V = 20.0$ are of low precision. The C-M diagram in Figure 3 shows about one-fifth the number of foreground stars of series A, consistent with the smaller sample size. Series B is a smaller but unbiased sample over the entire tip of the giant branch and shows well the location of the core of the giant branch extending from $V = 18.25$ mag at $B - V = 1.8$ through $V = 19.0$ mag at $B - V = 1.4$ to $V = 19.85$ mag at $B - V = 1.1$. This sample contains a very red (slightly variable) star No. 11365, $V = 18.3$ mag, $B - V = 2.5$. It is identified on Figure 1. Series A does not give an unbiased description of the giant branch because of the brighter limit. It does, however, give a clear indication of the upper envelope of the giant branch which extends from $V = 17.75$ mag at $B - V = 1.7$ through $V = 18.1$ mag at $B - V = 1.4$ to $V = 18.6$ mag at $B - V = 1.1$ lying more than half a magnitude above the giant branch core. The giant branch of Fornax is clearly very wide, reminiscent of ω Centauri (Woolley 1966).

IV. COLOR EXCESS

Since Fornax is situated at $b = -66°$, the galactic absorption in this direction should be small. We do not have at the present time a direct estimate of the color excess of Fornax. Two measures of the H I column density (Tolbert 1971), some 10° from Fornax, yield a color excess $E(B - V) = 0.05$, using Knapp's (1975) equation.

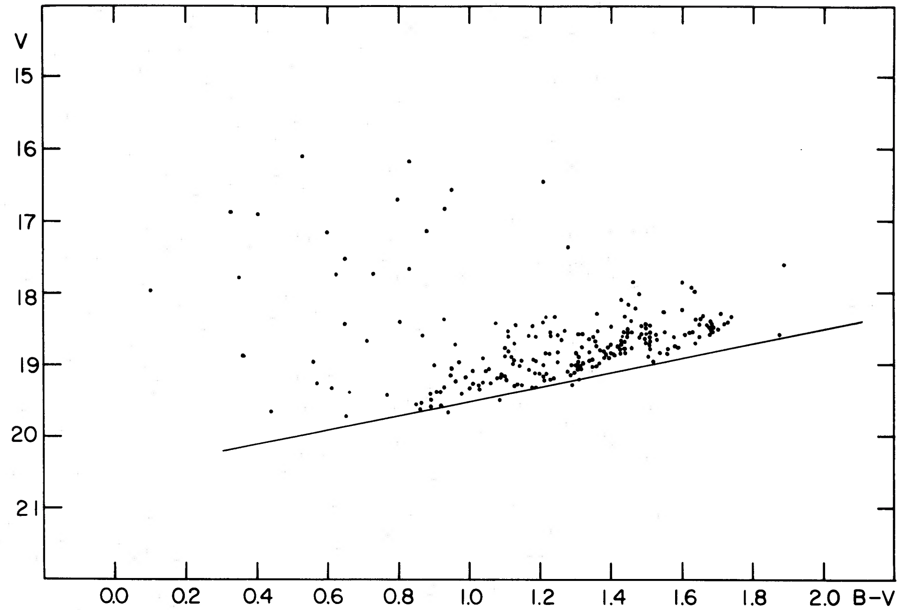

FIG. 2.—C-M diagram of series A; no color excess correction has been applied. The line represents the limiting magnitude of the sample at $B = 20.5$.

There are no known galactic globular clusters in the direction of Fornax. NGC 288 at the south galactic pole and NGC 1261 at $b = -50°$, are situated some 25° away. Racine (1973) estimated that the color excess of the former is $E(B - V) = 0.04$, while the latter is essentially free of absorption. The observed colors of the globular clusters of Fornax could in principle be used to estimate its color excess. Only three clusters have known spectral types, and the color of one of them is ill defined (van den Bergh 1969). Following Racine (1973) and transforming van den Bergh's types into Kinman's (1959) spectral types, one obtains $E(B - V) = 0.06 \pm 0.06$.

We can then assume for the purpose of this discussion that the color excess of Fornax is of the order of a few hundredths of a magnitude, a value expected for such high galactic latitude. A value of $E(B - V) = 0.0$ has been adopted.

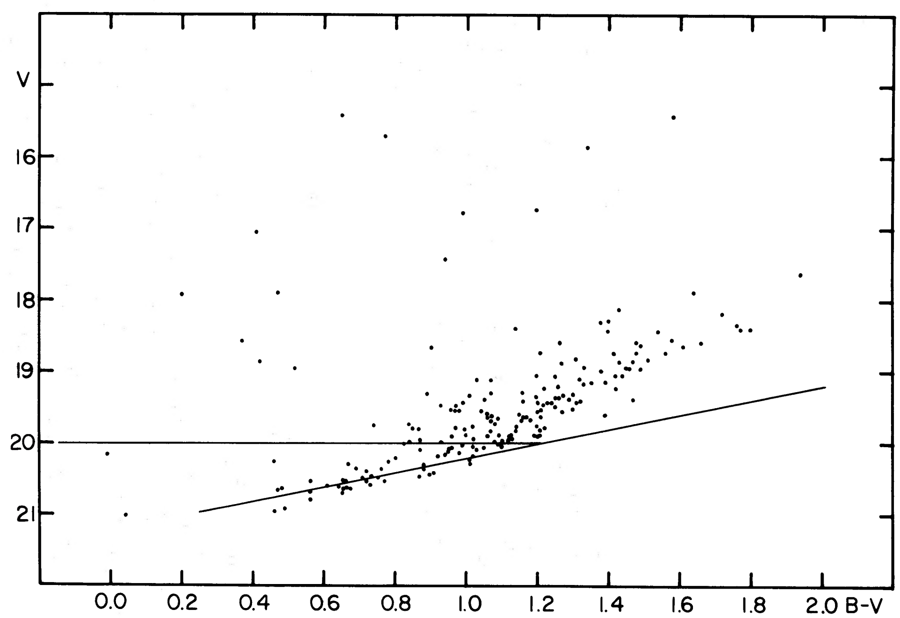

FIG. 3.—C-M diagram of series B; no color excess correction has been applied. The lines indicate the confidence limits of the photometry.

V. DISCUSSION

The dispersion of the red giants on the C-M diagram cannot be explained by differential reddening, since the color excess toward Fornax is almost certainly small, and the lack of neutral hydrogen or young stellar associations within Fornax points to negligible absorption arising within that galaxy. No obvious large-amplitude variables have been detected in the two areas examined.

We conclude that the width of the giant branch is intrinsic to the Fornax giants. One can draw a parallel between Fornax and ω Cen, the best-known system with a similarly wide giant branch (Cannon and Stobie 1973). For ω Centauri, present thinking tends to favor mixing as the dominant mechanism accounting for abundance variations, and, consequently, widening of the giant branch (Norris and Bessell 1977; Dickens and Bell 1976; Bessell and Norris 1976).

In the case of Fornax, primordial abundance variation, or the formation of second-generation stars, cannot be excluded *a priori*. Spectroscopic and photometric observations of the brighter globular clusters of Fornax show differences that are most probably associated with differences in abundance (van den Bergh 1969; Danziger 1973; Harris and Canterna 1977).

Estimates of the chemical composition of old stellar systems have used both the height and the slope of the giant branch (Sandage and Wallerstein 1960; Hartwick 1968). In these techniques the position of the horizontal branch must be known. Implicit in this earlier work is the suggestion that the influence of the abundance on the appearance of the giant branch may affect not only the base of the giant branch but also the region approaching the tip. In our data the giant branch is seen redward of $(B - V) = 1.2$, and comparison with globular cluster data is possible from this point to the tip. We define $\Delta V_{0,1.6-1.2}$ as the difference in the height of the giant branch at colors $(B - V)_0 = +1.6$ and $+1.2$. These differences are listed in Table 2 for those clusters in the catalog of Philip, Cullen, and White (1976) for which a ridge line defining the core of the giant branch could be drawn by eye, and for which abundance estimates of individual stars are available. Color excesses were taken from Harris (1977). Data of Sculptor and Draco are based, respectively, on the results of Kunkel and Demers (1977), Stetson (1979), and Zinn (1978).

A few clusters with only an [m/H] estimate from Kukarkin (1974) could be added to our list. Because of the low weight attached by Kukarkin himself to these estimates, we prefer to exclude them. To indicate more clearly the relationship for metal-rich clusters the integrated photometry of Harris and Canterna (1977) was included, using the same primary data for its calibration. We did not use ω Centauri because of its well-known range of abundances.

We present in Figure 4 the relation between the $\Delta V_{0,1.6-1.2}$ and the metal abundance of each system. A line fitted by eye is drawn through the points. The largest values of $\Delta V_{0,1.6-1.2}$ are found in those systems with the greatest metal abundance, such as NGC 6352 and M71, while clusters of extreme deficiency show the lowest values (when stars as red as $B - V = 1.6$ exist) in accordance to the curved shape of their giant branches.

The core of the giant branch of Fornax (Fig. 3) lies along a line that yields a $\Delta V_{0,1.6-1.2}$ of 1.0, and this value would suggest [Fe/H] ≈ -0.5. We believe this finding to be primarily of qualitative significance. The

TABLE 2

$\Delta V_{0,1.6-1.2}$ FOR POPULATION II SYSTEMS

OBJECT				
NGC	Name	$\Delta V_{0,1.6-1.2}$	[Fe/H]	REFERENCE
104	47 Tuc........	1.04	−0.4	3
362	....	0.88	−1.0	3
5024	M53..........	0.70	−1.9	4, 5
5272	M3...........	0.66	−1.8	1
5904	M5...........	0.83	−1.05	3, 4, 5
6171	M107.........	1.02	−0.7	4, 5
6205	M13..........	0.63	−1.6	1
6341	M92..........	0.44:	−2.4	2
6352	....	1.04	0.0	3
6637	M69..........	1.13	−0.4:	10
6656	M22..........	0.8	−1.7	5
6712	....	1.1:	−0.4	5
6723	....	0.79	−0.8:	10
6752	....	0.81	−1.70	8
6838	M71..........	1.03:	−0.1	3, 4, 5
7006	....	0.84:	−1.5	3, 4
...	Pal 4..........	0.4:	−2.4	6
...	Pal 12.........	0.9	−1.7	6
...	Draco.........	0.73	−1.86	7
...	Sculptor.......	0.9	−1.9	9

REFERENCES.—(1) Cohen 1978; (2) Cohen 1979; (3) Hesser *et al.* 1977; (4) Searle and Zinn 1978; (5) Butler 1975; (6) Canterna and Schommer 1978; (7) Zinn 1978; (8) Mallia 1977; (9) Kunkel and Demers 1977; (10) Harris and Canterna 1977.

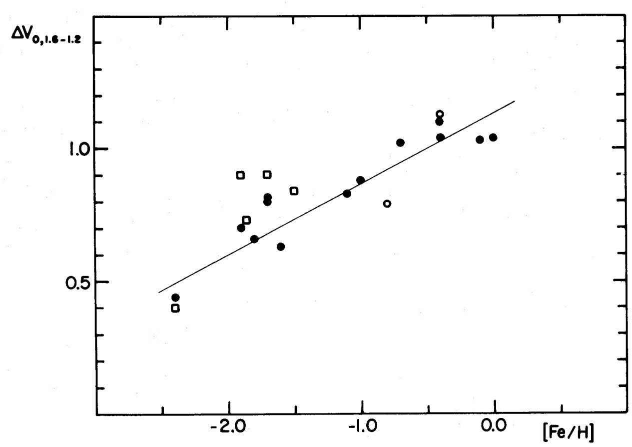

FIG. 4.—The $\Delta V_{0,1.6-1.2}$ of Population II systems presented as a function of their metal abundance. The line is fitted by eye to the data points. *Squares*, outer halo systems; *circles*, two clusters with integrated photometry.

upper envelope of the giant branch (Fig. 2) yields a $\Delta V_{0,1.6-1.2}$ of 0.6, suggesting a population component of more pronounced deficiency. We recall that Zinn (1978) and Norris and Bessell (1978) find a scatter of abundances in Draco and Sculptor as well. These two galaxies do not have a notably wide giant branch.

The ranges of abundances in Sculptor and Draco have been tentatively interpreted in terms of primordial inhomogeneities. This interpretation may also apply to Fornax, but the possibility of second-generation stars cannot be excluded. We must state here that it is not clear to us how to untangle effects on the shape of the observed giant branch due to age and/or metallicity variations. Fornax is at least 20 times more massive than Sculptor or Draco, and is surrounded by five (or perhaps six) globular clusters. Spectroscopic and photometric observations of the integrated light of four of the clusters (van den Bergh 1969; Danziger 1973; Harris and Canterna 1977) yield an abundance range of $-2.1 < [Fe/H] < -1.4$, with an average of -1.9. Photographic photometry of the outer giants, not affected by background variations, in clusters 1 and 5 by Verner (1978), shows that for these clusters the giants lie over or near the upper envelope defined by the field stars of Fornax. These results indicate that most of the clusters are not as metal-rich as the stars defining the core of the giant branch of Fornax, suggesting that an enrichment phase occurred during the early evolution of Fornax. Moreover, in our relatively small sample, the discovery of one very red star at the level of the tip of the giant branch may be indicative of the presence of an intermediate population. This star is redder than the CH stars in ω Centauri and the halo N stars defined by Eggen (1972), but is comparable in color to the carbon stars found near NGC 419, an intermediate-age SMC cluster (Lloyd Evans 1978). Star No. 11365 is too red to be a nearby red dwarf. However, as a member of Fornax, its absolute magnitude would be approximately $M_v \approx -3$ mag, in the range of magnitudes of carbon stars. Visual inspection of adjacent areas has revealed two other fainter, very red stars, with blue images too faint to be measured.

The presence of a range of abundances occasioned by the formation of second-generation stars seems to us a more likely explanation for the width of the giant branch. This would be in line with Hodge's (1973, 1974) observation that the dwarf ellipticals of the Local Group that are more massive than Fornax all show a component of hot luminous stars.

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