

HUBBLE SPACE TELESCOPE PHOTOMETRY OF THE FORNAX DWARF SPHEROIDAL GALAXY: CLUSTER 4 AND ITS FIELD

R. BUONANNO,¹ C. E. CORSI,¹ M. CASTELLANI,¹ G. MARCONI,¹ F. FUSI PECCI,² AND R. ZINN³

Received 1999 February 16; accepted 1999 July 9

ABSTRACT

Using observations from the *Hubble Space Telescope* archive, color-magnitude diagrams (CMDs) have been constructed for globular cluster 4 in the Fornax dwarf spheroidal galaxy and its surrounding field. These diagrams extend below the main-sequence turnoffs and have yielded measurements of the ages of the populations. The most prominent features of the CMD of the Fornax field population are a heavily populated red clump of horizontal-branch (HB) stars, a broad red giant branch (RGB), and a main sequence that spans a large range in luminosity. In this CMD, there are very few stars at the positions of the HBs of the five globular clusters in Fornax, which suggests that only a very small fraction of the field population resembles the clusters in age and chemical composition. The large span in luminosity of the main sequence suggests that star formation began in the field ≈ 12 Gyr ago and continued to ≈ 0.5 Gyr ago. There are separate subgiant branches in the CMD, which indicates that the star formation was not continuous but occurred in bursts. The CMD of cluster 4 has a steep RGB, from which we estimate $[\text{Fe}/\text{H}] \approx -2.0$. This is considerably lower than estimates from the integrated light of the cluster, and the origins of this discrepancy are discussed. Cluster 4 has a very red HB and is, therefore, a prime example of the second-parameter effect. Comparisons of cluster 4 with the other Fornax clusters and with M68, a very metal-poor globular cluster of the Galactic halo, reveal that cluster 4 is ≈ 3 Gyr younger than these other clusters, which have much bluer HBs. This age difference is consistent with the prediction that age is the second parameter to within the uncertainties. The CMD of cluster 4 is virtually identical to that of the unusual globular cluster of the Galactic halo Ruprecht 106, which suggests that they have very similar ages and chemical compositions. We discuss the possibility that cluster 4 also resembles R106 in having a higher $[\text{Fe}/\text{H}]$ than is indicated by its steep RGB and also a lower $[\alpha/\text{Fe}]$ ratio than is usual for a globular cluster, as indicated by some recent observations of R106. The CMDs of the five Fornax clusters indicate that cluster age is a major—but probably not the sole—second parameter. Buonanno et al. recently concluded that cluster density probably influenced the HB morphologies of clusters 1, 2, 3, and 5. Despite a very large difference in central density, the HBs of cluster 4 and R106 are very similar. This suggests that density may act as a second parameter in clusters that have HBs that are on the verge of moving toward the blue or are already blue for another reason, such as very old age.

Key words: galaxies: dwarf — galaxies: individual (Fornax) — galaxies: star clusters — galaxies: stellar content — Local Group — stars: distances — stars: horizontal-branch

1. INTRODUCTION

The dwarf spheroidal (dSph) galaxies of the Local Group provide an opportunity to study star by star the histories of star and star cluster formation in galaxies of the very lowest mass. While once these galaxies were thought to be relatively simple systems composed entirely of very old stars, they are now known to have experienced much more complex histories (see Da Costa 1998 and Mateo 1998 for recent reviews). The Fornax dSph galaxy is no exception, for it contains very old globular clusters (GCs; Buonanno et al. 1998b, hereafter BEA98), many stars of intermediate age, and even stars younger than 0.1 Gyr (Stetson, Hesser, & Smecker-Hane 1998). There remain, however, many unanswered questions regarding Fornax, which is one of the most thoroughly studied galaxies of this type. For example, did the star formation in Fornax occur in bursts, as it did in the Carina dSph galaxy (Smecker-Hane et al. 1994, 1996;

Mighell 1997), or was it relatively continuous? Also, what fraction of the field population in Fornax resembles its five GCs in age and chemical composition?

For more than two decades there has been speculation (see Zinn 1993 and Mateo 1998 for reviews) that the outer halo of the Milky Way was created by the tidal destruction of dwarf galaxies, particularly ones that resembled the dSph galaxies. Although the Sagittarius dSph galaxy is now in the process of being destroyed and blended into the halo, it remains to be seen whether or not this was the only or even the primary mechanism by which the halo formed. Additional observations of the cluster and field populations in Fornax and the other dSph galaxies are needed to test this idea, which will not be so simple, because the dSph galaxies that have survived to the present may have undergone much more evolution than the hypothetical ones that were destroyed in the past, perhaps at widely different epochs.

The most massive dSph galaxies, Fornax and Sagittarius, have their own systems of globular star clusters, which are very interesting objects in their own right. In the case of Fornax, the clusters can be considered to be at essentially the same distance from us, which means that comparisons among them are independent of the uncertain distance scale.

¹ Osservatorio Astronomico di Roma, via Frascati 33, I-00040 Monte Porzio Catone, Roma, Italy.

² Stazione Astronomica di Cagliari, I-09012 Capoterra, Cagliari, Italy.

³ Department of Astronomy, Yale University, Box 208101, New Haven, CT 06511.

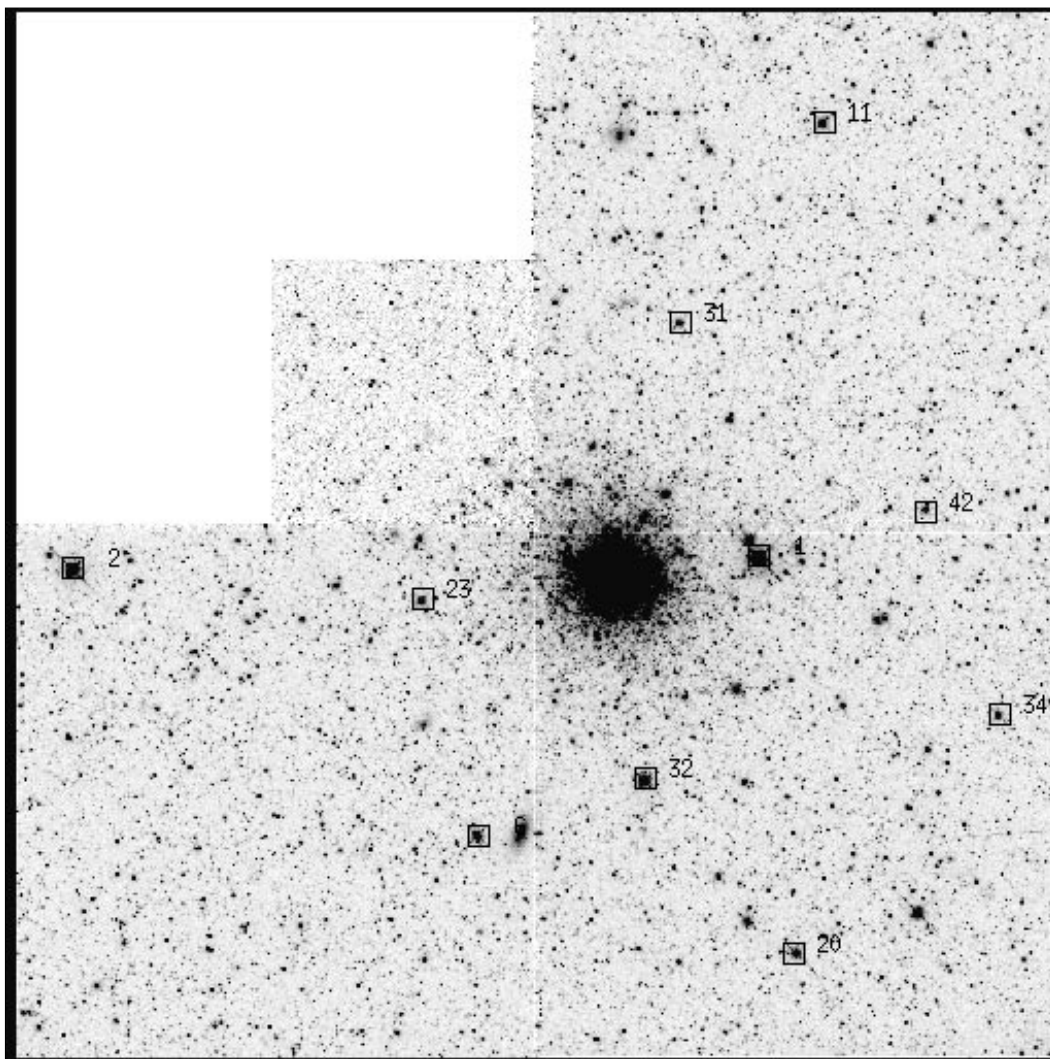


FIG. 1.—Fornax cluster 4 (WFPC2 mosaic). Objects enclosed in numbered squares are selected bright stars listed in Table 1A for identification purposes.

The several previous investigations of the Fornax clusters (see, e.g., Buonanno et al. 1985, hereafter BEA85; Beauchamp et al. 1995; Smith et al. 1996; Smith, Rich, & Neill 1997, 1998; BEA98) have shown that they differ in many important characteristics, which make them particularly valuable for studying stellar evolution and the possible connection between it and cluster dynamics. They present clear evidence of the “second-parameter effect” (e.g., Lee, Demarque, & Zinn 1994; Sarajedini, Chaboyer, & Demarque 1997), because the differences among the horizontal-branch (HB) morphologies of clusters 1, 3, and 5 (the most metal-poor of the Fornax clusters) are not explained by their small differences in metallicity. The luminosity profiles of clusters 1 and 2 resemble those of typical Galactic globular clusters, with large core radii and truncated halos, while clusters 3, 4, and 5 have smaller core radii and extended halos (Webbink 1985). The range of central densities spans from $\log \rho_0 = 0.454$ for cluster 1 to 3.83 and 3.93 for clusters 3 and 4, respectively (Webbink 1985). According to previous measurements, there is a substantial range in metallicity among the clusters, from $[\text{Fe}/\text{H}] = -2.2$ for clusters 1 and 5 (BEA98) to $[\text{Fe}/\text{H}] = -1.40$ for cluster 4 (Beauchamp et al. 1995).

Given the small back-to-front range in distance modulus of Fornax and this wide range in $[\text{Fe}/\text{H}]$, BEA85 noted that the Fornax clusters may provide a precise measurement of the dependence of HB luminosity on $[\text{Fe}/\text{H}]$.

Recently, BEA98 used the Wide Field Planetary Camera 2 (WFPC2) of the *Hubble Space Telescope* (HST) to construct the color-magnitude diagrams (CMDs) of clusters 1, 2, 3, and 5, in order to measure their ages and to explore the connection between HB morphology and cluster density. They concluded that the four clusters have the same age to within 1 Gyr and that this age difference is too small to explain the observed differences in HB morphology, unless the HB is more sensitive to age than previously thought. In addition, they noted that a correlation exists between the HB morphologies and the central densities of the clusters. Unfortunately, BEA98 could not obtain an estimate of the slope $M_V(\text{HB})$ versus $[\text{Fe}/\text{H}]$ relationship, because the range in metal abundance among these clusters is too small ($[\text{Fe}/\text{H}]_{\text{c12}} - [\text{Fe}/\text{H}]_{\text{c11}} \simeq 0.4 \pm 0.3$).

In this paper, we present the results of a study of the CMD of Fornax cluster 4 and its surrounding field. As a continuation of our previous work on the other Fornax clusters, we intended to focus primarily on the age of the

cluster 4 and the $M_V(\text{HB})$ – $[\text{Fe}/\text{H}]$ relation, but our results have motivated a shift in emphasis, which is explained below. Previous investigations of the CMD of cluster 4 (BEA85; Beauchamp et al. 1995) have been hampered by the high density of stars in the cluster and in the surrounding field, which is near the center of the galaxy. Because the images from the *HST* have much higher resolution than the previous ones from ground-based telescopes, they have enabled us to obtain photometry of below the main-sequence turnoff in cluster 4.

2. OBSERVATIONS AND REDUCTIONS

The observations consisted of two 1100 s and one 200 s exposure in each of the two filters F555W and F814W of the refurbished WFPC2. The data were retrieved electronically from the ESO Space Telescope European Coordinating Facility archive (proposal GTO/WFC 5637, PI: Westphal, data taken in 1995 March). Cluster 4 is located within the area of WF3, while the areas of WF1 and WF2 sample essentially only the field population of the dSph galaxy. Figure 1 shows the observed field with a few isolated stars marked for the purpose of identification.

The photometry of the stars in the three Wide-Field Cameras (WFs; scale $0''.0996 \text{ pixel}^{-1}$) were performed with DAOPHOT II, using the hybrid weighted technique described by Cool & King (1995). To push the detection of stars to the faintest possible limit, we co-added the deep images taken with the same filter. We first performed the DAOPHOT (Stetson 1987) detection step, did photometry of the detected stars, and then subtracted their images from the frame. We then performed the detection procedure a second time, which created a second list of stars to be added to the first. This procedure was very effective at detecting stars, even those hidden within the outskirts of the point-spread functions (PSFs) of the brighter stars. Because the Planetary Camera field is relatively small in size, it is unlikely to add any new information about the stellar populations of Fornax, and for this reason, we did not include it in our photometric reductions.

For each chip and each filter, the PSF was built using at least 15 bright and isolated stars in each frame. Corrections to $0''.5$ aperture were made in each case, and the F814W and F555W instrumental magnitudes were transformed into the WFPC2 “ground system” using equation (6) of Holtzman et al. (1995).

Before starting the reductions, the long exposures were processed by routines of ROMAFOT expressly developed to eliminate the cosmic rays by processing a series of frames with a median filter. Photometry was also performed, using ROMAFOT, in order to compare it with the technique of Cool & King (1995). The more complex but slower routines of ROMAFOT, which were developed for crowded fields, yielded fully compatible results. ROMAFOT was not used for our final reductions, because the Fornax fields are relatively uncrowded.

3. COLOR-MAGNITUDE DIAGRAMS

Figure 2 shows the V versus $V-I$ CMD for the three WFPC2 fields. On the left of the figure, the photometric errors at the different magnitude levels are reported. Local positions and photometry of the brightest stars are reported in Table 1A; the photometry for all the stars measured in this paper, referred to in the bottom left corner of each chip,

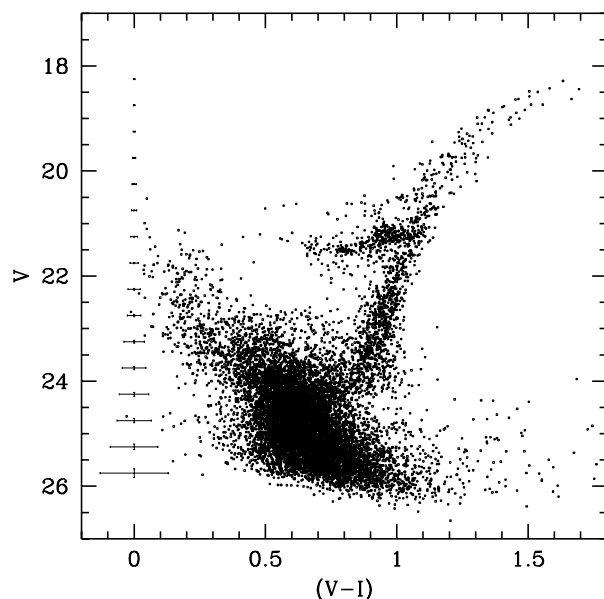


FIG. 2.—CMD obtained for the three WFPC2 fields. Photometric errors, for both magnitudes and colors, are shown on the left of the diagram.

is reported in Tables 1B, 1C, and 1D, for cameras WF2, WF3, and WF4, respectively.⁴

The major features to note in Figure 2 are, first, the bifurcated red giant branch (RGB) at $V \leq 19.5$, which indicates the presence of two stellar populations of different metallicity; second, the two distinct HBs, reminiscent of an “old” HB located at $V \approx 21.5$, and an intermediate-age red HB clump that is about 0.25 mag brighter and 0.1 mag redder than the old HB; and, third, the young main sequence (MS) on the blue side of the diagram. Each of these features clearly indicates that the CMD of Figure 2 contains at least two distinct populations, which most likely belong to cluster 4 and to the field of Fornax.

To investigate this further, we first plotted in Figure 3 the stellar density profile in units of stars per square arcminute,

TABLE 1
LOCAL POSITIONS AND PHOTOMETRY
A. THE BRIGHTEST STARS

Star	X	Y	V	$V-I$
34.....	552.7	−198.5	19.20	1.35
20.....	258.8	−544.5	18.89	1.45
32.....	38.1	−293.6	19.16	2.88
1.....	205.5	30.4	16.60	1.08
6.....	−253.9	−346.2	18.44	1.69
23.....	−335.5	−4.3	18.98	1.43
2.....	−841.3	39.5	18.23	2.64
11.....	299.8	719.2	18.63	1.66
31.....	91.9	428.1	19.12	1.43
42.....	449.6	156.9	19.39	1.25

NOTE.—Table 1 is presented in its entirety in the electronic edition of the *Astronomical Journal*. A portion is shown here for guidance regarding its form and content.

⁴ The same photometry, with coordinates referring to the center of the cluster, can be found at <http://www.mporzio.astro.it/~mkast/data.html>.

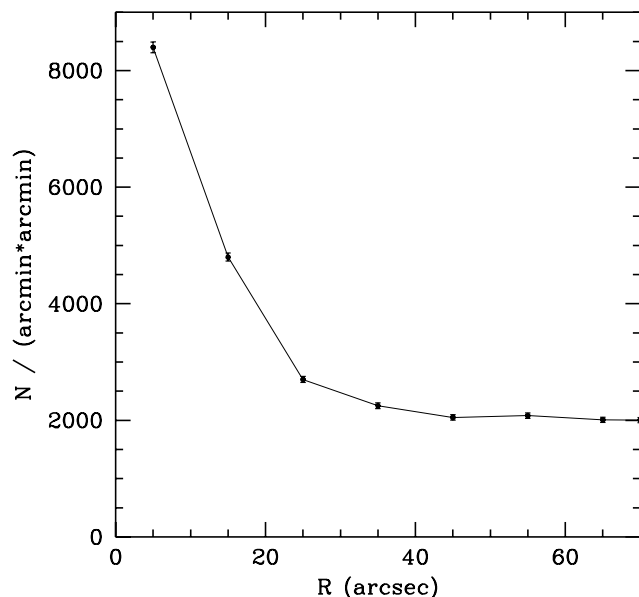


FIG. 3.—Stellar density profile of our field. Errors are shown as vertical bars at data points.

with the origin at the center of cluster 4. We then selected two samples that we believe are more representative of the cluster and of the field populations. The *cluster sample* consists of stars that lie at a distance $R \leq 18''$ from the cluster center, i.e., the region where the mean star density is at least twice the field density. The *field sample* is drawn from the region where the density of stars is constant, which is at $R \geq 60''$.

3.1. The Field of Fornax around Cluster 4

The V versus $V-I$ CMD of the sample of the field of Fornax, as defined above, is displayed in Figure 4. This diagram, which is based on 4742 stars, clearly shows a prominent population of relatively blue stars and a rich clump of stars centered at $V-I \simeq 0.97$. Both features are characteristic of an intermediate-age population, whose

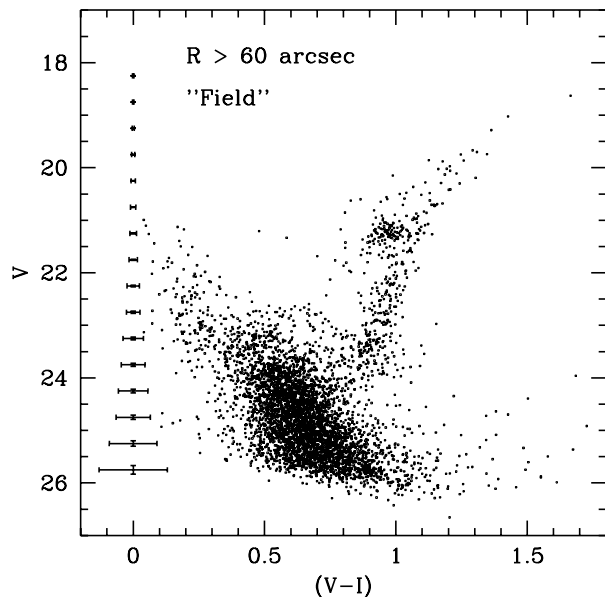


FIG. 4.—CMD of the field of Fornax

presence in Fornax has been suggested by several other workers (e.g., BEA85; Beauchamp et al. 1995; Stetson et al. 1998; Da Costa 1998). Another important feature in Figure 4 is the RGB extending to $V = 18.63$ and $V-I = 1.66$, which, however, is broader than expected on the basis of the photometric errors alone. This could be caused by a spread in metallicity of the Fornax field stars and/or the presence of a few asymptotic giant branch (AGB) stars around $V \simeq 20.5$. The more extensive but less deep CMDs of the field of Fornax that have been published previously have indicated that a significant range in $[\text{Fe}/\text{H}]$ exists (see Da Costa's 1998 review). Two very red stars have not been plotted in Figure 4. They lie at $V = 18.23$, $V-I = 2.64$ and $V = 19.54$, $V-I = 3.06$; for both colors and magnitudes such stars could be AGB stars, or also blue straggler progeny similar to that found in 47 Tuc (Montegriffo et al. 1995).

The fiducial line of the RGB of the Fornax field, as defined by our photometry, is listed in Table 2. The procedure adopted for determining the ridgeline discarding the outliers in CMD boxes. The boxes have dimensions ± 0.1 mag in V , ± 3 times the photometric error in $V-I$ evaluated at each magnitude level. After such a selection, the resulting "cleaned" CMD has been checked by eye. We adopted the mode of the histogram in each bin as representative of the true mean color at a given magnitude, and the resulting curve has been smoothed. The errors in color listed in the third column of Table 2 are the standard errors calculated within each box.

As noted above, HB of the field population consists primarily of a red clump of stars. The few bluer stars of roughly

TABLE 2
MEAN LINE OF RGB OF
FORNAX FIELD

V	$V-I$	$\sigma(V-I)$
18.630.....	1.674	0.015:
19.014.....	1.446	0.015:
19.283.....	1.373	0.015:
19.680.....	1.301	0.018
19.859.....	1.264	0.027
20.077.....	1.225	0.026
20.250.....	1.190	0.026
20.526.....	1.150	0.028
20.692.....	1.130	0.018
20.833.....	1.104	0.023
20.961.....	1.092	0.018
21.140.....	1.071	0.015
21.256.....	1.041	0.016
21.409.....	1.040	0.022
21.589.....	1.029	0.023
21.717.....	1.027	0.022
21.858.....	1.009	0.019
21.998.....	0.999	0.018
22.139.....	0.990	0.018
22.319.....	0.968	0.016
22.460.....	0.968	0.015
22.652.....	0.957	0.022
22.793.....	0.945	0.018
22.933.....	0.934	0.019
23.177.....	0.911	0.022
23.292.....	0.910	0.020
23.433.....	0.910	0.024

the same magnitude may belong to a relatively sparsely populated second HB, which is much more evident in the CMD published by Stetson et al. (1998; see also Da Costa 1998). To measure the luminosity of the red clump in our diagram, we selected the stars in Figure 4 in the intervals $20 \leq V \leq 22$ and $0.88 \leq V-I \leq 1.04$ and found a mean value $V_{\text{clump}} = 21.25 \pm 0.20$, where the error is the standard error of the mean. Subsequently, we found for the RGB color at the HB level $(V-I)_{g, \text{field}} \simeq 1.04 \pm 0.05$, where the uncertainty is the combination of the uncertainties in V_{clump} and the ridgeline of the RGB.

To estimate the average metallicity of the field population we used the parameter “sl,” defined by Buonanno et al. (1993) as $\text{sl} = (V-I)_{-2.4} - (V-I)_{-1}$, where $(V-I)_i$ is the color of the RGB at i mag brighter than the HB. The parameter “sl” has been calibrated using six template clusters (see Table 5 of Buonanno et al. 1993).

From the data in Table 2, we find $\text{sl} = 1.51 - 1.19 = 0.32$ and, then, $[\text{Fe}/\text{H}] = -1.36 \pm 0.16$, where the uncertainty in $[\text{Fe}/\text{H}]$ is the combination of the assumed uncertainty in the metallicity of calibrators ($\sigma_{[\text{Fe}/\text{H}]} = 0.15$) and in the estimate of the RGB average color ($\sigma_{V-I} = 0.05$). Adopting the calibration of Sarajedini (1994), $E(V-I) = (V-I)_g - 0.1034[\text{Fe}/\text{H}] - 1.100$, we obtain $E(V-I) = 0.08 \pm 0.05$ for the reddening of Fornax. These measurements of mean $[\text{Fe}/\text{H}]$ and $E(V-I)$ are in good agreement with previous ones (e.g., BEA85; Beauchamp et al. 1995).

The photometry in Figure 4 can be used to establish an upper limit to the true distance modulus of the Fornax dSph galaxy. We start by assuming that the bright star at $V = 18.63$ and $V-I = 1.66$ is actually at the tip of the RGB (TRGB). According to Lee, Freedman, & Madore (1993), the I magnitude of the TRGB is a weak function of metallicity and therefore is a distance indicator. Adopting $M_I = -4.0 \pm 0.1$ as the absolute I magnitude of the TRGB, the apparent distance modulus of Fornax turns out to be $(m-M)_I = 16.97 + 4.0 = 20.97 \pm 0.10$. Then with $A_I = 1.29E(V-I)$ and $A_V = 2.66E(V-I)$ (Cardelli, Clayton, & Mathis 1989), we obtain for the true distance modulus $(m-M)_0 = (m-M)_I - A_I = 20.97 - 0.10 = 20.87 \pm 0.11$, and $(m-M)_V = 20.87 + 0.21 = 21.08 \pm 0.11$. Because the TRGB has been defined by a single star, this distance modulus must be regarded as an upper limit.

A more definite estimate of the distance modulus can be obtained from Figure 5, where we have superposed the ridgelines of the GC M5 (Johnson & Bolte 1998) and the Fornax field. The metallicity of M5 is $[\text{Fe}/\text{H}] = -1.40 \pm 0.06$ (Zinn & West 1984), which is essentially the same as that found here for mean $[\text{Fe}/\text{H}]$ of Fornax. In Figure 5 the M5 loci were shifted in color by $E(V-I) = 0.04$, to account for the reddening of Fornax [$E(V-I)_{\text{M5}} = 0.04$; Zinn & West 1984], and vertically by $\Delta V = 6.55$.

To obtain the distance modulus of M5 and therefore that of Fornax from the match of the RGBs in Figure 5, we use the luminosity of the HB in M5, $V(\text{HB}) = 15.11 \pm 0.1$ (Buonanno, Corsi, & Fusi Pecci 1989), to set the distance scale. Adopting $M_V(\text{RR}) = 0.82 + 0.17[\text{Fe}/\text{H}]$ from Lee, Demarque, & Zinn (1990), we obtain $M_V(\text{RR}) = 0.58$ and, then, $(m-M)_V^{\text{M5}} = 14.53 \pm 0.10$. Consequently, we obtain $(m-M)_V^{\text{Fornax}} = 14.53 + 6.55 - 20.66(0.04) = 20.97 \pm 0.10$, which is consistent with the upper limit from the TRGB. The true distance modulus by this method is 20.76 ± 0.10 . It is important to note that this procedure is relatively

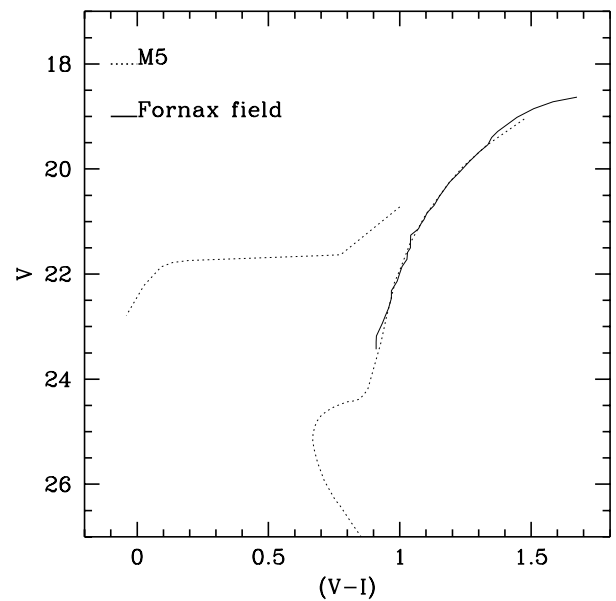


FIG. 5.—Ridgeline of the Fornax field and of the GC M5

insensitive to age differences between the population of Fornax and that of M5, because the age sensitivity of the RGB is small, being $\Delta(V-I)/\Delta t \simeq 0.007 \text{ mag Gyr}^{-1}$ (Da Costa & Armandroff 1990, hereafter DCA90).

Another estimate of the distance modulus of Fornax can be obtained from the four globular clusters that are similar in age to the GCs in the Milky Way. Using the values of $V(\text{HB})$, $E(V-I)$, and $[\text{Fe}/\text{H}]$ that BEA98 list in their Table 2 for clusters 1, 2, 3, and 5, and the same relation for $M_V(\text{RR})$ as above, we obtain an average $(m-M)_0 = 20.62 \pm 0.08$. This value is the same, to within the errors, as our estimate from the RGB of the Fornax field, which builds confidence in our photometry.

Given the present considerable uncertainty over the distance scales for RR Lyrae variables and globular clusters (cf. Chaboyer et al. 1998; Popowski & Gould 1998), the major uncertainty in the distance modulus of Fornax is the scale applied to parameters such as $V(\text{HB})$ and not their observational errors. Since the scale of Lee et al. (1990) lies near the middle of the range of several alternatives, we suggest a value of 20.68 ± 0.20 for the true distance modulus of Fornax.

3.2. Star Formation History of Fornax

The large range in luminosity of the main sequence of the Fornax field population (see Fig. 4) indicates that Fornax has experienced a long history of star formation. While this has been detected previously by several teams of investigators (e.g., BEA85; Beauchamp et al. 1995; Stetson 1997; Da Costa 1998), our data provide some additional information.

The bright limit of the main sequence in Figure 4 is $V \simeq 21.0$, which corresponds to $M_V \simeq +0.1$. With the assumption that these stars are near the stage of central exhaustion of core H burning, the isochrones of Bertelli et al. (1994) indicate an age of about 0.5 Gyr, and this result depends only weakly on the assumed metal abundance (see Fig. 9 of Bertelli et al. 1994). While this result is very remarkable for a galaxy that was once thought consist of a single population of very old stars, the CMD presented by Stetson (1997) and also discussed by Da Costa (1998) indi-

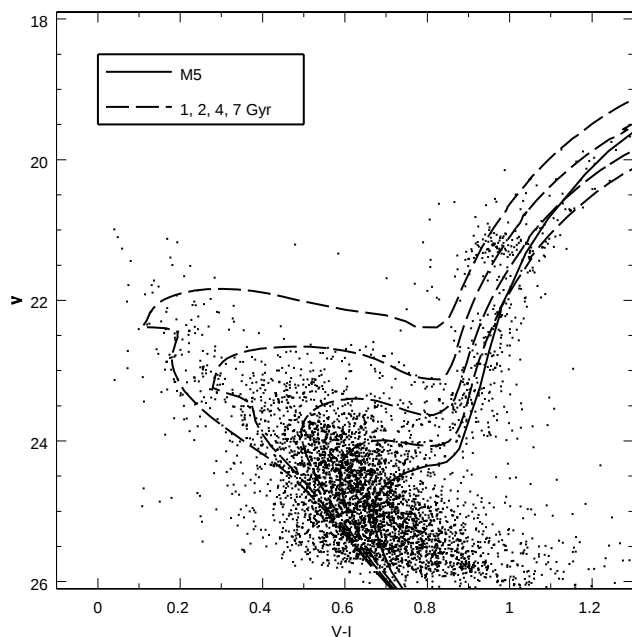


FIG. 6.—CMD of the field, compared with the ridgeline of M5 and Yale theoretical isochrones for selected ages.

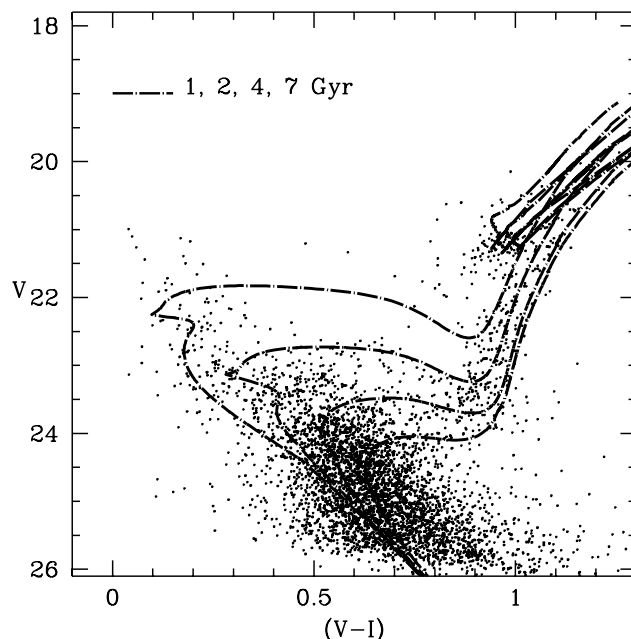


FIG. 7.—Same as Fig. 6, but with the isochrones of A. Chieffi, O. Straniero, & M. Limongi (1999, private communication) for the same ages.

cates that Fornax contains a few stars younger than 0.1 Gyr.

At fainter magnitudes in Figure 4, one sees a subgiant branch (SGB) peeling off from the main sequence. Only in stellar populations older than about 3 Gyr is the Hertzsprung gap closed by the development of a well-populated SGB (see, e.g., the discussion by Hardy et al. 1984 on the LMC bar). With reasonable estimates for the metal abundance of Fornax, the Yale isochrones (Demarque et al. 1996)⁵ shown in Figure 6 and those of A. Chieffi, O. Straniero, & M. Limongi (1999, private communication) in Figure 7 indicate an age of about 2–4 Gyr for the population responsible for the brightest SGB in Figure 4. The core He burning phase of this population will produce a red clump centered near $M_V = 0.3$ (Bertelli et al. 1994). This corresponds to $V = 21.2$ in Fornax and coincides with the red clump in Figure 4. The fainter SGBs in Figure 4 indicate the presence of older stars, which have core He burning phases that slowly decrease in M_V with the increasing age of the population. Thus, the prominence of the red clump in Fornax can be attributed to the funneling of stars of a wide range of ages to approximately the same point in the CMD. The populations that are younger than 3 Gyr also have core He burning phases, which produce brighter but shorter-lived red clumps. The dispersion in magnitude of the red clump in Fornax is probably due to the presence of a few of these stars in addition to the evolution of older stars from the red clump to the AGB.

As noted above, one of the striking features of Figure 4 is the absence of an HB resembling those seen in old GCs. The four oldest clusters in Fornax, clusters 1, 2, 3, and 5, have HBs that extend over wide ranges in color and include many RR Lyrae variables (see BEA98 and references therein). There are at most very few stars in Figure 4 that

can be attributed to such an HB population or even to a red HB resembling the one in cluster 4, which is shown below to be about 3 Gyr younger than these other clusters. Since a weakly populated blue HB is seen in the photometry of a larger field (Stetson et al. 1998; see also Da Costa 1998) and since Mateo (1998) reports that more than 400 RR Lyrae variables have been discovered in Fornax, the field population of Fornax does have an old, metal-poor component. Evidently, it is a minor one in comparison with the intermediate-age populations. Therefore the absence of BHB stars in the CMD of the field ($r \geq 60''$) could be explained with the expected number (about 1) of RR Lyrae variables obtained by scaling the Stetson et al. (1998) results to the small area covered by our data.

Finally, in contrast to the CMD constructed by Stetson et al. (1998), which provided no evidence for bursts of star formation like the ones that are so evident in the CMD of the Carina dSph galaxy (Smecker-Hane et al. 1994, 1996), our deeper and probably more precise CMD from *HST* observations reveals signs of a variable star formation rate. If star formation was continuous in our field, we would expect to see a smooth distribution of stars between the main sequence and the RGB in Figure 4. Instead, there appear to be gaps between separate SGBs, which are suggestive of separate bursts of star formation.

This is illustrated in Figure 6, which is an enlarged version of Figure 4. Using our best estimates for $(m - M)_V$ (20.89) and $E(V - I)$ (0.08), we have also plotted in Figure 6 the ridgeline of M5 (from Johnson & Bolte 1998) and the Yale isochrones for ages of 1, 2, 4, and 7 Gyr (Demarque et al. 1996). This diagram shows that while the ridgeline of M5 matches the giant branch, as was illustrated previously in Figure 5, its SGB forms a lower limit on the luminosities of the subgiants in this field of Fornax. Under the assumption of similar chemical compositions, which is reasonable given the coincidence of the giant branches, this suggests that the majority of the Fornax stars are younger than M5. The near absence of any stars resembling the HB stars in M5 is

⁵ See <http://shemesh.gsfc.nasa.gov/iso.html>.

also consistent with this. To be precise about the age distribution of the Fornax stars requires much more information about their chemical compositions than we currently have. Consequently, the following estimates from the comparison with the isochrones should be considered only very rough estimates.

Since there are few constraints on the metal enrichment history of Fornax, we have chosen to plot isochrones of different ages but for the same chemical composition ($Y = 0.23$, $Z = 0.004$, and a solar mix of elements). Salaris, Chieffi, & Straniero (1993) have shown that in the region of the main-sequence turnoff (TO) and the SGB the isochrones for the solar mixture closely approximate ones for a mixture in which the α -elements are enhanced. According to their relationship, the isochrones used here are appropriate for an α -enhancement of a factor of 3 and metal content of $Z = 0.0018$ ($[\text{Fe}/\text{H}] \simeq -1.05$), which is only slightly more metal-rich than some measurements for M5 ($[\text{Fe}/\text{H}] \simeq -1.11$; Carretta & Gratton 1997). The main sequence and subgiant region of M5 are approximated by a 12 Gyr isochrone of this composition. The younger stellar populations of Fornax may have more nearly solar ratios of $[\alpha/\text{Fe}]$, as do populations of similar age in the Milky Way. This change in $[\alpha/\text{Fe}]$ is thought to be caused by an increase in the abundances of the Fe-peak elements once Type Ia supernovae begin to explode. Hence, these isochrones for a solar mix and $Z = 0.004$ ($[\text{Fe}/\text{H}] \simeq -0.7$) may not be far off for these populations, although we emphasize that there currently no observational evidence to support this.

The comparison of the isochrones in Figures 6 and 7 suggests that this field of Fornax had major episodes of star formation at ages of roughly 7, 4, and 2.5 Gyr, with relatively little star formation in between. We must emphasize that these ages are sensitive to the choices for the distance modulus and the reddening of Fornax and the distance scale, as well as the chemical compositions of the isochrones. The most important point is that a highly variable star formation rate, as illustrated by these separate isochrones, is consistent with the observed SGBs. Also, the luminosity and the color of the main sequence is consistent with star formation continuing until ≤ 1 Gyr ago.

Note that these conclusions are independent of the particular set of isochrones adopted. This is clearly illustrated in Figure 7, where another set of isochrones (A. Chieffi, O. Straniero, & M. Limongi 1999, private communication) for the same metallicities and ages are plotted with the same data that were plotted in Figure 6. One additional interesting feature of Figure 7 is the luminosity of the core helium burning stars, which coincides with the observed clump and supports the adopted distance modulus.

3.3. Cluster 4

The V versus $V-I$ CMD of cluster 4 is displayed in Figure 8. The diagram is based on 1343 stars within a distance of $18''$ from the cluster center and reaches $V \simeq 26.0$. The overall morphology is similar to that of a Galactic globular cluster with a well-developed RGB extending to $V \simeq 18.28$ and $V-I \simeq 1.63$. The subgiant and the TO regions, although clearly delineated, appear somewhat contaminated by the Fornax field.

The V magnitude of the HB was determined by an iterative procedure that rejected the 2σ outliers from the mean value. It yielded $V_{\text{HB}} = 21.52 \pm 0.05$. The fiducial line of the

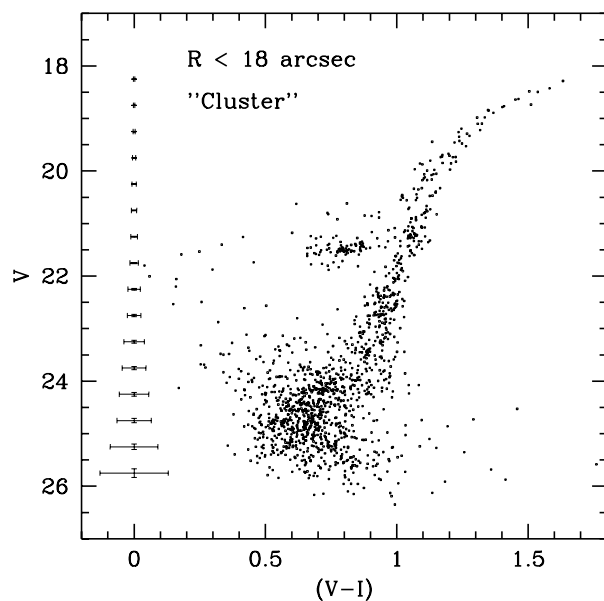


FIG. 8.—CMD of Fornax cluster 4

CMD of Fornax cluster 4 is given in Table 3. In order to derive the fiducial line of the cluster, we followed the same procedure adopted for the field (see § 3.1 for details and error estimates). In the TO region, the determination of the fiducial line could be affected by the presence of field stars along the MS and, in particular, by the bright and blue stars lying above the SGB. We carefully checked that such stars have been rejected as outliers by our selection procedure. Moreover, having adopted the mode of the histogram, the presence of field stars should not be a

TABLE 3
MEAN LINE OF RGB OF
FORNAX CLUSTER 4

V	$V-I$	$\sigma(V-I)$
18.300.....	1.622	0.010:
18.400.....	1.558	0.012
18.600.....	1.462	0.010
18.800.....	1.400	0.010
19.000.....	1.343	0.006
19.200.....	1.305	0.010
19.400.....	1.260	0.008
19.600.....	1.230	0.008
19.800.....	1.202	0.012
20.000.....	1.173	0.009
20.200.....	1.148	0.009
20.400.....	1.126	0.009
20.600.....	1.103	0.007
20.800.....	1.084	0.010
21.000.....	1.068	0.011
21.200.....	1.052	0.004
21.400.....	1.036	0.010
21.600.....	1.020	0.010
21.800.....	1.006	0.012
22.000.....	0.993	0.011
22.200.....	0.981	0.008
22.400.....	0.970	0.010
22.600.....	0.961	0.009
22.800.....	0.952	0.010

major problem if one accepts that a large majority of the stars belong to the cluster.

3.4. The Metallicity and Reddening of Cluster 4

The RGB of cluster 4 is the bluer of the two branches seen in Figure 2, which suggests that it is more metal-poor than the mean abundance of the field population ($[\text{Fe}/\text{H}] = -1.36$; see above). To estimate the metallicity of cluster 4, we followed the same procedure that we used for the field and computed from Table 3 the parameter $sl = (V-I)_{-2.4} - (V-I)_{-1} = 1.305 - 1.103 = 0.202$. From inspection of Table 5 of Buonoanno et al. (1993) we conclude that the metallicity of cluster 4 is intermediate between M15 and NGC 6397, and from linear interpolation we obtain $[\text{Fe}/\text{H}] = -2.01 \pm 0.14$, a metallicity very similar to those of the other Fornax clusters. Once the metal abundance is known, the reddening can be estimated from the color of the RGB. Adopting $[\text{Fe}/\text{H}] = -2.01 \pm 0.20$ and from our measurement of $(V-I)_g = 1.028 \pm 0.05$, we obtain $E(V-I) = 0.14 \pm 0.05$ for the reddening of cluster 4.

Since nearly all previous determinations found much higher values of $[\text{Fe}/\text{H}]$ (approximately -1.3 ; see below), we have also estimated the metallicity and the reddening of cluster 4, by placing the ridgeline of its RGB in the $[M_I, (V-I)_0]$ -plane, following DCA90. Although this procedure is not independent of the method applied above, it checks whether or not the whole RGB is consistent with the value of $[\text{Fe}/\text{H}]$ that was inferred from sl . Figure 9 shows that for $E(V-I) = 0.15$ and $(m-M)_I = 20.9$, the RGB of cluster 4 lies between those of M15 and NGC 6397, confirming that $[\text{Fe}/\text{H}]_{\text{cl4}} \simeq -2.00$ [note that neither V_{HB} nor $(V-I)_g$ was used in this comparison]. On the basis of the previous measurements, one would expect the RGB of cluster 4 to match that of NGC 1851 ($[\text{Fe}/\text{H}] = -1.29$), but as Figure 9 shows this is totally inconsistent with the slope of the RGB of

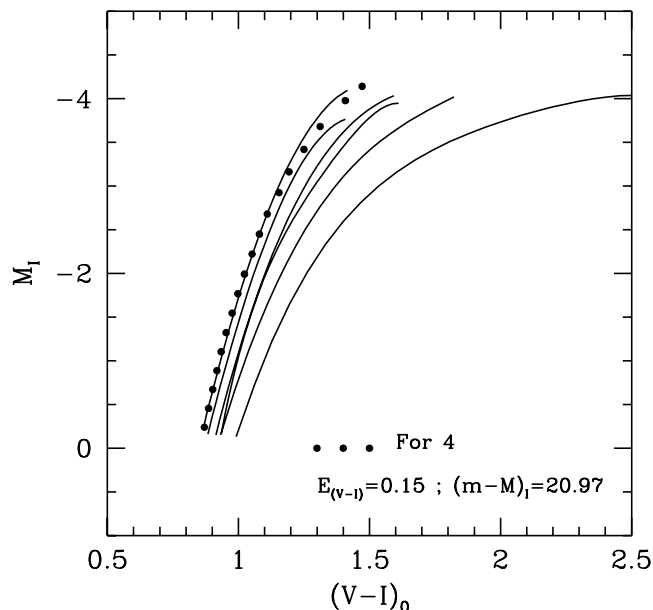


FIG. 9.—Ridgeline of Fornax cluster 4 compared with ridgelines of GGCs in DCA90. Left to right, M15 ($[\text{Fe}/\text{H}] = -2.17$), NGC 6397 (-1.91), M2 (-1.58), NGC 6752 (-1.54), NGC 1851 (-1.29), and 47 Tuc (-0.71). Metallicities are taken also from DCA90.

cluster 4. By adjusting the distance modulus and reddening of cluster 4 within acceptable limits, one can force an approximate match of its RGB to that of M2 ($[\text{Fe}/\text{H}] = -1.58$). For the following reasons, we believe cluster 4 is more metal-poor than this.

In Figure 10, cluster 4 is compared with Fornax cluster 2, which is the most metal-rich of the other Fornax clusters according to several measurements. The slope of its RGB indicates $[\text{Fe}/\text{H}] = -1.78 \pm 0.20$ (BEA98), which is within the combined errors of the value obtained above for cluster 4 by the same technique. In the bottom panel of Figure 10 the ridgelines of the two clusters have been plotted after making the same reddening and extinction corrections for each cluster. These corrections are based on the reddening that BEA98 measured for cluster 2, which is only 0.01 mag higher than the value obtained above for the reddening of the field near cluster 4. One can see from this comparison that although the giant branches of the two clusters run roughly parallel, the giant branch of cluster 4 is definitely redder. The HB of cluster 4 is also offset $\simeq 0.17$ mag fainter than the HB of cluster 2, which is too large to be a result

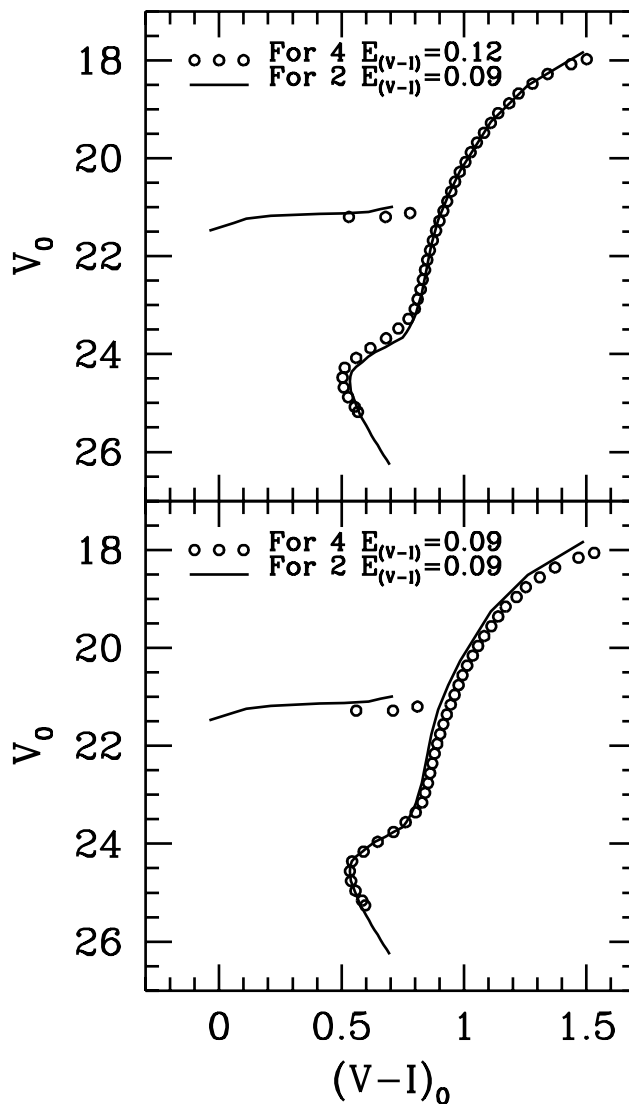


FIG. 10.—Ridgelines of clusters 2 and 4 under two different assumptions for the reddening of cluster 4.

of either a difference in distance modulus or a modest difference in $[\text{Fe}/\text{H}]$. These offsets can be partially explained by higher reddening of cluster 4, which is illustrated in the top panel of Figure 10, where the reddening of cluster 4 has been raised to $E(V-I) = 0.12$. Now the RGBs of the two clusters match, but the difference in V_{HB} is still surprisingly large, ≈ 0.09 mag, if the clusters have the same chemical composition. While this match with cluster 2 is acceptable, the offset in V_{HB} suggests that cluster 4 may be even more metal-poor and somewhat more heavily reddened, as indicated by Figure 9 and the sl-parameter.

A confirmation of this conclusion is provided by the comparison of the ridgelines of cluster 4 with those of the metal-poor Galactic GC M68 ($[\text{Fe}/\text{H}] = -2.09$; Zinn & West 1984), which is shown in Figure 11. Cluster 4 has been dereddened by 0.15 mag and shifted by $\Delta V = 0.40$ mag to account for the absorption. The M68 ridgeline from Walker (1994) has been dereddened by $E(V-I) = 0.09$ (see BEA98) and shifted by $\Delta V = 5.50$ mag in V to match the HB luminosity of cluster 4. Figure 11 shows that the RGB of cluster 4 is very similar to that of M68 and confirms the low metallicity estimate obtained above. Note, however, that the TO of cluster 4 is significantly brighter ($\Delta V = 0.2 \pm 0.1$ mag) than the TO of M68. Adopting $\Delta V = 0.07$ mag Gyr^{-1} (VandenBerg, Stetson, & Bolte 1996), we estimate that cluster 4 is approximately 2.9 ± 1.5 Gyr younger than M68. According to the top panel of Figure 10, the turnoff of cluster 4 is also brighter than the turnoff in cluster 2. A more detailed comparison of the ages of cluster 4 and the other Fornax clusters is made in § 3.5.

The low value of $[\text{Fe}/\text{H}]$ obtained above disagrees with estimates from photometry and spectroscopy of cluster 4's integrated light from blue to near-infrared wavelengths, which have consistently yielded values of $[\text{Fe}/\text{H}]$ near that of the field population of Fornax, i.e., approximately -1.3 (Harris & Canterna 1977; Zinn & Persson 1981; Dubath, Meylan, & Mayor 1992; Beauchamp et al. 1995). Our value agrees, however, with the value that Beauchamp et al. (1995) estimated from their CMD of cluster 4, which was con-

structed from ground-based photometry that barely reached the HB. Beauchamp et al. (1995) considered the inconsistency between the position of the RGB in their CMD and the conclusions drawn from integrated light measurements a mystery to be resolved by *HST* observations. We believe the much improved CMD produced by the *HST* observations has at least partially done this by conclusively showing that cluster 4 has a steeply sloped RGB of a very metal-poor cluster.

We have thought of three factors that either individually or, more likely, collectively may account for the discrepancy with the inferences from the integrated light measurements. These observations measured either the broadband colors of the cluster or the strengths of metal absorption lines, either spectroscopically or photometrically. For old globular clusters, there are tight relationships between these quantities and $[\text{Fe}/\text{H}]$ because of the dependence of the color of the RGB on $[\text{Fe}/\text{H}]$ (e.g., Zinn & West 1984). The integrated light observations have demonstrated that cluster 4 is redder and has stronger absorption lines than three other Fornax clusters (2, 3, and 5) and also other very metal-poor GCs belonging to the Milky Way, such as M68. The conclusion that cluster 4 is more metal-rich than these clusters depends critically on whether or not the relationships established among the globular clusters of the Milky Way are applicable to it. The CMDs of Fornax clusters 2, 3, and 5 (see BEA98) are similar to that of M68 and other very metal-poor GCs in the Milky Way, and not surprisingly, there is good agreement between the values of $[\text{Fe}/\text{H}]$ that are inferred from their CMDs and from the integrated light observations. However, as shown in Figures 10, 11, and 12, the CMD of cluster 4 is much different from those of the other Fornax clusters and M68 in that it has a much redder HB and a brighter SGB. Consequently, both the CMD and the integrated light measurements are in agreement that cluster 4 is unlike the other Fornax clusters and M68. The greater information provided by our CMD suggests that its relatively red color and stronger absorption lines are not due to a redder RGB, as has been inferred previously, but to

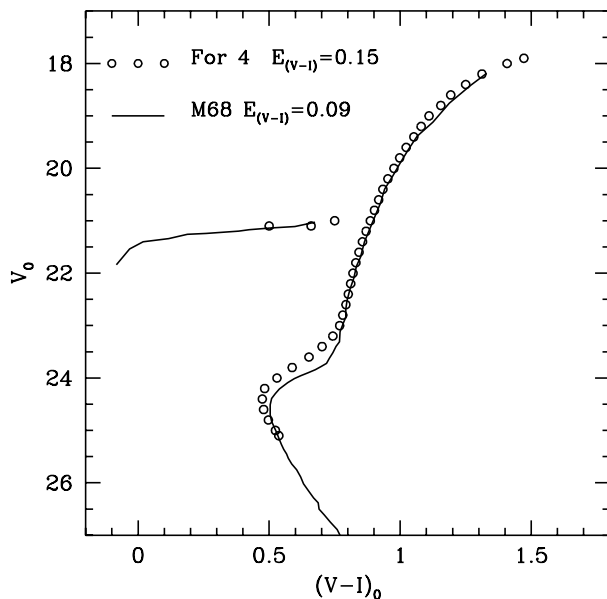


FIG. 11.—Ridgelines of cluster 4 and of M68

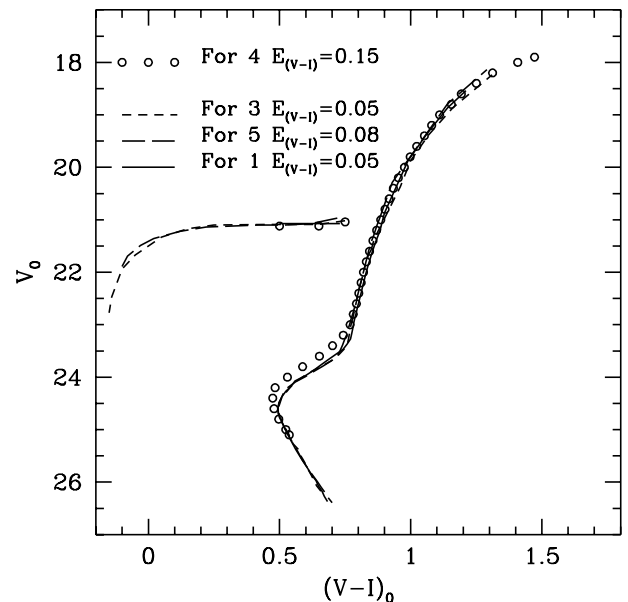


FIG. 12.—Fiducial lines of Fornax clusters 1, 3, 4, and 5

something else, and a likely candidate is the light contributed by the redder HB and brighter SGB in cluster 4.

These may not be the only differences, however. Below we will show that the CMD of cluster 4 is nearly identical to that of the Milky Way globular cluster Ruprecht 106 (see Fig. 13), which is younger by about 4 Gyr than the typical GC in the Galactic halo (Buonanno et al. 1993). Several studies of the CMD of R106 have shown that it has a steep RGB that is indicative of $[\text{Fe}/\text{H}] = -1.9$ (Buonanno et al. 1993; Sarajedini & Layden 1997). However, spectroscopic observations of red giants have yielded significantly higher values than this (François et al. 1997; Brown, Wallerstein, & Zucker 1997), and the observations of Brown et al. (1997) indicate that R106 has an anomalously low value of the $[\alpha/\text{Fe}]$ ratio. A similar discrepancy exists between the $[\text{Fe}/\text{H}]$ inferred from the RGB and spectroscopic measurements for the metal-rich, young globular cluster Pal 12, and it too appears to be $[\alpha/\text{Fe}]$ -deficient compared with other GCs (Brown et al. 1997). It is possible that cluster 4 is another example of this phenomenon (see Fusi Pecci et al. 1995 and Sarajedini & Layden 1997 for discussions of its possible origin). This would at least partially explain why the integrated spectrum of cluster 4 has relatively strong metal lines, and yet its RGB is quite steep.

Finally, it is possible that the integrated light observations have been contaminated by light from stars belonging to the field population of Fornax. Unlike the other globular clusters in Fornax, cluster 4 lies near the center of the galaxy, where the density of the field population is largest. Consider, for example, the $3'' \times 5.9''$ slit that Beauchamp et al. (1995) used to measure the spectrum of cluster 4. According to the curve in Figure 3, which for this calculation we extrapolated inward, this slit included about 400 stars down to the limit of our photometry. However, only about 80 of them (20%) belong to the cluster. Because the field population has a relatively red RGB, mean $[\text{Fe}/\text{H}] = -1.36$, and heavily populated red clump (see above), the removal of only part of the contamination from the field may produce spuriously red colors and/or metal line strengths.

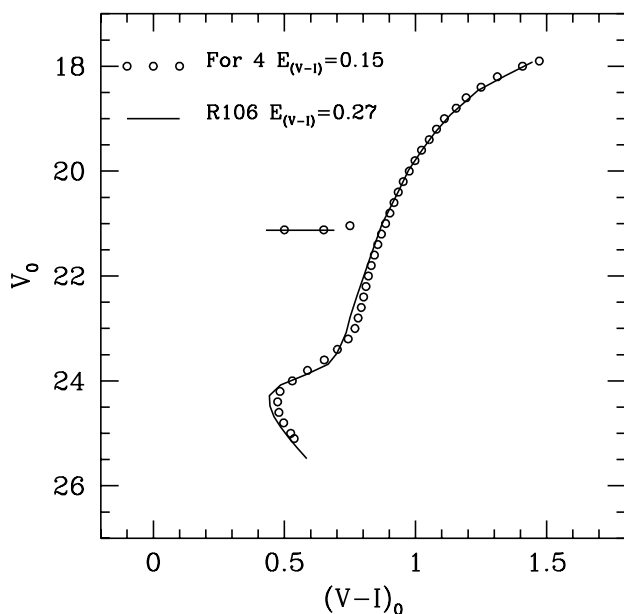


FIG. 13.—Fiducial lines of cluster 4 and of Ruprecht 106

Given that cluster 4 is either very metal-poor like the other Fornax clusters or (more speculatively) has an unusual mix of elements like R106, it and the other Fornax clusters do not provide a reliable sample to empirically derive the slope of the $M_V(\text{HB})$ versus $[\text{Fe}/\text{H}]$ relationship. The Fornax clusters do provide, however, important information on the origin of the second-parameter effect.

3.5. Comparison with the Other Fornax Clusters

Cluster 4 differs from the other Fornax clusters in two very important respects: HB morphology and age. Because BEA98 used the HB index $(B - R)/(B + V + R)$ (Lee et al. 1994) to quantify HB morphologies of Fornax clusters 1, 2, 3, and 5, we will also use it here. However, the present data are not well suited to detect variables, and the contamination of the CMD by the field population contributes to the uncertainty of this index for cluster 4. Nevertheless, considering that in Figure 8 all the HB stars are redder than $V - I \simeq 0.63$ [i.e., $(V - I)_0 \simeq 0.48$] with, at most, a handful of stars bluer than this limit, and considering that the average of the red edges of instabilities strips of clusters 1, 2, 3, and 5 gives $(V - I)_0(\text{red edge}) = 0.46 \pm 0.06$, we can safely assume that all of the HB stars of cluster 4 are red and therefore estimate $(B - R)/(B + V + R) = -1.0 \pm 0.2$.

If we adopt $[\text{Fe}/\text{H}] \simeq -2$ for cluster 4, as indicated by its RGB, then it is one of the most extreme examples of a very metal-poor cluster with a red HB. If it is anomalous like R106 (which remains to be determined), then its $[\text{Fe}/\text{H}]$ might be as much as 0.4 dex higher. Even in this case, it is as an extreme example of the second-parameter effect as the GCs Pal 3, Pal 4, Eridanus, and AM 1 (see Fig. 7 in Lee et al. 1994), which populate the remote halo of the Milky Way (as the Fornax dSph galaxy does itself).

3.6. Relative Ages

We will concentrate now on the important issue of the spread in age of the Fornax clusters, which is most accurately measured among clusters of very similar composition. Under the assumption that the Fornax clusters have the same relative abundances of the elements, the redder and more gently sloped RGB of cluster 2 indicates it is slightly more metal-rich than clusters 1, 3, and 5 ($[\text{Fe}/\text{H}] = -1.78$ as opposed to $[\text{Fe}/\text{H}] \simeq -2$). We have therefore made separate comparisons of cluster 4 with clusters 1, 3, and 5 and with cluster 2. The following analysis achieves high precision by comparing simultaneously all the relevant branches of the CMDs (see Buonanno et al. 1993). A similar procedure was performed by BEA98 for clusters 1, 2, 3, and 5.

In Figure 12 we show the ridgelines of Fornax clusters 1, 3, 4, and 5 after shifting them by the amounts required by their HB luminosities and reddenings. The relevant data are reported in Table 4. Adopting $M_V(\text{HB}) = 0.82 + 0.17[\text{Fe}/\text{H}]$ and using the reddenings reported in Table 4, we obtained the following shifts: $\Delta V = 0.13$ for cluster 1, $\Delta V = 0.13$ for cluster 3, $\Delta V = 0.40$ for cluster 4, and $\Delta V = 0.21$ for cluster 5.

From inspection of Figure 12 one immediately sees that, despite the excellent agreement of the RGBs, the TO of cluster 4 is both brighter and bluer than the others. This effect clearly deserves further investigation.

The detailed analysis by BEA98 of the relative ages of clusters 1, 2, 3, and 5 was based on the estimate of two

TABLE 4
PROPERTIES OF FORNAX CLUSTERS

Parameter	Cluster 1	Cluster 2	Cluster 3	Cluster 4	Cluster 5
[Fe/H]	-2.20 ± 0.20	-1.79 ± 0.20	-1.96 ± 0.20	-1.9 ± 0.20	-2.20 ± 0.20
V_{RR}	21.25 ± 0.05	21.35 ± 0.05	21.20 ± 0.05	21.52 ± 0.05	21.30 ± 0.05
E_{V-I}	0.05 ± 0.06	0.09 ± 0.06	0.05 ± 0.06	0.15 ± 0.06	0.08 ± 0.06
Δ_V	-0.25 ± 0.15	-0.22 ± 0.15	-0.31 ± 0.15	...	-0.30 ± 0.15
δ_{V-I}	0.027 ± 0.006	0.021 ± 0.006	0.035 ± 0.006	...	0.034 ± 0.006
$\log \rho_0$	0.454	1.599	3.836	3.936	2.469
$(B-R)/(B+V+R)$	-0.2 ± 0.2	0.38 ± 0.07	0.50 ± 0.06	-1.0 ± 0.1	0.44 ± 0.09
Δt^a	-2.6 ± 1.7	-2.5 ± 1.7	-3.2 ± 1.7	...	-3.1 ± 1.7
Δt^b	-2.4 ± 0.5	-2.3 ± 0.6	-3.1 ± 0.5	...	-3.0 ± 0.5

^a From ΔV (Gyr).

^b From δ_{V-I} (Gyr).

double-differential parameters: Δ_V and δ_{V-I} . Δ_V is defined as $\Delta V_{HB}^{TO}(\text{ref}) - \Delta V_{HB}^{TO}(\text{prog})$, where ΔV_{HB}^{TO} is the difference in luminosity between the TO point and the HB at the variability strip. The parameter Δ_V is defined by a pair of clusters, the first being the reference cluster and the second the current “program” cluster. δ_{V-I} is defined as $\Delta(V-I)_{TO}^{RGB}(\text{ref}) - \Delta(V-I)_{TO}^{RGB}(\text{prog})$, where $\Delta(V-I)_{TO}^{RGB}(\text{ref})$ is the color difference between the TO and the base of the RGB and is the equivalent in the $(V, V-I)$ -plane of the $\delta(B-V)$ defined by VandenBerg, Bolte, & Stetson (1990) in the $(V, B-V)$ -plane.

Under the assumption of similar mixes of elements, the metal abundances of clusters 1, 3, 4, and 5 are so close that they can be treated as having the same abundance. We concentrate on cluster 4 because BEA98 have recently reached the following conclusions regarding the other clusters:

1. The globular clusters 1, 2, 3, and 5 have essentially the same age ($\delta t \leq 1$ Gyr).
2. The GCs 1, 2, 3, and 5 are essentially coeval with the old, metal-poor clusters of our Galaxy, M68 and M92.
3. The observed HB morphologies are not explained by differences in age, unless the HB is more sensitive to age differences than has been previously estimated. However, a correlation exists between the HB types and the central densities of the clusters that is qualitatively similar to that among the globular clusters of the Milky Way.

To obtain a quantitative estimate of the age differences between cluster 4 and the other Fornax clusters, we use again the procedure adopted above and the calibrations $\delta t_9 = 11.6\Delta_V$ (Buonanno et al. 1993) and $\delta t_9 = -107.5\delta_{V-I}$ (Buonanno et al. 1998a) (valid around $[\text{Fe}/\text{H}] = -2$ and $t = 14$ Gyr) and list in Table 4 the differential quantities. In Table 4, cluster 4 is the reference cluster and the observational errors have been computed following Buonanno et al. (1993) and BEA98. The data for cluster 1, 2, 3, and 5 are from BEA98.

The mean age difference is then

$$\Delta t(\text{cl4} - \text{cl1,3,5}) = -2.97 \pm 0.54 \text{ (from } \Delta_V),$$

$$\Delta t(\text{cl4} - \text{cl1,3,5}) = -2.83 \pm 0.46 \text{ (from } \delta_{V-I}),$$

where the associated error is 3 times the standard error, σ . From the mean of the two determinations, we conclude that cluster 4 is about 2.9 Gyr younger than clusters 1, 3, and 5.

The comparisons made in Figure 10 between cluster 4

and cluster 2 suggest that cluster 4 is younger than 2 by a significant amount. Assuming the clusters have similar $[\text{Fe}/\text{H}]$, $\Delta t(\text{cl.4} - \text{cl.2}) = -2.5 \pm 1.7$ and -2.3 ± 0.6 , according to Δ_V and δ_{V-I} , respectively.

These results for the age differences may change if we relax the condition that relative abundances of the elements are identical in the clusters, but without knowing the abundance differences, firm predictions cannot be made. If cluster 4 is truly analogous to R106, it may be more Fe-rich but also more $[\alpha/\text{Fe}]$ -poor than the other Fornax clusters. Because these differences have offsetting effects on both ΔV_{HB}^{TO} and $\Delta(V-I)_{TO}^{RGB}$, the relative ages of the clusters may not be affected by much. There is strong evidence, therefore, for a several-gigayear range in age among the Fornax clusters.

It is important to see whether this age difference is consistent with the very red HB morphology of cluster 4. Since cluster density may affect HB morphology (Buonanno et al. 1997; BEA98), this comparison is best done between clusters 4 and 3, which have nearly identical central densities (Webbink 1985). These clusters differ by 1.5 ± 0.2 in HB type. Nearly the same differences exist between cluster 4 and clusters 5 and 2, whose HBs are only slightly redder than that of cluster 3.

The synthetic HB calculations by Lee et al. (1994) show that for $[\text{Fe}/\text{H}] = -2$ and an absolute age near 14 Gyr, an age difference of $\delta t \simeq 3$ Gyr is expected to produce a difference in HB type of about this size. This can be illustrated using the comparison that Lee et al. (1994) made between the two Milky Way GCs R106 and NGC 6397, whose HB types (-0.82 and 0.93 , respectively) differ by 1.75 . From the analysis of their Figure 16, Lee et al. (1994) concluded that for a metallicity near $[\text{Fe}/\text{H}] = -1.9$ and for an absolute age of 15 Gyr, this difference in HB type would be explained if R106 were younger than NGC 6397 by 3.6 Gyr (under the assumption of variable mass loss on the RGB). This age difference is in agreement with the result of Buonanno et al. (1993), who, from the TO luminosities, concluded that R106 is about 4 Gyr younger than typical metal-poor clusters such as NGC 6397. The age difference predicted by Lee et al. (1994) under the assumption of constant mass loss is somewhat too large, 5.4 Gyr, which illustrates the uncertainty of any estimate of age differences from HB morphology. It is important to add that the unusual mix of elements in R106 is unlikely to be the major reason why its HB is so red in comparison with NGC 6397 and most other metal-poor globular clusters. As we have discussed previously, the measurements by Brown et al. (1997) indicate that R106 has

a higher $[\text{Fe}/\text{H}]$ than NGC 6397 but probably also a lower $[\alpha/\text{Fe}]$, which have opposite effects on HB morphology. While the uncertainties are many, the difference in age between cluster 4 and the other Fornax clusters is of the correct sign and magnitude to explain their difference in HB type.

3.7. Comparison with the Milky Way Cluster Ruprecht 106

As noted in § 1, the tidal destruction of dwarf satellite galaxies has been widely discussed as a possible origin for the outer halo of the Milky Way, in part because this may explain the greater dispersion in HB types, particularly the relatively high frequency of red HB types among the metal-poor outer halo ($R_{\text{GC}} \geq 8$ kpc) clusters (e.g., Searle & Zinn 1978). This possibility has motivated several comparisons between the Fornax clusters and more recently the clusters of the Sagittarius dSph galaxy with the GCs of the outer halo (Zinn 1993; Smith et al. 1998; Marconi et al. 1998). The close similarity between cluster 4 and R106, which we now discuss, lends weight to the hypothesis that R106 and the other unusual outer halo clusters were once members of dwarf galaxies.

The comparison of the fiducial line of cluster 4 with that of R106 (Buonanno et al. 1993) is made in Figure 13. The line for Fornax cluster 4 has been dereddened and shifted according to the quantities already adopted for Figure 12. The mean points of R106 have been shifted by $E(V-I) = 0.27$ and $\Delta V = +3.28$. The first quantity is nearly identical to the reddening found by Buonanno et al. (1993), who measured $E(V-I) = 0.23$, and the second is exactly the difference between the absorption-free HB magnitudes $[V_{\text{HB}}(\text{R106}) = 17.85]$. To estimate the age difference between cluster 4 and R106, we use again the procedure adopted above. From Figure 13 we find $\Delta_V(\text{cl4} - \text{R106}) = 0.02$, $\delta_{V-I}(\text{cl4} - \text{R106}) = -0.05$, and then $\delta t = 0.2$ Gyr and $\delta t = 0.5$ Gyr, respectively. Cluster 4 and R106 are therefore essentially coeval. While R106 and cluster 4 appear to be very similar as far as age, HB morphology, and metallicity are concerned, they are very different in central density $[\log \rho_0(\text{cl4}) = 3.936, \log \rho_0(\text{R106}) = 1.216 M_{\odot} \text{pc}^{-3}]$. This difference appears to have had little if any effect on the HB morphologies of the clusters.

The investigations of the Fornax clusters reported here and in BEA98 have not found compelling evidence that the second parameter can be identified with only one quantity. Our results suggest that age differences alone may explain the difference in HB morphology between cluster 4 and the other clusters, if one accepts the calculations of Lee et al. (1994) for the variable mass-loss case. However, these same calculations predict a larger age difference than is observed between cluster 1 and clusters 2, 3, and 5 (BEA98). This suggests that the second-parameter phenomenon may be caused by a mixture of age with other effects.

As discussed earlier by Buonanno et al. (1997) and BEA98, it is attractive to identify cluster density as an additional factor that presumably affects HB morphology by influencing the amount of mass loss on the RGB. The effective temperatures of HB stars depend on their envelope masses, and this sensitivity is greatest among the blue HB stars, which have the lowest envelope masses. If in clusters of high density the stars evolving on the RGB lose a little additional mass through stellar encounters, then the effect on HB morphology will be greatest in clusters that have blue HBs for another reason, such as very old age. This may

explain why density appears to be correlated with the HB morphology of blue HB clusters and with the oddities of blue HBs, such as “blue tails,” but at the same time appears to have little effect on the morphologies of red HB clusters such as cluster 4 and R106. Theoretical investigations of this question, the more general question of the sensitivity of HB morphology to age and other factors (rotation, mixing, etc.), and the mass-loss mechanism or mechanisms are urgently needed.

4. SUMMARY AND CONCLUSIONS

We have constructed deep CMDs of cluster 4 in Fornax and of the field population around the cluster using data from the *HST* archive. From these CMDs, we measured the metal abundances and estimated the ages of their stellar populations.

Our results for the field population of Fornax are in good agreement with previous investigations in that they reveal a very long period of star formation (≈ 12 to 0.5 Gyr). While a small fraction of the field stars may be coeval with the Fornax clusters and as metal-poor, the majority of them are significantly younger than the youngest cluster and more metal-rich. The multiple SGBs in the field CMD suggest that the rate of star formation was not constant but resembled more bursts.

In contrast to the field population, all five globular clusters in Fornax appear to be older than about 10 Gyr but not, however, without a significant spread in age. BEA98 showed that clusters 1, 2, 3, and 5 are essentially coeval ($\delta t \leq 1$ Gyr) with each other and with the very metal-poor GCs in the Milky Way. Our results indicate that cluster 4 is younger, $\delta t \approx 3$ Gyr, than the other Fornax clusters. The RGB of cluster 4 is very steep, which under the standard assumptions is a sign that it is very metal-poor, $[\text{Fe}/\text{H}] \approx -2$. The very close similarity between the CMDs of cluster 4 and R106 suggests, however, that it may be also like R106 in having an unusual mix of elements, a possibility that warrants further investigation.

Although the uncertainties are large, the very red HB of cluster 4 may be explained entirely by its relatively young age. In contrast, BEA98 found that age differences alone were unlikely to account for the range in HB types among the other Fornax clusters, and they suggested that cluster density also played a role. Our comparison between cluster 4 and R106, which are very similar in CMD morphology despite very different central densities, suggests that cluster density has at most a small effect among relatively youthful clusters that have very red HBs.

The two most massive dSph galaxies orbiting the Milky Way, Fornax and Sagittarius, have their own globular cluster systems in which there are different cluster-to-cluster variations in metal abundance, HB type, and age (see also Marconi et al. 1998; BEA98). The similarities found here and in BEA98 between the Fornax clusters and both “normal,” e.g., M68 and M92, and “anomalous,” e.g., R106, halo clusters support the hypothesis that the tidal destruction of similar galaxies in the past, as is now happening to the Sagittarius dSph galaxy, is the reason for the diversity in properties among the outer halo GCs.

This research is based on observations with the NASA/ESA *Hubble Space Telescope*, obtained at the Space Telescope Science Institute, which is operated by the

Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555. The support of the CNAA for M. C. and the NSF (AST 93-19229 and 98-03071) and STScI (GO-05917.01-94A) for R. Z. is gratefully acknowledged. We acknowledge J. R. Westphal,

principal investigator of GTO proposal WFC 5637, for designing the very useful observations we used in this paper. We also thank A. Chieffi for providing us updated theoretical isochrones and for helpful suggestions and comments.

REFERENCES

- Beauchamp, D., Hardy, E., Suntzeff, N. B., & Zinn, R. 1995, *AJ*, 109, 1628
 Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, *A&AS*, 106, 275
 Brown, J. A., Wallerstein, G., & Zucker, D. 1997, *AJ*, 114, 180
 Buonanno, R., Corsi, C., Bellazzini, M., Ferraro, F., & Fusi Pecci, F. 1997, *AJ*, 113, 706
 Buonanno, R., Corsi, C. E., & Fusi Pecci, F. 1989, *A&A*, 216, 80
 Buonanno, R., Corsi, C. E., Fusi Pecci, F., Hardy, E., & Zinn, R. 1985, *A&A*, 152, 65 (BEA85)
 Buonanno, R., Corsi, C. E., Fusi Pecci, F., Richer, H., & Fahlman, G. G. 1993, *AJ*, 105, 184
 Buonanno, R., Corsi, C. E., Pulone, L., Fusi Pecci, F., & Bellazzini, M. 1998a, *A&A*, 333, 505
 Buonanno, R., Corsi, C. E., Zinn, R., Fusi Pecci, F., Hardy, E., & Suntzeff, N. B. 1998b, *ApJ*, 501, L33 (BEA98)
 Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, *ApJ*, 345, 245
 Carretta, E., & Gratton, R. G. 1997, *A&AS*, 121, 95
 Chaboyer, B., Demarque, P., Kernan, P. J., & Krauss, L. M. 1998, *ApJ*, 494, 96
 Cool, A. M., & King, I. R. 1995, in *Calibrating Hubble Space Telescope: Post Servicing Mission*, ed. A. Koratkar & C. Leitherer (Baltimore: STScI), 290
 Da Costa, G. S. 1998, in *Stellar Astrophysics for the Local Group*, ed. A. Aparicio, A. Herrero, & F. Sánchez (Cambridge: Cambridge Univ. Press), 351
 Da Costa, G. S., & Armandroff, T. E. 1990, *AJ*, 100, 162 (DCA90)
 Demarque, P., Chaboyer, B., Guenther, D., Pinsonneault, M., Pinsonneault, L., & Yi, S. 1996, *Yale Isochrones 1996* (Greenbelt, MD: GSFC)
 Dubath, P., Meylan, G., & Mayor, M. 1992, *ApJ*, 400, 510
 François, P., Danziger, J., Buonanno, R., & Perrin, M. N. 1997, *A&A*, 327, 121
 Fusi Pecci, F., Bellazzini, M., Cacciari, C., & Ferraro, F. R. 1995, *AJ*, 110, 1664
 Hardy, E., Buonanno, R., Corsi, C. E., Janes, K. A., & Schommer, R. A. 1984, *ApJ*, 278, 592
 Harris, H. C., & Canterna, R. 1977, *AJ*, 82, 798
 Holtzman, J. A., Burrows, C. J., Casertano, S., Hester, J. J., Trauger, J. T., Watson, A. M., & Worthey, G. 1995, *PASP*, 107, 1065
 Johnson, J. A., & Bolte, M. 1998, *AJ*, 115, 693
 Lee, M. G., Freedman, W. L., & Madore, B. F. 1993, *ApJ*, 417, 553
 Lee, Y.-W., Demarque, P., & Zinn, R. 1990, *ApJ*, 350, 155
 ———. 1994, *ApJ*, 423, 248
 Marconi, G., Buonanno, R., Castellani, M., Iannicola, G., Molaro, P., Pasquini, L., & Pulone, L. 1998, *A&A*, 330, 453
 Mateo, M. L. 1998, *ARA&A*, 36, 435
 Mighell, K. J. 1997, *AJ*, 114, 1458
 Montegriffo, P., Ferraro, F. R., Fusi Pecci, F., & Origlia, L. 1995, *MNRAS*, 276, 739
 Popowski, P., & Gould, A. 1998, *ApJ*, 506, 271
 Salaris, M., Chieffi, A., & Straniero, O. 1993, *ApJ*, 414, 580
 Sarajedini, A. 1994, *AJ*, 107, 618
 Sarajedini, A., Chaboyer, B., & Demarque, P. 1997, *PASP*, 109, 1321
 Sarajedini, A., & Layden, A. 1997, *AJ*, 113, 264
 Searle, L., & Zinn, R. 1978, *ApJ*, 225, 357
 Smecker-Hane, T. A., Stetson, P. B., Hesser, J. E., & Lehnert, M. D. 1994, *AJ*, 108, 507
 Smecker-Hane, T., Stetson, P. B., Hesser, J. E., & Vandenberg, D. A. 1996, in *ASP Conf. Ser. 98, From Stars to Galaxies*, ed. C. Leitherer, U. Fritze-von Alvensleben, & J. P. Huchra (San Francisco: ASP), 328
 Smith, E. O., Neill, J. D., Mighell, K. J., & Rich, R. M. 1996, *AJ*, 111, 1596
 Smith, E. O., Rich, R. M., & Neill, J. D. 1997, *AJ*, 114, 1471
 ———. 1998, *AJ*, 115, 2369
 Stetson, P. B. 1987, *PASP*, 99, 191
 ———. 1997, *Baltic Astron.*, 6, 3
 Stetson, P. B., Hesser, J. E., & Smecker-Hane, T. A. 1998, *PASP*, 110, 533
 Vandenberg, D. A., Bolte, M., & Stetson, P. B. 1990, *AJ*, 100, 445
 Vandenberg, D. A., Stetson, P. B., & Bolte, M. 1996, *ARA&A*, 34, 461
 Walker, A. R. 1994, *AJ*, 108, 555
 Webbink, R. F. 1985, in *IAU Symp. 113, Dynamics of Star Clusters*, ed. J. Goodman & P. Hut (Dordrecht: Reidel), 541
 Zinn, R. 1993, in *ASP Conf. Ser. 48, The Globular Cluster-Galaxy Connection*, ed. G. H. Smith & J. P. Brodie (San Francisco: ASP), 302
 Zinn, R., & Persson, S. E. 1981, *ApJ*, 247, 849
 Zinn, R., & West, M. J. 1984, *ApJS*, 55, 45