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THE AGES OF THE GLOBULAR CLUSTERS IN THE FORNAX DWARF GALAXY

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ABSTRACT

From observations with the *Hubble Space Telescope*, color-magnitude diagrams (CMDs) have been constructed for the four most metal-poor globular clusters in the Fornax dSph galaxy. These diagrams confirm that cluster 1 has a redder horizontal-branch (HB) morphology than the other three clusters despite its similarity in metallicity (the second parameter effect). The near coincidence of the fiducial lines of the CMDs indicates that the ages of the Fornax clusters are identical to within 1 Gyr. Since a larger range is predicted if age is the second parameter, we conclude that either the sensitivity of the HB to age has been underestimated or some parameter besides age is acting as a second parameter. The Fornax clusters exhibit a correlation between HB morphology and central density that is similar to the one among galactic globular clusters, which suggests that some mechanism related to density is influencing HB morphology. No significant differences in age have been found between the Fornax clusters and the metal-poor galactic globular clusters M68 and M92, which suggests that cluster formation began nearly simultaneously over a large volume of space.

Subject headings: galaxies: star clusters — globular clusters: general — Local Group

1. INTRODUCTION

Previous investigations of the color-magnitude diagram (CMD) and the integrated light of the five globular clusters in the Fornax dwarf spheroidal (dSph) galaxy have shown that they span significant ranges in metallicity ([Fe/H] ~ -2.2 to ~ -1.4) and horizontal-branch (HB) morphology (see Buonanno et al. 1985; Demers, Kunkel, & Grondin 1990; Dubath, Meylor, & Mayor 1992; Beauchamp et al. 1995; Smith et al. 1996; Smith, Rich, & Neil 1997; Jorgensen & Jimenez 1997; and references therein). Because four of the Fornax clusters (1, 2, 3, and 5) are substantially more metal poor than the mean abundance of the field population of Fornax and have bluer HBs, they are thought to be representative of the oldest stellar population in Fornax (e.g., Buonanno et al. 1985). These same four clusters provide an opportunity to increase our understanding of the "second parameter effect" because their HB morphologies differ much more than expected on the basis of their differences in metallicity (Buonanno et al. 1985; Beauchamp et al. 1995; Demers et al. 1990; Smith et al. 1996). The measurement of the ages of these clusters provides a test of the hypothesis that age is primarily responsible for the second parameter effect (e.g., Lee, Demarque, & Zinn 1994; Sarajedini, Chaboyer, & Demarque 1997). Some features of HB morphology, such as "blue tails," defy explanation by the age hypothesis, but they and the second parameter may be related to the central densities of the clusters (Buonanno et al. 1997 and references therein). Since the Fornax clusters span a wide range in central density, they provide another opportunity to explore this possibility.

This investigation of the CMDs of the four metal-poor clusters from the tip of the red giant branch (RGB) to below the main-sequence turnoff (TO) is based on observations with the Wide Field Planetary Camera 2 (WFPC2) of the *Hubble Space Telescope* (*HST*) during cycle 5. We consider here the ages of the Fornax clusters with respect to each other and to galactic globular clusters of similar metal abundance. The observations, reductions, calibrations, and other issues pertaining to the CMDs are described in a subsequent paper (Buonanno et al. 1998b).

2. COLOR-MAGNITUDE DIAGRAMS

Each cluster was centered in the $35'' \times 35''$ field of view of the PC2, which encompassed only ~1 core radius (r_c) of cluster 1, but more than $3r_c$ of the other, more concentrated clusters (Smith et al. 1996 and references therein). We were able to measure precise magnitudes for even the faintest stars at the very center of cluster 1. Since this was not possible for the other three clusters, we measured a "bright sample" ($V_{\rm lim} \sim 24.5$) drawn from a large area of the PC2 field and a "faint sample" ($V_{\rm lim} \sim 26.5$) from an annulus where the image density did not compromise photometry to very faint magnitudes. The inner and outer boundaries of these areas ($R_{\rm min}$, $R_{\rm max}$, in arcseconds) and the numbers of measured stars are listed in Table 1, where "0" and "PC" mean the cluster center and the limit of the PC2 field, respectively. The CMDs of clusters 2, 3, and 5 consist of the stars in the faint sample with $22.0 > V > 26.5$ and stars from the bright sample down to $V \sim 22$ along the RGB, but to fainter magnitudes at bluer colors, so that any stars populating the faint blue extension of the HB are included.

The CMDs (Fig. 1) confirm that the steep RGBs of clusters 1, 2, 3, and 5 resemble those of the metal-poor globular clusters. The HBs are well defined and have different morphologies: cluster 1 has most of its HB stars on the red side of the RR Lyrae variability strip, cluster 3 has a relatively long HB blue tail, while the HB morphologies of clusters 2 and 5 lie between those of clusters 1 and 3. We have identified 8, 39, 66, and 36 candidate RR Lyrae variables in clusters 1, 2, 3, and 5, respectively, on the basis that their frame-to-frame variations exceeded 3 σ. Clusters 1 and 2, the clusters of lowest central concentration, contain many blue stragglers.

To quantify HB morphology, we have selected the index $(B-R)/(B+V+R)$, hereafter HB type, where B, V, and R are the numbers of blue, variable, and red HB stars, respectively (Lee et al. 1994). For clusters 2, 3, and 5, our CMDs yield values of HB type (Table 2) that are larger (bluer HB) than

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TABLE 1
Area and Number of Measured Stars

Cluster	Bright Sample			Faint Sample		
	$R''_{\min}$	$R''_{\max}$	Stars	$R''_{\min}$	$R''_{\max}$	Stars
1	0	PC	...	0	PC	1169
2	0	PC	253	8	PC	3739
3	2	PC	415	6	16	3968
5	2	PC	318	6	16	2916

previous estimates, which failed to detect as many blue HB stars as our much deeper *HST* observations. Our PC2 data for cluster 1 suggest that its HB consists of only red stars, of which ∼50% are probable RR Lyrae variables. CMDs of larger areas (Buonanno et al. 1985, 1996; Demers et al. 1990; Smith et al. 1996) contain a few blue HB stars in addition to many red ones, and Buonanno et al. (1996) and Smith et al. (1996) detected 17 and 21 candidate RR Lyrae variables, respectively. The frequency of RR Lyrae variables is exceptionally high in cluster 1, which can be seen from the quantity N_{RR}, the number of variables normalized to a cluster absolute magnitude of $M_v = -7.5$ (Suntzeff, Kinman, & Kraft 1991). Given that, for cluster 1, $M_v = -5.5$ (Buonanno et al. 1985) and under the assumption that it contains more than 13 variables, we obtain $N_{RR} > 80$. Clusters 2, 3, and 5, which are more luminous than cluster 1, also have high frequencies of variables, but not as extreme as cluster 1. Only four Milky Way clusters have $N_{RR} > 80$ (Suntzeff et al. 1991), and each of these has an HB type ∼0. The HB type of cluster 1 is estimated to be -0.2 ± 0.2, because every CMD shows that its HB is more heavily populated with red than blue stars.

The apparent magnitude of the HB at the instability strip, V_{HB}, was measured by averaging the magnitudes of the stars lying slightly outside the RR Lyrae gap. We have calculated the V_{HB} of cluster 1 from the mean of the red HB stars, which was then increased by 0.1 mag. This correction was estimated

TABLE 2
Parameters for Fornax Clusters

Cluster	V_{HB}	$E(V-I)$	[Fe/H]	$(B-R)/(B+V+R)$
1	21.25 ± 0.05	0.05 ± 0.06	−2.20 ± 0.20	−0.2 ± 0.2
2	21.35 ± 0.05	0.09 ± 0.06	−1.78 ± 0.20	0.38 ± 0.07
3	21.20 ± 0.05	0.05 ± 0.06	−1.96 ± 0.20	0.50 ± 0.06
5	21.30 ± 0.05	0.08 ± 0.06	−2.20 ± 0.20	0.44 ± 0.09

from the V, $V-I$ photometry of the very metal poor globular cluster M68 (Walker 1994).

We have estimated the reddenings and metallicities of each cluster from the color of the RGB at V_{HB}, $(V-I)_g$, and from the slope of the RGB, using the standard $[M_I, (V-I)_0]$ giant branches of Da Costa & Armandroff (1990). There is good agreement between our results (Table 2) and previous ones. All four clusters are very metal poor, with cluster 2 being slightly more metal rich than the other three.

3. RELATIVE AGES

To compare the ages of the Fornax clusters, we have used the technique of Buonanno et al. (1993), which achieves high precision by comparing simultaneously all the relevant branches of the CMDs. In Figure 2, the ridge lines of the clusters have been shifted in color and in magnitude by the reddenings and the concomitant absorptions [$A_V = 3.3E(B-V)$ and $E(V-I) = 1.24E(B-V)$; Cardelli, Clayton, & Mathis 1988]. From Figure 2, we have measured the relative age indicator $\Delta_V = \Delta V^{TO}_{HB^{ref}} - \Delta V^{TO}_{HB^{prog}}$, where ΔV^{TO}_{HB} is the difference between the luminosity of the TO (V_{TO}) and the luminosity of the HB at the variable strip V_{HB}. This double-differential index relates the age-sensitive ΔV^{TO}_{HB} parameter of one cluster, the "reference cluster," to that of a second, the "program cluster." It is particularly useful when the difference in metal abundance is so small that its effect on HB luminosity can be ignored (Buonanno et al. 1993). A second double-differential index, $\delta_{(V-I)}$, is defined as the difference $\Delta(V-I)^{RGB}_{TO^{ref}} - \Delta(V-I)^{RGB}_{TO^{prog}}$, where $\Delta(V-I)^{RGB}_{TO}$ is the color difference between the

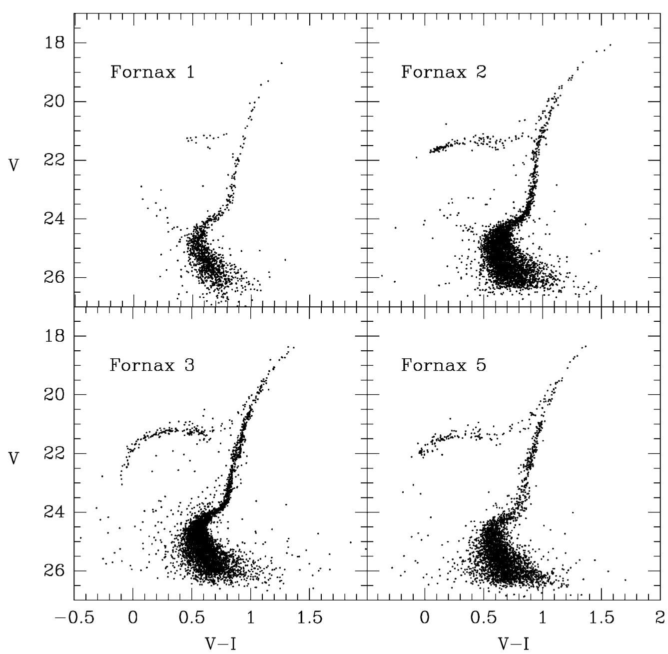

Fig. 1.—Color-magnitude diagrams of the four most metal-poor Fornax clusters. These diagrams are based on *HST* PC2 exposures with total integration times of ∼5000 and ∼7000 s in the filters F555W and F814W, respectively.

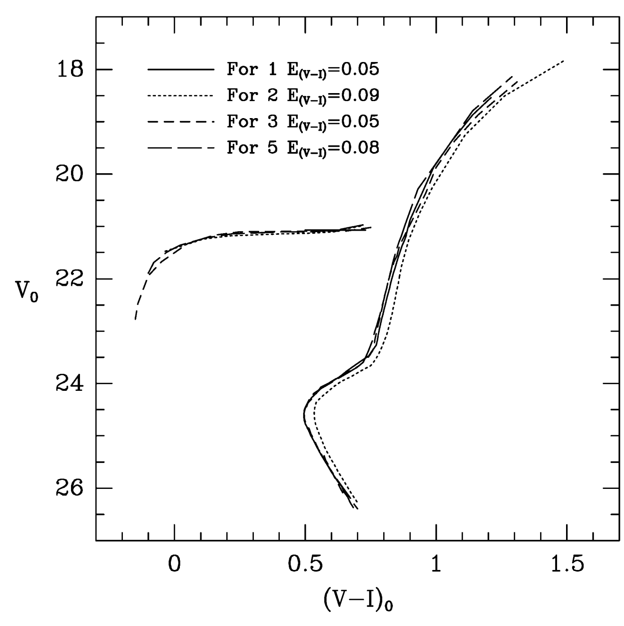

Fig. 2.—The fiducial lines (dereddened and absorption free) of the four Fornax clusters are compared. The lines for clusters 1, 3, and 5, which have similar metallicities, are nearly coincident.

TABLE 3

Age Indicators, Central Densities, and HB Morphologies

Cluster	[Fe/H]	Δ_V	$\delta_{(V-I)}$	$\log \rho_0$	$(B-R)/(B+V+R)$
1 ……	-2.20 ± 0.20	…	…	0.454	-0.2 ± 0.2
2 ……	-1.78 ± 0.20	$+0.03 \pm 0.15$	0.006 ± 0.006	1.599	0.38 ± 0.07
3 ……	-1.96 ± 0.20	-0.06 ± 0.15	0.008 ± 0.006	3.836	0.50 ± 0.06
5 ……	-2.20 ± 0.20	-0.05 ± 0.15	0.007 ± 0.007	2.469	0.44 ± 0.09

TO and the base of the RGB. $\Delta(V-I)_{\rm TO}^{\rm RGB}$ is the equivalent in the V, $(V-I)$ plane to the parameter $\delta_{(B-V)}$ that was defined by VandenBerg, Bolte, & Stetson (1990). Because the metallicity dependence of this index is not yet well determined, it can be used only in cases where the differences are very small. The observational errors of these indices (Table 3) have been estimated following Buonanno et al. (1993). The error in Δ_V is the combination of errors of 0.05 mag in $V_{\rm HB}$ and 0.1 mag in $V_{\rm TO}$ for all the clusters. The errors in $\delta_{(V-I)}$ result from the combination of the standard errors in $(V-I)_{\rm TO}$ and $(V-I)_{\rm RGB}$, which were computed by fitting parabolic arcs in appropriate boxes of the CMDs.

For a pair of clusters of similar metallicity, Buonanno et al. (1993) obtained for the difference in age $\delta \log(t_9) = (0.44 + 0.04[{\rm Fe/H}])\Delta_V$. Adopting an average [Fe/H] of -2.0 for the Fornax clusters and assuming an absolute age near 14 Gyr, the following age differences are obtained from Δ_V: $\delta t_{\rm (cl1-cl2)} = +0.4 \pm 2.0$ Gyr, $\delta t_{\rm (cl1-cl3)} = -0.7 \pm 2.0$ Gyr, and $\delta t_{\rm (cl1-cl5)} = -0.6 \pm 2.0$ Gyr. For $\delta_{(B-V)}$, Buonanno et al. (1993) obtained $\delta \log(t_9) = (-4.32 - 0.78[{\rm Fe/H}])\delta_{(B-V)}$. According to the empirical transformation between $(B-V)$ and $(V-I)$ colors in Marconi et al. (1998), $\delta_{(V-I)} \sim 1.208\delta_{(B-V)}$. The age differences between the Fornax clusters are then $\delta t_{\rm (cl1-cl2)} = -0.5 \pm 0.5$ Gyr, $\delta t_{\rm (cl1-cl3)} = -0.7 \pm 0.5$ Gyr, and $\delta t_{\rm (cl1-cl5)} = -0.6 \pm 0.6$ Gyr. The relations $\Delta_V/\delta t = 0.073$ and $\delta_{(V-I)}/\delta t = 0.013$ from Harris et al. (1997) yield very similar results. We conclude that the metal-poor clusters of the Fornax dSph have essentially the same age ($|\delta t| < 1$ Gyr).

Consequently, it may be difficult to explain the relatively red HB of cluster 1 by the hypothesis that age alone is the second parameter. We have estimated the difference expected under this hypothesis from the synthetic HB calculations of Lee et al. (1994), which assumed an absolute age near 14 Gyr. Lee et al. made separate calculations for fixed and variable mass-loss rates on the RGB. At [Fe/H] $= -2$, these calculations suggest that a δt of -1.9 ± 0.6 Gyr (fixed mass loss) or -1.5 ± 0.5 Gyr (variable mass loss) is required to explain the difference of 0.64 ± 0.2 in HB type between cluster 1 and the mean of the other three clusters. Differences of this size may be missed by the relatively imprecise Δ_V method, but this is not true of $\delta_{(V-I)}$ (but see Chaboyer, Demarque, & Sarajedini 1996b!). The δt between cluster 1 and the mean of the other clusters by the $\delta_{(V-I)}$ method, -0.6 ± 0.4, is inconsistent with the model predictions by 1.8 σ (fixed) and 1.4 σ (variable). Either the sensitivity of the HB to age has been underestimated or something besides age is acting as a second parameter. According to Figure 14 in Lee et al. (1994), the age sensitivity is larger by a factor of ~2 at absolute ages less than 10 Gyr, which would remove the disparity with the observations. Such young ages seem unlikely on the basis that the Fornax clusters are coeval with the globular clusters of the galactic halo (see below), whose ages are 10–14 Gyr (e.g., Reid 1997; Pont et al. 1998; Gratton et al. 1997; Chaboyer et al. 1998).

Inspection of Table 3 reveals a correlation between the HB types of the four clusters and their central densities ($M_\odot$ pc^{-3}; Webbink 1985), which is qualitatively similar to the one among the Milky Way globular clusters (see Buonanno et al. 1997 and references therein). These correlations have suggested that some mechanism related to the cluster environment has influenced stellar evolution, possibly by affecting the mass-loss processes.

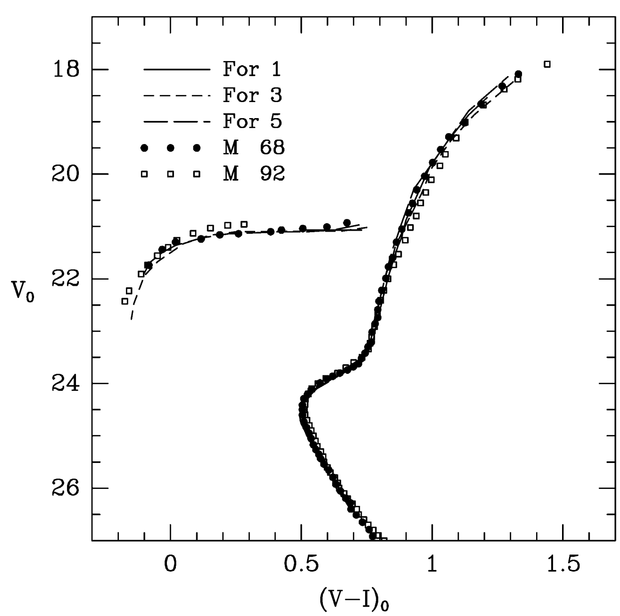

Fig. 3.—The fiducial lines of the metal-poor Fornax clusters 1, 3, and 5 are compared with those of two galactic globular clusters of similar metallicity. There is a close match between the galactic and the Fornax clusters.

4. COMPARISON WITH GALACTIC GLOBULAR CLUSTERS

Several studies of the most metal-poor globular clusters in the Milky Way have shown that their ages are identical to within the precisions of the determinations (e.g., VandenBerg et al. 1990; Richer et al. 1996), with the possible exception of M68, which, according to Chaboyer et al. (1996a), is ~2.5 Gyr younger than the others. Since all authors agree that M92 is one of the very oldest clusters, it and M68 were selected for comparison with the Fornax clusters. M92 and M68 and the three most metal-poor clusters in Fornax have similar metallicities. Because cluster 2 is somewhat more metal rich, it has been excluded from the following comparison. The HB type of M68, 0.44 (Walker 1994), is identical to those of Fornax clusters 2, 3, and 5, while that of M92, 0.88 (Lee et al. 1994), is significantly bluer.

In Figure 3, the fiducial lines of clusters 1, 3, and 5 from Figure 2 are compared with those of M68 (Walker 1994) and M92 (Buonanno et al. 1998a), after they have been corrected for reddening [$E(V-I) = 0.09$ and 0.04] and shifted in magnitude by $\Delta V = +5.4$ and $+5.8$, respectively. These shifts produce a close match between the Fornax clusters and M68 at every point in the CMD. This is also true for M92, with the important exception of the HB near the instability strip, where M92 is brighter than the other clusters by ~0.1 mag. The stars populating the red end of the very blue HB in M92 are likely to be more evolved from the zero-age horizontal branch and hence brighter than the stars of similar effective temperature in the other clusters. The offset of 0.1 mag is consistent with synthetic HB calculations (Lee, Demarque, & Zinn 1990; Lee 1993).

Adopting as the reference cluster the average of the fiducial lines of the clusters 1, 3, and 5, we obtain, from Figure 3, $\Delta_V = -0.05 \pm 0.15$ mag for M92 and $\Delta_V = 0.09 \pm 0.15$ mag for M68. The value for M92 includes the correction for the greater luminosity of its HB stars near the instability strip. In terms of age, $\delta t_{(\mathrm{For-M92})} = -0.6 \pm 1.9$ Gyr and $\delta t_{(\mathrm{For-M68})} = +1.1 \pm 2.0$ Gyr. The differences in $\delta_{(V-I)}$ between these Fornax clusters and M92 and M68 are 0.016 ± 0.010 and 0.004 ± 0.010 mag, respectively. Transforming the differences into age yields $\delta t_{(\mathrm{For-M92})} = -1.2 \pm 1.0$ Gyr and $\delta t_{(\mathrm{For-M68})} = -0.3 \pm 0.9$ Gyr. The metal-poor clusters of the Fornax dSph are essentially coeval with the old, metal-poor clusters of our Galaxy.

5. CONCLUSIONS

We have shown that the four Fornax clusters have the same age to within about 1 Gyr and that the age differences are too small to explain the differences in HB morphology unless theoretical models of the HB have underestimated its age sensitivity. A correlation exists between the HB morphologies and the central densities of the clusters in the same sense as the one among galactic globular clusters. The Fornax clusters are essentially the same age as galactic globular clusters with a similar [Fe/H]. As discussed by Harris et al. (1997), this may be evidence for a sharply defined epoch when star and cluster formation ignited in the universe.

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REFERENCES

Beauchamp, D., Hardy, E., Suntzeff, N. B., & Zinn, R. 1995, AJ, 109, 1628
Buonanno, R., Corsi, C. E., Bellazzini, M., Ferraro, F., & Fusi Pecci, F. 1997, AJ, 113, 706
Buonanno, R., Corsi, C. E., Ferraro, F. R., Fusi Pecci, F., & Bellazzini, M. 1996, in ASP Conf. Ser. 92, Formation of the Galactic Halo—Inside and Out, ed. H. l. Morrison & A. Sarajedini (San Francisco: ASP), 520
Buonanno, R., Corsi, C. E., Fusi Pecci, F., Hardy, E., & Zinn, R. 1985, A&A, 152, 65
Buonanno, R., Corsi, C. E., Fusi Pecci, F., Richer, H. B., & Fahlman, G. G. 1993, AJ, 105, 184
Buonanno, R., et al. 1998a, in preparation
———. 1998b, in preparation
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1988, ApJ, 329, L33
Chaboyer, B., Demarque, P., Kernan, P. J., & Krauss, L. M. 1998, ApJ, 494, 96
Chaboyer, B. C., Demarque, P., Kernan, P. J., Krauss, L. M., & Sarajedini, A. 1996a, MNRAS, 283, 683
Chaboyer, B., Demarque, P., & Sarajedini, A. 1996b, ApJ, 459, 558
Da Costa, G. S., & Armandroff, T. E. 1990, AJ, 100, 162
Demers, S., Kunkel, W. E., & Grondin, L. 1990, PASP, 102, 632
Dubath, P., Meylan, G., & Mayor, M. 1992, ApJ, 400, 510
Gratton, R. G., Fusi Pecci, F., Carretta, E., Clementini, G., Corsi, C. E., & Lattanzi, M. 1997, ApJ, 491, 749
Harris, W. E., et al. 1997, AJ, 114, 1030
Jorgensen, U. G., & Jimenez, R. 1997, A&A, 317, 54
Lee, Y. W. 1993, in New Perspectives on Stellar Pulsation and Pulsating Variable Star, ed. J. M. Nemec & J. M. Mathews (Cambridge: Cambridge Univ. Press), 294
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
Pont, F., Mayor, M., Turon, C., & VandenBerg, D. A. 1998, A&A, 329, 87
Reid, I. N. 1997, AJ, 114, 161
Richer, H. B., et al. 1996, ApJ, 463, 602
Sarajedini, A., Chaboyer, B., & Demarque, P. 1997, PASP, 109, 1321
Smith, E. O., Neill, J. D., Mighell, K. J., & Rich, R. M. 1996, AJ, 111, 1596
Smith, E. O., Rich, R. M., & Neil, J. D. 1997, AJ, 114, 1471
Suntzeff, N. B., Kinman, T. D., & Kraft, R. P. 1991, ApJ, 367, 528
VandenBerg, D. A., Bolte, M., & Stetson, P. B. 1990, AJ, 100, 445
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: Kluwer), 541