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Globular clusters 1 and 3 in the Fornax dwarf galaxy

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Abstract. We have performed photometric CCD observations of the giant and horizontal branches of the globular cluster 1, and of the giant branch of cluster 3, in the Fornax dwarf spheroidal galaxy. The observations were performed in the V and I standard broad-band filters as well as through two narrow-band filters especially designed to distinguish between carbon and M type stars. The AGB is richly populated with carbon-rich stars, and all of them are considerably below the theoretical lower luminosity limit for such stars. If the Fornax clusters are interpreted as resembling an earlier epoch of the Galactic globular clusters, the low luminosities of the carbon stars therefore point to a larger role of the low-mass stars in the chemical enrichment of our Galaxy.

The giant branches of the Fornax clusters are much broader than canonical giant branches in Galactic globulars, and the AGB is more well populated. We suggest that the morphology and stellar population of the giant branches indicate that the dwarf galaxies are ≈ 3 Gyr younger than the Galactic halo, which in turn seems to be ≈ 3 Gyr younger than the Galactic globular clusters.*

Key words: stars: carbon – stars: AGB – galaxies: formation – galaxies: individual: Fornax dSph (A0237-34) – galaxies: star clusters

1. Introduction

The Fornax dwarf spheroidal galaxy (Fornax dSph or A0237-34; α, δ_{1950} = $2^{\rm h}37^{\rm m}.8, -34°44'$, $b = -66°$), first recognised by Shapley (1938, 1939) on Harvard plates, is the largest of the 7 known dwarf galaxies associated with the outer halo of our Galaxy. Its mass (M $\approx 1.7 \times 10^7 M_\odot$; Eskridge 1988) puts it between the mass of the largest Galactic globular clusters (ω Cen with a mass of M $\approx 1.1\ 10^6$ $M_\odot$) and the normal dwarf irregular or elliptical galaxies. It is also the brightest ($M_V \approx -12.4$ mag), the largest in diameter (≈ 5 kpc), and the brightest in central surface intensity among the seven. Its form can be fitted well with an ellipse, and the intensity distribution can be described with a strongly truncated King model (with core radius 16.8$'$ and tidal radius 108$'$; Eskridge 1988).

Fornax dSph is the only one of the 7 dwarfs known to contain globular clusters – though Canterna & Flower (1977) mentioned the possibility of three globular clusters associated with the Phoenix dSph galaxy as well. It is the smallest among all galaxies known to have globular clusters of its own, and it is the galaxy with the highest number of globular clusters per galaxy luminosity unit (Harris 1991). We observed the giant branch of the brightest and of the most dim of the clusters (integrated M_v = -8.07 and -5.50, respectively), in two narrow band filters (designed to distinguish between carbon stars and M type stars) and in two broad-band filters (V and I). The clusters are described as cluster 3 (the brightest one) and cluster 1, following the nomenclature of Hodge (1961, 1969). Cluster 1 is more diffuse and with lower surface brightness than the other clusters, and it is situated on the outer part of the galaxy, whereas cluster 3 is closer to the center.

The 6 clusters represent a surprisingly diverse system, considering the small size of their host galaxy. The range of metallicities among the 6 clusters is comparable to the range spanned by the 91 known old globular clusters (GCs) in our entire Galaxy (Zinn 1985). Cluster 1 and 2 follow truncated King profiles with very extended radii, indicating a tidal interaction, whereas cluster 3, 4, and 5 show absence of tidal truncation (contrary to typical Galactic globular clusters) with small core radii and extended halos, not well fitted by King profiles (Rodgers & Roberts 1994, Demers et al. 1990, Webbink 1985).

The integrated light from the Fornax GCs has B$-$V values comparable to the reddest clusters in M31, M33, the Galaxy, and LMC, on the contrary, in the (U$-$B) versus (B$-$V) diagram, Fornax clusters fall among the oldest Galactic clusters (M92, M15, M3, M5), and far from younger globular clusters (M107, 47 Tuc). Discussion of the ages of these and other Galactic globular clusters have been given recently by, for example, Zinn (1985), Dorman et al. (1989), Chaboyer et al. (1992), Jørgensen & Thejll (1993), Jimenez et al. (1996). Also the mass to light ratio, $M/L_V = 3 - 5\ (M/L_V)_\odot$ (Dubath et al. 1992 for clusters 3, 4, and 5) puts the cluster system of Fornax dSph among the oldest Galactic globular clusters (which have $M/L_V \approx 2-3$) and

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* Tables 1 and 2 only available in electronic form

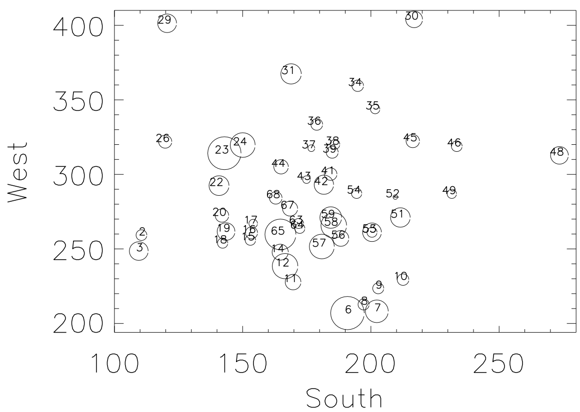

Fig. 1. Finding chart for Cluster 1. Center of the circles indicates the position of the stars observed, and the diameters of the circles are made such that they scale linearly with the observed V magnitudes. The numbers correspond to the numbers in Table 1. The tick marks along the x- and y-axis indicate the pixel number on the CCD frame. Each pixel corresponds to 0.4″. West is to the left, and south is downward. The cluster is resolved all the way to the center.

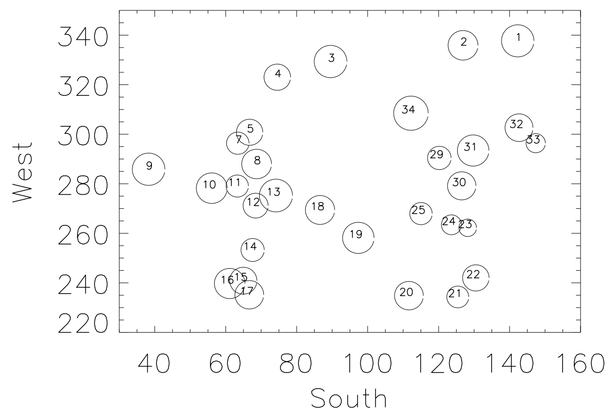

Fig. 2. Finding chart for Cluster 3, produced and oriented as for Fig. 1. The cluster is not resolved in the central regions, and no stars are therefore marked or analysed in that part of the frame.

very different from the young LMC GCs which can have $M/L_V \approx 30$.

All these properties, together with other integrated light properties (van den Bergh 1969, Zinn & Persson 1981, Jones & Hyland 1982), indicate that the Fornax clusters are old. Integrated light properties cannot, however, quantify their age well. Detailed B and V photometry of one or more of the clusters have been obtained by Demers et al. 1979 (DKH79), Verner et al. 1981 (VDHK81), Buonanno et al. 1985 (BCFHZ85), and Demers et al. (1990) (DKG90). Most of this photometry is, however, based on the same photographic plates, obtained at Las Campanas Observatory with the 2.5 m du Pont telescope, and reduced relative to the same sequence of photoelectric standard stars exposed onto the glass plates. We present here independent CCD photometry obtained with the Danish 1.54 m telescope at La Silla and reduced relative to a sequence of CCD standard stars observed during the same nights. Our observations include the first observations of cluster stars in the I filter, and, in particular, the first observations performed to distinguish M type stars from carbon stars in the area of these clusters.

2. Observations and data reductions

The set of observations was carried out at the European Southern Observatory (ESO), La Silla, with the Danish 1.54 m telescope, equipped with a 360 × 512 pixels CCD, covering 2.5 × 4 arc minutes. The seeing during the observations was 0.7″, which allowed us to resolve cluster 1 entirely to the center, whereas the more dense cluster 3 could not be fully resolved in stars in the central region. Finding charts for the observed stars in the two clusters are presented in Fig. 1 and Fig. 2. The size of the plotted symbols scales linearly with the observed V magnitude. The tick marks along the axis represent pixel numbers, and each pixel corresponds to 0.4″. The numbers associated with the symbols in the plot refers to the numbers in the list of our observational results presented in Table 1 and Table 2 (for cluster 1 and 3, respectively). Beside the standard V and I broad-band photometry, we obtained narrow-band photometry through two interference filters centered at 8120 Å and at 7795 Å, respectively, with a maximum transmission of 85% and a full band width of 96Å at half maximum transmission. The total exposure time (and number of individual exposures that was added) for Cluster 1 was 50 minutes (on 5 frames) in V, 60 min. in I (on 4 frames), 120 min. in the 8120 Å filter (on 2 frames), and 120 min. in the 7795 Å filter (on 2 frames). The corresponding numbers for Cluster 3 are 60 min. (on 3 frames) in V, 60 min. (on 3 frames) in I, 120 min. in the 8120 Å filter (on 2 frames), and 120 min. in the 7795 Å filter (on 2 frames).

The two narrow-band filters (which were purchased especially for the present observations) resemble closely the filters suggested by Palmer & Wing (1982) for identification of C and M stars, and are basically a broadened version of two of the filters in the Wing 8 colour photometric system (Wing 1967). The filter at 7795 Å covers the region where a strong TiO band appears in M type stars, whereas the filter at 8120 Å is situated in the region of a strong CN absorption feature in carbon stars. The magnitude difference Δm_{81-78} = m(8120Å) − m(7795Å) is therefore a measure of the difference in the relative strength of the TiO and the CN band systems, such that high values of Δm_{81-78} correspond to stars with relatively strong CN bands (i.e., carbon stars), and stars with low Δm_{81-78} index corresponds to stars with relatively strong TiO bands (i.e., M type stars). As opposed to the colour indices suggested by Palmer & Wing (1982), where a third narrow-band filter defines the continuum, we plot directly the instrumental 8120Å − 7795Å magnitude difference against the reduced V − I colours; a method previously applied by Richer & Pritchet (1985) in the search for carbon stars in NGC 205. Our results are plotted for the two clusters in Fig. 3 and Fig. 4, respectively. Obvious carbon stars are indicated by triangles, and obvious M type stars are indicated by stars, whereas stars on the transition are indicated by crosses.

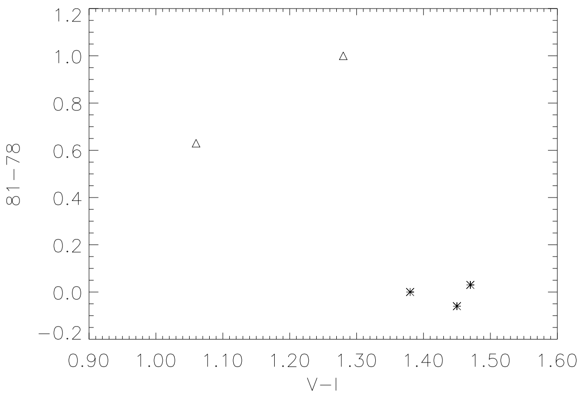

Fig. 3. The Δm_{81-78} versus V−I colour-colour diagram for Cluster 1. $\Delta m_{81-78} = m(8120Å) - m(7795Å)$ measures the magnitude difference in the region of a CN band (at 8120Å; in C type stars), and a TiO band (at 7795Å; in M type stars) such that high values of Δm_{81-78} correspond to carbon stars and lower values correspond to M type stars. Obvious carbon stars a marked with triangles, and obvious M type stars are marked with stars.

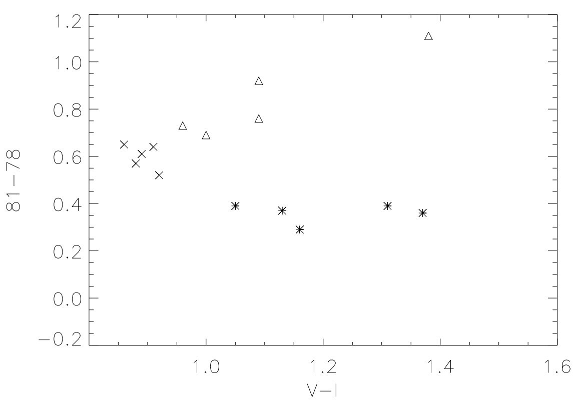

Fig. 4. The Δm_{81-78} versus V−I colour-colour diagram for Cluster 3, as in Fig. 3. Obvious carbon stars a marked with triangles, and obvious M type stars are marked with stars, whereas stars on the transition are marked with crosses.

Data reductions were performed with the utilities in IRAF. The frames were bias corrected and then flat fielded using twilight flat-fields. The dark current was negligible. Standard stars from the catalog of Graham (1985) were observed at several air masses throughout the nights, in the V and I filters, and the V and I magnitudes of the program stars were calibrated using these standards. In total, around 25 standard stars were used every night per filter, monitoring the sky every 15 minutes. No attempt was made to calibrate the narrow-band observations, since they were only meant to be used as a qualitative tool to distinguish between carbon and oxygen-rich stars. The magnitudes were calculated using DAOPHOT/IRAF, both for the cluster frames and for the standard star frames, and the point spread function was calculated from 5 isolated stars in the science frames.

In order to transform from the observed magnitudes to bolometric magnitudes, we first corrected the derived V and I magnitudes for interstellar absorption, $V_0 = V - 3.2\,E(B-V)$ and

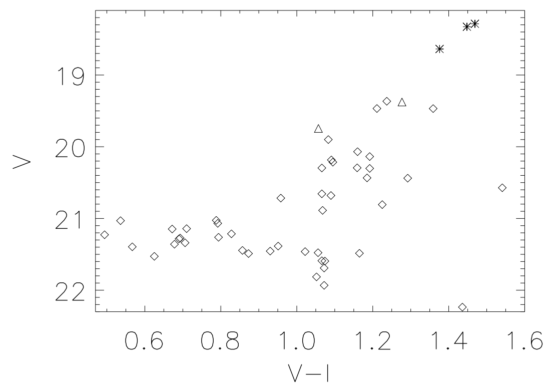

Fig. 5. The V versus V−I colour-magnitude diagram for Cluster 1. Stars symbols represent M-type stars, triangles carbon stars and diamonds are stars which have not been classified.

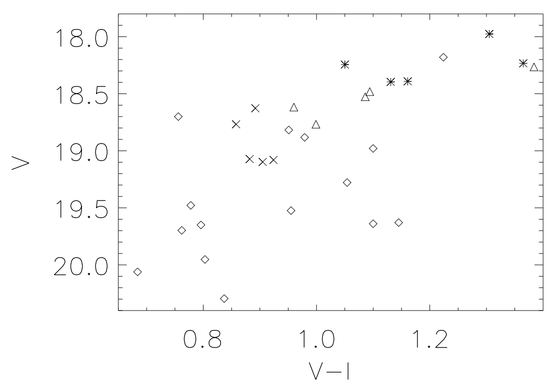

Fig. 6. The V versus V−I colour-magnitude diagram for Cluster 3. Symbols as in Figs. 3 to 5.

$I_0 = I - 1.5\,E(B-V)$, adopting $E(B-V) = 0.05$. The resulting V_0 versus $(V-I)_0$ colour-magnitude diagrams for cluster 1 and cluster 3 are shown in Fig. 5 and in Fig. 6, respectively. As in Fig. 3 and Fig. 4, triangles represent classified carbon stars, star-symbols represent classified M type stars, and crosses indicate stars on the transition between C and M type stars, whereas diamonds mark stars which we have not classified.

The bolometric correction, BC_I, defined as $mbol = BC_I + I_0$, was computed from the relation derived by Bessell & Wood (1984):

$$BC_I = 0.3 + 0.38(V-I)_0 - 0.14(V-I)_0{}^2 \qquad (1)$$

This relation was derived as a fit to observations of M and C stars with V−I between 1 and 6. For $(V-I)_0 \gtrsim 2.5$ the carbon stars may deviate considerably from this relation, but since all our carbon stars have $(V-I)_0 \lesssim 1.5$, no attempt was made to refine the adopted BC_I for the carbon stars beyond what is given by this relation.

The transformation from $(V-I)_0$ to effective temperature was derived from a polynomial fit (Jimenez 1995) to the results of the model atmosphere computations of Busser & Kurucz (1992). The derived transformation equation has the form

$$T_{\rm eff} = 10663 - 12714(V-I)_0 + 11326(V-I)_0{}^2$$

$$-5764(V-I)_0{}^3 + 1230(V-I)_0{}^4 \quad (2)$$

The resulting luminosity versus effective temperature diagrams (Fig. 8 and Fig. 9) – based on the distance modulus from BCFHZ85 – for the two clusters are shown in connection with the discussion below of the morphology of the giant branches.

3. Comparison with V magnitudes from other work

Our photometry in I and in the two narrow-band filters are the first observations published for the Fornax clusters, so we have no other results from the literature to compare with, but one or both of the two clusters have been observed in the V filter by Demers et al. 1979 (DKH79), by Verner et al. 1981 (VDHK81), by Buonanno et al. 1985 (BCFHZ85), and by Demers et al. (1990) (DKG90). The photometry by DKH79 and by VDHK81 is a presentation of photographic material exposed on a 103aD ($\approx$ V) and a 103aO ($\approx$ B) emulsion. The observations were obtained with the 2.5 m du Pont telescope at Las Campanas Observatory, and measured by use of Iris photometry relative to a sequence of photographic standard stars exposed onto the plates. In the work of BCFHZ85 the same photographic plates were measured again, with the main improvement relative to the two previous investigations that the plates were scanned with a microphotometer, such that a point spread function could be fitted to the stellar images. BCFHZ85 found that this technique allowed them to reach stars two magnitudes fainter than what was possible with the Iris technique. Comparison between the three studies of the du Pont photographic plates was given by VDK81 and by BCFHZ85, so we compare here our results for the V magnitudes only with the most recent of the three.

In Fig. 7 we compare our results for the V magnitudes with those of BCFHZ85 and those of DKG90. The V magnitudes given by BCFHZ85 for cluster 3 are averages of the photographic magnitude and magnitudes derived from a 30 minute CCD exposure with the Danish 1.54 m telescope at La Silla. The addition of CCD photometry in this study has increased the internal accuracy, but the external accuracy is, however, still dependent on the photographic standard sequence on the glass plates, according to the description of the reduction procedure given by BCFHZ85. The BCFHZ85 photometry of cluster 1, which we also compare with in Fig. 7, is from the photographic material only.

Demers et al. (1990) presented independent V (and B) CCD photometry of cluster 1, carefully reduced relative to standard stars observed with the CCD. This technique would generally give more accurate results than photographic material. Surprisingly good agreement between the photographic magnitudes of BCFHZ85 and the CCD magnitudes of DKG90 were found. When excluding what DKG90 regard as obvious variable stars, they estimated $V_{DKG90}-V_{BCFHZ85} = -0.03\pm0.09$ and $(B-V)_{DKG90}-(B-V)_{BCFHZ85} = +0.06\pm0.14$ (for 20 stars in common). In Fig. 7 we compare our V magnitudes with the results of BCFHZ85 and with the results of DKG90 for cluster 1 and with the result of BCFHZ85 for cluster 3. For cluster 1 we find slightly better agreement with the CCD photometry of DKG90 than with the photographic photometry of BCFHZ85, as should be expected. For cluster 3, which was only observed by BCFHZ85, we also find very good agreement.

In the panels of Fig. 7 we show V versus V, for the various combinations of the three investigations plotted against one another, the 1:1 line is shown. In the panels where ΔV versus V is shown, the regression lines are drawn. For cluster 1, two stars stand out as falling very far from the regression line compared to the rest of the stars. These are number 8 and number 67 in our list (numbers 210 and 154 in the list of DKG90, and numbers 4 and 16 in the list of BCFHZ85). We remark that our magnitudes compare very well with those of BCFHZ85 for both stars, and that the stars are not in a region of the HR diagram which should make them particularly likely variable star candidates. The same is true for the two stars with somewhat higher magnitude difference than the average in the plot of our results for cluster 3 versus the results of BCFHZ85. When excluding star 8 and star 67 from the comparison with DKG90, we find the correlation between our V magnitudes, V_{JJ}, and those of BCFHZ85 and those of DKG90, respectively, to be $V_{DKG9O}-V_{BCFHZ85} = 0.00 + 0.03 \times V_{DKG90}$, $\sigma = 0.1$ mag for cluster 1 and $V_{JJ}-V_{DKG90} = 0.00 - 0.03 \times V_{DKG90}$, $\sigma = 0.05$ mag for cluster 1, and $V_{JJ}-V_{BCFHZ85} = 0.02 + 0.01 \times V_{JJ}$, $\sigma = 0.06$ mag for cluster 3.

Westerlund et al. (1987; WEL87) measured V and B for 231 red (i.e., $(B-V) \gtrsim 1.0$) stars in the field of Fornax by use of 5 photographic plates (obtained by Westerlund at the prime focus of the 3.6 m ESO telescope) and an Iris-diaphragm photometer. The measurements included identification of 47 C stars, 30 M stars, and 1 S star. The plates were calibrated by use of the red stars in common with DKH79 and Demers & Kunkel (1979), and were therefore based on the same standard sequence on the photographic du Pont plates as the one used by DKH79, VDHK81, and by BCFHZ85. It was therefore somewhat surprising when WEL87 obtained a systematic difference between their results and those of BCFHZ85 (for 8 stars in common), $V_{WEL87}-V_{BCFHZ85} = +0.32$ mag, $\sigma = \pm0.16$, but only $V_{WEL87}-V_{DK79} = +0.01$ mag, $\sigma = \pm0.32$ for 81 stars in common with DKH79. Our results agree on the zero point with those of BCFHZ85, for the 37 stars in common, but unfortunately none of our stars are in common with the stars in the fields observed by WEL87.

We will comment further on the systematic magnitude differences in connection with the discussion below of the distance modulus, but here we conclude our discussion of the comparison, with previous results from the literature, by stating that the general agreement on the V magnitudes is better than about ±0.05 mag between independent measurements, when a few stars (some of which might be variables, miss-identifications, or due to errors in some of the observational material) are excluded.

4. Discussion

Various approximate methods have been applied in the literature to derive the age, metallicity, and stellar content of stellar systems without having access to detailed high-resolution spectra

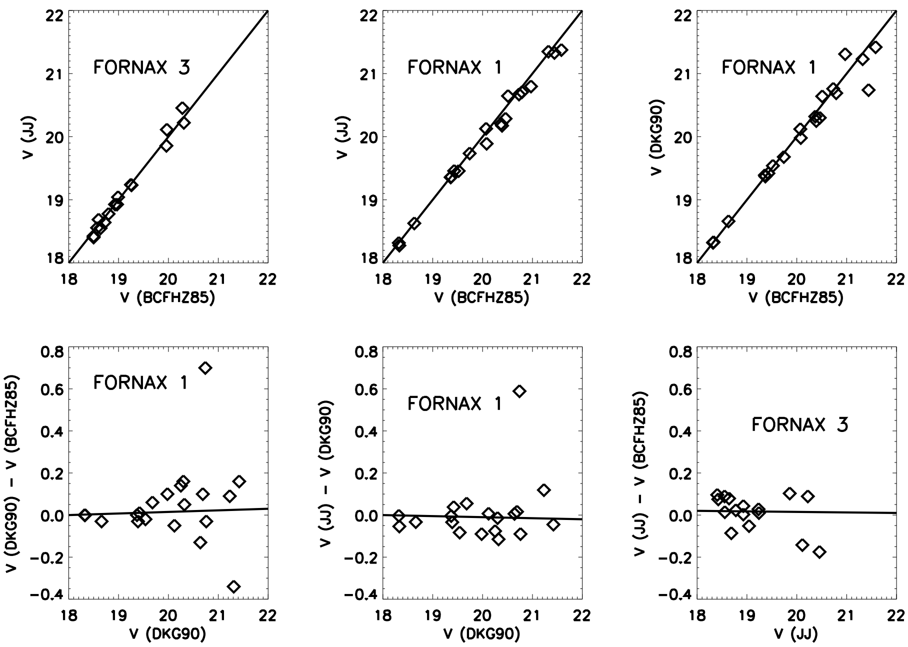

Fig. 7. The figure shows the result of a comparison with previous studies.

of individual stars. For globular clusters, such methods include models for the integrated spectra of the whole cluster, integrated spectra of selected strong spectral features, the slope of the red giant branch, and the colour of the red giant branch at a given luminosity.

One of the main problems in quantitative modelling of the morphology of the red giant branch is the strong dependence of its intrinsic colour (at a given luminosity) on the choice of the mixing length parameter. Previous morphological studies of the giant branches in the Fornax clusters have used either the slope or the intrinsic colour of the giant branch, but in fact these two properties are strongly related to one another, and it is an advantage in the interpretation of the data to include information from both simultaneously. With full computations of a sufficiently dense grid of evolutionary tracks, one can of course vary any basic parameter independently, and compare the results with the observations. We use such a grid for our analysis, but first approximate it by analytical formulas, which are improved further by taking advantage of the best observational results from Galactic globular clusters. These formulas are then used for high speed, high accuracy production of all the necessary evolutionary tracks.

Our computational method, hence, combines the speed and flexibility of numerical solution of simple analytical formulas, with the accuracy of fits to observational data of a sample of globular clusters. In short, the relation between intrinsic colour and the mixing-length parameter is fixed by fits to observed globular clusters with known metallicities, whereas the intrinsic RGB slope is related to the metallicity and the mass loss scenario, which in turn can be related to the horizontal branch morphology. In a series of papers we have successfully applied the method to study the solar future evolution (Jørgensen 1991), to the first and second parameter problems and ages of Galactic globular clusters (Jørgensen & Thejll 1993a, Jimenez

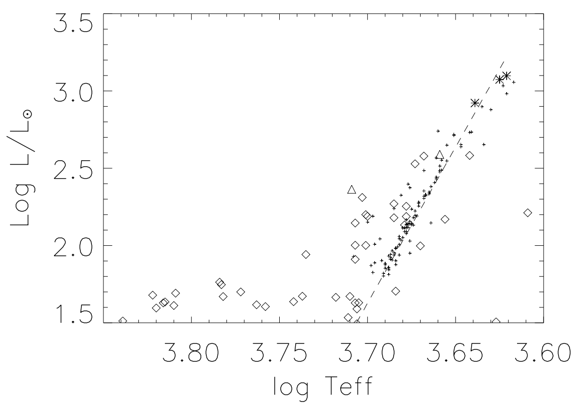

Fig. 8. The $\log(L/L_{\odot})$ versus effective temperature diagram for Cluster 1. Symbols as in Figs. 3–6. The small crosses represent observations of the RGB and AGB stars in the Galactic globular cluster M68, and the dashed line is our model for the RGB of a cluster with [Fe/H]= -2.0 and M= 0.8 $M_{\odot}$.

et al. 1996), and to the UV excess in metal-rich elliptical galaxies (Jørgensen & Thejll 1993b). A detailed description of the method can be found in these papers. Somewhat similar methods have been applied successfully to other problems by other groups (e.g., Eggelton, Fitchett & Tout 1989).

We have transformed our observed V and I broad-band photometry to luminosity and effective temperature as described in Sect. 2, and in Figs. 8 − 11 we compare our observed giant branches of cluster 1 and cluster 3 with the results of our computed tracks for clusters of various basic parameters. We impose, for comparison, also our recent observational results for the Galactic globular cluster M 68 (Jimenez et al. 1996).

When comparing our photometry of the Fornax clusters with our theoretical stellar evolution models and with our photometry of M 68, in Fig. 8 and Fig. 9, we immediately notice that it is much harder to fit the data of the Fornax clusters with model tracks, than it is to fit M 68. We interpret this as being primarily due to a more complex star formation history in the Fornax clusters than in the Galactic globular clusters. The RGB and the AGB stars in M 68 fall along two well separated narrow bands in the diagram, which can be well fitted by an evolutionary track of one metallicity ([Fe/H]=−2.0) and one mass (M_{RGB} = 0.8$M_\odot$), as demonstrated by the dashed line in Fig. 8 and Fig. 9, determined by the semi-analytical method described above.

We have chosen to compare our results with the results from M 68 because M 68 deviates exceptionally from the theoretical track near the RGT; a morphology which it has in common with the Fornax clusters, in particular with cluster 3, as will be discussed below. Most other Galactic globular clusters look much more like the theoretical tracks also in the part close to the RGT (Jørgensen & Thejll 1993a, Jimenez et al. 1996). For the highest luminosities, the sequence defined by the observations of the RGB stars in M 68 bends considerably more toward lower temperatures than do our best fit track. We interpret this as due to a combination of a too simplified treatment of the atmospheric boundary condition (gray atmospheres) and a lack of mass loss in the present fit (i.e., two common problems in all computed evolutionary tracks). For M 68 mass loss alone cannot account for the bending, since numerical experiments show that mass loss corresponding to η = 2 (in Reimers' mass loss law) would be required, and the reality is even more complicated than this, because several, otherwise similar globular clusters bend much less than M 68 compared to the model tracks. A detailed description of the Galactic globular cluster observations is given elsewhere (Jimenez et al. 1996). The main point here is to demonstrate the accuracy of the fit to observations (except for the highest luminosities) and the narrowness in the distribution of the Galactic cluster stars.

It should finally be mentioned that the position of the theoretical red giant tip (the helium core flash; RGT) in the diagram defines the real RGT with very high accuracy (probably within 0.01 dex). Any stars found above the predicted RGT is therefore an indication that, 1) they are non-members, 2) they are AGB stars, 3) they are high-amplitude variables accidentally in the vicinity of their maximum, 4) there is an error in the photometry or 5) the distance modulus has been badly determined. The uncertainty in the photometry of the Fornax clusters, determined as the scatter between our V magnitudes and those independently obtained by BCFHZ85 and by DKG90 (and assuming the same scatter in our I photometry), gives rise to an uncertainty in log(Teff) of less than 0.01 dex, and an uncertainty in the relative absolute luminosity, Δ log(L/$L_\odot$), of less than 0.05 dex. Additional uncertainty of systematic character will arise due to an uncertainty in the bolometric correction, in the model atmosphere colour-effective-temperature transformation (the uncertainty in the fit itself, as expressed in Eq. 2, is however negligible), and in the distance modulus. Since we have used identical methods for our analysis of Galactic GCs and our present analysis of the Fornax clusters, comparison with the Galactic GCs is considerably less affected by possible systematic effects than is an absolute analysis.

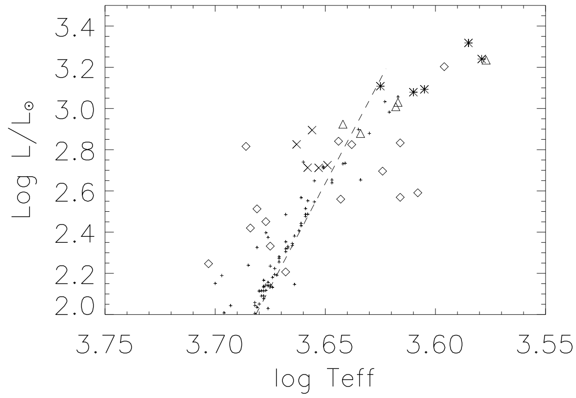

Fig. 9. The log(L/$L_\odot$) versus effective temperature diagram for Cluster 3. Symbols as in Fig. 8.

Seen on this basis, the photometry comprises several interesting differences between the Fornax globular clusters and the Galactic globular clusters, some of which have been touched upon by others before us, and some of which have only been made possible to discuss by use of the present observations. We will discuss separately the metallicity, the age, the content of carbon stars, and the distance modulus.

4.1. The metallicity

Once the mixing-length parameter is fixed (from fit to Galactic globular clusters with known metallicity and approximately known mass of the RGB stars), the metallicity can be determined quite accurately for the Fornax clusters by fitting evolutionary RGB tracks to the photometry. However, a glance at Fig. 8 and Fig. 9 immediately reveals the problem that the photometry cannot be fitted with one specific metallicity, as can the photometry of Galactic globular clusters. An additional, but minor, problem is that the RGB mass of the Fornax clusters is not a priori as narrowly restricted as is the Galactic globular cluster RGB stellar mass. This second problem could be eliminated by refined observations of the full horizontal branch and below it.

Both cluster 1 and cluster 3 have a well developed AGB which at the luminosity level of the horizontal branch is approximately 0.4 dex warmer than the RGB at the same luminosity and approaches the RGB temperature asymptotically at higher luminosities. At the luminosity level of the horizontal branch, the colour of the RGB is not very sensitive to metallicity, and if we interpret the 5 stars in cluster 1 at log($T_{\rm eff}$) ≈ 3.7, with luminosities below the HB luminosity, as defining the tip of the part of the RGB less luminous than the HB, then stars with (M≈0.8$M_\odot$and) any metallicity between [Fe/H] = −1.6 and −2.4 fits this part of the RGB well, whereas the track for [Fe/H] = −1.1 (and M=0.8$M_\odot$) is seen (from Fig. 10) to give too cool models compared to the observations (for M=1.3$M_\odot$ even this high metallicity track pass through the position of the 5 stars). For the upper part of the giant branches, the fit is more ambiguous because of mixing with AGB stars, but all metallicities between −1.6 and −2.4 are consistent with the data, the lower

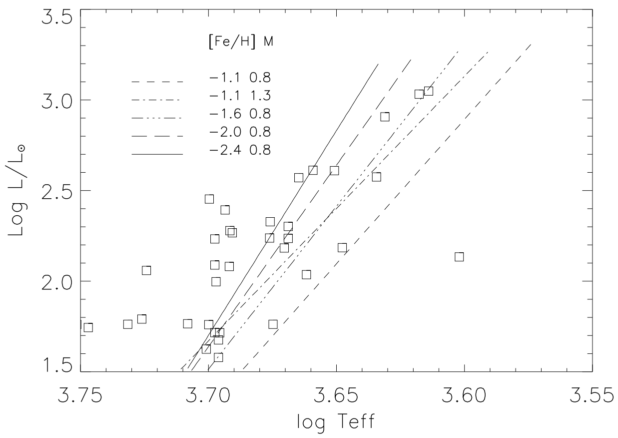

Fig. 10. The log(L/L$_\odot$) versus effective temperature diagram for Cluster 1, superimposed with evolutionary tracks corresponding to various choices of metallicity and mass.

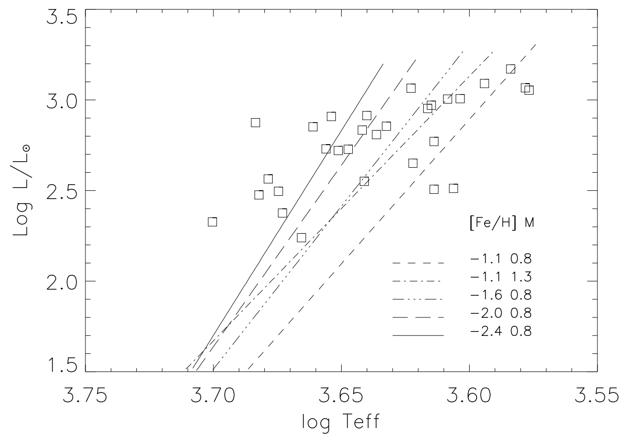

Fig. 11. The log(L/L$_\odot$) versus effective temperature diagram for Cluster 3, superimposed with evolutionary tracks corresponding to various choices of metallicity and mass.

values are, however, only consistent with the observations provided the giant branches of the Fornax clusters bend (compared to the theoretical tracks) as much toward lower temperatures as do M 68, which is not the most common scenario among the Galactic globulars.

As described in Chapter 2, the data reduction is done assuming E(B−V) = 0.05. Adopting instead E(B−V) = 0.03, as in BCFHZ85, would lead to a change of −82 K for the derived effective temperature of the lower part of the RGB and a change of −35 K for the upper part of the presented RGB (of Cluster 1), as can be estimated from Eq. 2 and other numbers given in Chapter 2 above. This would lead to an almost unchanged conclusion about the metallicity. The corresponding numbers if E(B−V) = 0.0 would be −207 K and −85 K, respectively, which would lead to a slightly steeper observed (transformed) RGB (in slightly better agreement with our theoretical tracks) and to an [Fe/H] estimate nearly 0.5 dex larger than the one based on E(B−V) = 0.05.

None of the choices of evolutionary tracks can, however, explain the colour of all the observed bright stars in the field of the clusters. It is seen (from Fig. 10) that in cluster 1 at least three stars (excluding the object at log $T_{\rm eff}$ = 3.6 which is most likely a faint galaxy or a foreground M type dwarf) can only be fitted with the assumption of a metallicity as high as [Fe/H] ≈ -1.1, and in cluster 3 at least 4 stars are inconsistent with metallicities much lower than this value too (assuming that they are members of the cluster, assuming the adopted distance modulus of m-M = 20.6 is valid, and assuming that the reddening is the same toward all the stars). Comparison with the density of stars outside the region of the cluster, and brighter than the HB, indicates that we should expect about 5 non-member stars, out of which about 1 to 2 should be expected to be foreground stars (according to the model by Bachall & Soneira 1981) or faint galaxies (based on counts by Tyson & Jarvis 1979). It is seen, from Figs. 1 and 2, that stars redder than the [Fe/H] = −1.6 track neither are particularly far from nor close to the cluster centers, but if they are non-member field stars from the Fornax dSph itself, then it of course implies the existence of such high metallicities in the field of Fornax instead.

Zinn & West (1984) collected the metallicity estimates from a number of authors (who used many different methods) for 121 Galactic globular clusters, and derived relations between the estimated average [Fe/H] values and various metallicity indexes. One of the indexes studied is the colour $(B-V)_{0,g}$ of the red giant branch at the luminosity where it meets the horizontal branch, fitted by Zinn & West (1984) to relate to the metallicity as [Fe/H] = −5.00 + 4.30$(B-V)_{0,g}$. This relation was used by BCFHZ85 to derive [Fe/H] = -1.99 ± 0.17 and [Fe/H] = -2.12 ± 0.17 for cluster 1 and 3, respectively. As mentioned above, and as seen from our evolutionary tracks in Fig. 10, one problem with this index is that the isochrones are relatively insensitive to metallicity, exactly at the luminosity of the HB. Our estimate of [Fe/H] = -2.0 ± 0.4 would on the scale of Zinn & West (1984) correspond to $(B-V)_{0,g} = 0.7 \pm 0.1$, which we find consistent with the data presented by BCFHZ85, although it is a considerably larger spread in the metallicity than estimated by BCFHZ85 ($\Delta(B-V)_{0,g} = \pm 0.04$). The main difference between the numbers given by BCFHZ85 (and other analysis based on fits to a single index) and the numbers given by us here, is that our estimated value is a measure of the spread in metallicity necessary to explain all the RGB stars (i.e., not a measure of the uncertainty in a single best fit), whereas fits to single indexes represent best fit regressions. We believe that our detailed comparison with evolutionary tracks shows that for the Fornax clusters it is (in contrast to the situation for almost all the Galactic globular clusters) *not* possible to fit the RGB with a single value of the metallicity.

Demers et al. (1990) applied two different relations between $B-V$ and metallicity (both from Zinn & West 1984) on the data for cluster 1, and found [Fe/H] = -2.3 ± 0.3 and [Fe/H] = -2.0 ± 0.2 from the two methods, respectively. Dubath et al. (1992) obtained integrated spectra of the three brightest Fornax clusters. By use of a cross-correlation technique for the 4380−5880Å spectral interval, they obtain [Fe/H]

= -1.93 ± 0.15 for cluster 3. Rydt et al. (1991) determined, based on Washington photometry, [Fe/H] = -1.5 ± 0.3 for the field population and [Fe/H] ≈ -2.3 for cluster 3 (with a more narrow distribution for cluster 3 than for the field).

DKH79 derived a relation between [Fe/H] and the slope of the giant branch, and estimated [Fe/H] ≈ -0.5 for a field far from the center of the Fornax galaxy. Westerlund et al. (1987; hereafter WEL87) used the same criteria to estimate the metallicity in a region very close to the center of the galaxy, and found [Fe/H] $\approx -2.2 \pm 0.5$, comparable to the most metal-poor globulars in Fornax. They therefore concluded that the Fornax dSph is metal-poor in its central regions and more metal-rich toward the edges. BCFHZ85 studied a field close to the center and one close to the galactic edge, too, and found $-2.2 \lesssim$ [Fe/H] $\lesssim -0.7$, with mean ≈ -1.4 for both fields. The different conclusion regarding the field stars is, however, most likely due to the small number of stars studied in the BCFHZ85 fields (Fusi Pecci 1987). WEL87 found that the data in the BCFHZ85 fields are in agreement with their result of a large metallicity difference between the central and the outer regions.

Sagar et al. (1990) also used a relation between $(B-V)_{0,g}$ and [Fe/H] in their study of the giant branch in a field $18'$ southwest of the center of the galaxy by use of the McMullan electronographic camera at the Danish 1.54m telescope. They obtained B and V magnitudes for 1300 stars down to V=21 mag, and concluded that $\delta(B-V) \approx 0.14$ mag for the giant branch field stars. They suggested several interpretations, including a metallicity spread of $\Delta[Fe/H] \approx$0.3, a slightly smaller spread in metallicity plus a variation in age of 3 to 17 billion years, and an age of ≈ 5 Gyr and metallicity between [Fe/H] = -0.7 and [Fe/H] = -1.7. We conclude in the next section that while the photometry can be well described by a multi-metallicity distribution, nothing can in reality be said about the age.

4.2. The age of the clusters

In our method of fitting evolutionary tracks to observed data, the various relevant relations are first fitted to the numerical model tracks by polynomials, as described above. This in turn also allows us to analyse, in a very illustrative way, the effect of varying various parameters differentially. By setting log(L/L$_\odot$)=3.0, Y=0.24, and α=1.4 in Eq. 1 of Jørgensen & Thejll (1993a) one gets

$$log(T_{\rm eff}) = 3.321 + 0.031\,M - 0.127\,log(Z) - 0.0130\,(log(Z))^2 \quad (3)$$

If one, as a first guess, was assuming that the mass of evolved stars in the Fornax clusters is 0.8M$_\odot$ (as in the old Galactic globular clusters), then one could test, by use of Eq. 3, the broadness it would impose on the giant branch if the cluster in addition contained stars with masses up to 1.3M$_\odot$ (see below). The age of AGB stars with initial masses of 1.3M$_\odot$ and 0.8M$_\odot$ will, according to Eq. 1 in the work of Jørgensen & Thejll (1993b), be 2.3 Gyr and 14.1 Gyr, respectively. Such an age spread among the Fornax stars would therefore imply a continuous star formation (or at least more than one star formation epoch) over a very extensive period of time compared to the star formation period in the Galactic globular clusters. With the metallicity adopted to be [Fe/H]=-2.0, a variation in RGB mass between 0.8M$_\odot$ to 1.3M$_\odot$ would, nevertheless, give rise to a variation in log($T_{\rm eff}$) between 3.55 and 3.56 only (according to Eq. 3 and for log(L/L$_\odot$)=3.0). A variation of [Fe/H] between -1.6 and -2.4, on the other hand, would give rise to a variation of log($T_{\rm eff}$) between 3.54 and 3.58 (assuming the mass constant at M=0.8M$_\odot$), consistent with the observations.

We are therefore able to explain the spread in the obtained photometry by an assumption of a spread in [Fe/H] between -1.6 and -2.4 alone, but not as a spread in mass (age) alone. We therefore conclude that nothing can be said about the possible age spread of the stars in the clusters (anything from zero to the age of the universe will be in agreement with observations, if the assumed spread in the corresponding metallicity is adjusted accordingly), whereas a spread in metallicity in all instances is necessary in order to fit the photometry.

Gratton et al. (1986) analysed several regions in the field of the Fornax (and the Phoenix) dSph galaxies. They interpreted the existence of faint blue stars as a young population with $M \approx 1.3$M$_\odot$, and speculated that this population represent the progenitors of the carbon star population.

Demers et al. (1990) mention that the red morphology of the cluster 1 HB is consistent with a younger population than the Galactic globular clusters. Rydt et al. (1991) used Washington photometry in an attempt to determine age, and age spread in cluster 3, and estimated an age of 10$\pm$2 Gyr for both the field population and the cluster. Sagar et al. (1990) found, in agreement with our conclusions, that a variation in age cannot alone explain the giant branch $(B-V)$ spread. They estimated that an age of 5 Gyr and a $(B-V)$ somewhere between the Yale isochrones corresponding to [Fe/H] = -1.7 and [Fe/H] = -0.7 "perhaps" gives the best fit to the giant branch observations.

4.3. The carbon star population in the clusters

Carbon stars in the field of the Fornax dSph galaxy were first identified by Westerlund (1979), and spectroscopy has further been obtained by Demers & Kunkel (1979), Aaronson & Mould (1980), Frogel et al. (1982), Richer & Westerlund (1983) and WEL87. The M-type stars and C-type stars in the field were found to span the same magnitude interval (17.5 $\lesssim$ V $\lesssim$ 20.0), and B$-$V up to 3.7 were observed (6 M stars were found by WEL87 to be brighter than the brightest carbon stars, but they may be foreground M type dwarfs). The number ratio, N_C/N_M, of carbon to M type giants is ≈ 25. The variable stars are semi-regular (i.e., $\Delta M_{\rm v} \approx 1^{\rm mag}$ LPVs; no genuine Miras), and they span the same V, B$-$V region as the carbon stars. They were described in detail by Demers & Irwin (1987). We presented in Figs. 3 and 4 the first identifications of carbon stars in the Fornax clusters; in fact the first classification of the giant branch stars in the clusters at all.

WEL87 summarized the B, V photometry of red stars in the field of Fornax, and concluded that the carbon stars populate the magnitude interval 15.2$\leq$m$_{\rm bol}\leq$18.3 (17.5$\leq$V$\leq$20.0)

Table 3. Summary of the estimated metallicities ([Fe/H]) mentioned in the text.

	JJ95	DKG90	DKG90	DMM92	BCFHZ85	Rydt et al.
cluster 1:	−2.0±0.4	−2.3±0.3	−2.0±0.2		−1.99±0.17	
cluster 3:	−2.0±0.4			−1.93±0.15	−2.12±0.17	−2.3
	BCFHZ85	WEL87	DKH79	Rydt et al.		
central field	−1.4±0.7	−2.2±0.5		−1.5±0.3		
outskirts field	−1.4±0.7		−0.5	−1.5±0.3		

corresponding to $2.8 \leq \log(L/L_\odot) \leq 4.0$ with a distance modulus of 20.6 (BCFHZ85) and corresponding to $3.0 \leq \log(L/L_\odot) \leq 4.3$ with a distance modulus of 21.2 (WEL87). The carbon stars in cluster 1 and cluster 3 populate only the lower 30% of this luminosity interval as is seen from Figs. 8 and 9. If field stars of $\approx 1.3\,M_\odot$ are the progenitors of the bright carbon stars in the field (as suggested by Gratton et al. 1986), then the carbon star population in the clusters indicate the lack of a similar young population in the clusters.

Lattanzio (1986) found that the core mass at the first helium shell flash, and the core mass luminosity relation, (setting Y = 0.24 and [Fe/H]=−2.0) can be expressed as

$$M_c \approx 0.53 - (1.3 + log(Z))(Y - 0.20) = 0.61 \quad (4)$$

$$log(L/L_\odot) = 4.78 + log(M_c - 0.512) = 3.8 \quad (5)$$

Similar results were obtained by Boothroyd & Sackmann (1988) (M_c=0.55+0.02 $M/M_\odot$, leading also to $\log(L/L_\odot)$ = 3.8 for M=0.8$M_\odot$). With a distance modulus of 20.6 our carbon stars fall in the luminosity interval $2.9 \leq \log(L/L_\odot) \leq 3.2$ and with m−M = 21.2 in the interval $3.1 \leq \log(L/L_\odot) \leq 3.4$. In both cases we draw the conclusion that all of the cluster carbon stars fall considerably below the minimum of the theoretical carbon star luminosity function, and most of the field carbon stars fall somewhat below the theoretical carbon star luminosity, too.

The existence of carbon stars in the Fornax globular clusters therefore imposes at least two interesting theoretical challenges. One is that the observed (cluster) carbon stars are considerably less luminous than predicted by theory. The other challenge is that if the Fornax globular clusters have the same metallicity as the Galactic globular clusters, then why do the Fornax globulars show a relatively large number of carbon stars when the Galactic clusters presumably show none?

In connection with this it is worth mentioning that the Galactic halo seemingly shows a number of carbon stars (per M type giant or per mass unit, Kipper et al. 1996) in between that of the Globular clusters and that of the Fornax clusters. We speculate that this might be an indication that the Galactic globular clusters were formed before the halo, and the halo before the dwarf galaxies. An age difference of at least 3 billion years between the formation of the Galactic globular clusters and the halo would be necessary in order to explain the difference in carbon star population (Kipper & Jørgensen 1994, Kipper et al. 1996), and it is likely that a similar age difference between the formation of the halo and the dwarf galaxies is necessary in order to explain the difference in the carbon star population of these two systems. An age difference of $6\,10^9$ years between the Fornax clusters and the oldest Galactic globular clusters, would imply that the mass of the stars at the RGB in the Fornax clusters should be around M = 0.93$M_\odot$ (following the formulas in Jørgensen & Thejll 1993b and adopting the RGB mass of the oldest Galactic globular clusters to be M≈ 0.8 $M_\odot$ as in the work by Jimenez et al. 1996). Such stars (with [Fe/H]≈ −2.0) would develop into the carbon star phase according to our algorithms for stellar evolution, but at considerably higher luminosities ($\log(L/L_\odot) \approx 3.9$) than observed. An accurate quantification of the age based on the method of counting the number ratio of carbon to M-type stars is obviously impossible as long as the problem that no carbon star models for any choice of mass, age, or metallicity predict carbon stars of the observed luminosities.

Westerlund (1979) pointed at a large variation in the carbon star content over the field of the Fornax galaxy, and WEL87 pointed out that their region C close to the center is the region of the Fornax galaxy with most carbon stars. Here [Fe/H] ≈ −2.2±0.5 (WEL87), which is comparable to our metallicity estimates for the clusters. The giant branch in region C is populated with many more extreme red stars (1.9 ≤ B−V ≤ 3) than field B ([Fe/H]≈−0.5, DKH79) further out in the galaxy (29 very red stars in field C compared to 2 in field B when the two fields are scaled to the same size). The number of giant stars in the range 1.0 ≤ B−V ≤ 1.9 is almost identical in the B and C fields.

If the metallicity estimates of the two field regions are correct, then it is of course tempting to postulate that the larger carbon star content in field C is a consequence of its low metallicity, but still this does not solve the fact that Galactic globular clusters of the same low metallicity do not contain intrinsic carbon stars (a very small number of CH stars are believed to be due to mass transfer in close binaries), that Fornax clusters of the same metallicity contain carbon stars of lower luminosities only, and that the existence of carbon stars in both the field and the clusters is in disagreement with the existing theoretical results.

4.4. The distance to the Fornax dSph

BCFHZ85 notice that $< V_{\rm HB} >$ of all the clusters 1, 2, 3, 5 is 21.60±0.04. By adopting M_v(HB) = +0.6±0.2 (≈ the mean value for Galactic metal-poor globular clusters) and $A_V = 3.2\,E(B-V)$, and E(B−V) = 0.03±0.03, BCFHZ85 find $m_v - M_V$ = 20.59±0.22 corresponding to 131±13 kpc, which is no-

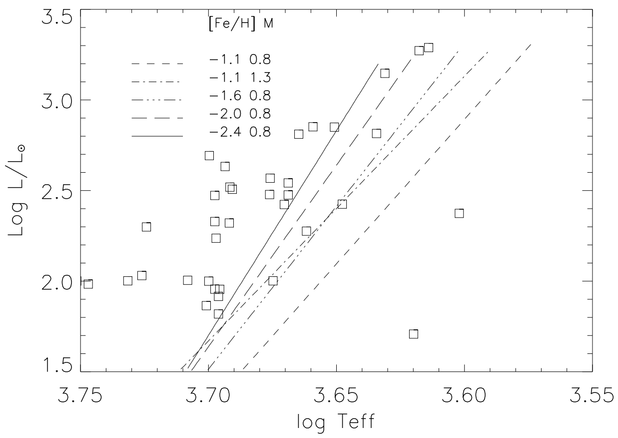

Fig. 12. The log(L/L$_\odot$) versus effective temperature diagram for Cluster 1, superimposed on evolutionary tracks corresponding to various choices of metallicity and mass. A distance modulus of m−M=21.2 (i.e., 0.6 magnitude larger than in Fig. 10) was adopted in the calculation of log(L/L$_\odot$) for this figure. Otherwise the figure is identical to Fig. 10.

ticed by BCFHZ85 to be considerably lower than often quoted older values.

Rodgers & Harding (1989) find a distance of 123 kpc, and DKG90 determined $< V_{HB} >$ = 21.36±0.14, which with the assumption of M_v(HB) = 0.6 and E(B-V) = 0.0 gives m-M = 20.76, whereas their fit of the Fornax HR-diagram to that of M15 gives m-M = 20.85.

WEL87 noticed that the luminosity distribution function of the Fornax field carbon stars has the same form as the distribution function for the SMC carbon stars, and that the two distributions fall on top of one another if a distance modulus of 21.2 is adopted. In Fig. 12 we plot our HR diagram of cluster 1 together with the same tracks as in Fig. 10, but now under the assumption of a distance modulus of 21.2. It is seen that the required metallicity, in order to fit the upper part of the giant branch, is considerably lower than if a distance modulus of 20.6 is assumed (as in Fig. 10), and that the 5 stars at $T_{\rm eff}\approx$3.7 and log(L/L$_\odot$)≈1.8−2.0 (≈ 1.5−1.7 in Fig. 10) are very difficult to fit (if interpreted as part of the RGB) with the large distance modulus. Our observations therefore favour a distance modulus close the the value 20.6 suggested by BCFHZ85.

5. Conclusions

We have observed the giant branch of globular cluster 3, and the giant and horizontal branches of cluster 1, in the Fornax dSph galaxy, and have classified the giant branch stars into carbon stars, M type stars, and stars on the transition. We conclude the following:

- Our obtained V-photometry is in good agreement with previous results where overlap exists.
- The Δm_{81-78} versus V−I diagram clearly shows the existence of at least 7 carbon stars in the two clusters, in strong contrast to the almost complete lack of carbon stars in the Galactic globular clusters.
- The luminosities of the carbon stars are considerably below the theoretical lower limit of the luminosity function for metal-poor carbon stars.
- The RGBs are considerably broader than the corresponding RGBs of Galactic globular clusters. This colour-spread can be modelled as a star-to-star variation in metallicity, with RGB stars spanning the full interval from −2.4 to −1.6 in [Fe/H]. The broadness can not be explained by a spread in mass/age alone (i.e., a continuing star formation in the clusters over an extended period of time) as has been suggested in the literature.
- The sequence of an increasing ratio of the number of carbon stars to M-type stars, N_C/N_M, from the Galactic globular clusters, over the Galactic halo, to the Fornax clusters, may indicate an age difference, with Fornax being $\approx 3\,10^9$ years younger than the halo, which in turn seems to be $\approx 3\,10^9$ years younger than the Galactic globular clusters. Since this estimate, however, is based on the difference in formation of carbon stars at various stellar masses and metallicities, it is hampered by the fact that the luminosity of the carbon stars does not fit the theoretical predictions.

The definite existence of carbon stars on the AGB in both of the observed Fornax clusters is a challenge to the theoretical models of the third dredge up episode and to galactic chemical evolution models. It raises the central question of why the carbon stars in Fornax form already well below the theoretical carbon star luminosity limit, and also why they are present in relatively large numbers in the Fornax clusters and not at all in the Galactic globular clusters of the same metallicities.

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