Spectroscopy of Dwarf Elliptical Galaxies in the Fornax Cluster

Enrico V. Held
Osservatorio Astronomico di Bologna – via Zamboni 33, Bologna 40126, Italy
and
Jeremy R. Mould
Palomar Observatory, California Institute of Technology – Pasadena, California 91125, U.S.A.
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ABSTRACT

We present the results of spectroscopic observations of 10 nucleated dwarf elliptical galaxies (dE’s) in the Fornax cluster. The blue spectra of Fornax dE galaxies indicate a wide range of metallicities at a given luminosity, similar to those of intermediate to metal-rich globular clusters. Metal abundances derived in this paper are well correlated with optical colors and agree with previous spectroscopic results. A discrepancy with metallicities inferred from infrared colors is evident; possible causes include an intermediate age population and dilution of spectral features by a blue light excess. Dwarf ellipticals exhibit a wide variation of hydrogen line strength which points to a complex star formation history. Prominent Balmer absorption lines are the signature of a young stellar population in the nuclei of some (but not all) dE’s, while moderately strong Balmer lines in relatively

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1 Based on data obtained at the European Southern Observatory, La Silla, Chile
metal-rich dE’s are more consistent with an extended main sequence. In a few metal-
poor dE galaxies, the hydrogen lines are consistent with or perhaps weaker than those
found in Galactic globulars of similar metallicity. In the limited magnitude range of this
sample, there is no apparent correlation of metallicity either with effective and central
surface brightness, or with total and nuclear magnitudes. The velocity distribution of the
Fornax dwarfs is flatter than that of brighter galaxies at the 75% confidence level, possibly
indicating a difference in the kinematics of the two samples.

*Subject headings:* clusters: galaxies – galaxies: kinematics – galaxies: stellar content
1. INTRODUCTION

Noting that the star formation histories of dwarf spheroidal galaxies are clearly complex and varied, Da Costa (1988) remarks in his review that the histories of more luminous dwarf ellipticals (dE's) are also likely to be complex and varied. Indeed, broad band photometry has provided hints of complex star formation histories in dwarf ellipticals (Caldwell 1983, Caldwell & Bothun 1987, hereafter CB87). These authors showed that dwarf ellipticals have bluer $U - B$ colors than globular clusters with similar $B - V$, which may indicate an additional contribution to the B light. They also argued that the dispersion in $U - V$ colors is too large to be explained by a pure metallicity variation. In a few cases, dwarf ellipticals are bluer in the $B - H$ optical-infrared colors than globular clusters of similar $J - K$ color (Bothun & Caldwell 1984, Zinnecker et al. 1985), a result which may indicate the presence of a warmer stellar component, possibly a younger main-sequence turn-off. In general, $B - H$ colors of dE's, which measure the relative importance of giant and main-sequence populations, are typical of metal-rich globular clusters (Bothun & Caldwell 1984) – the exact range is made, however, somewhat uncertain by the use of photographic blue magnitudes.

Additional evidence for an intermediate age population came from spectroscopy (Bothun et al. 1985, Bothun & Mould 1988). In a study of 12 Virgo dE’s, Bothun & Mould (1988) found that dE spectra resemble those of metal-rich globular clusters (GC’s), but with Balmer lines most likely due to an extended (F-type) main sequence. Also, in a recent brief paper, Gregg’s (1992) argues that nucleated dwarfs have too small a 4000 Å break for their Mg strength, possibly due to an intermediate age population.

Since in evolved populations, the UV-blue spectral region is dominated by light from the main-sequence turn-off, blue spectroscopy allows one to study directly the young and the metal-poor population, while infrared photometry samples the red giants. In this paper we have obtained spectroscopy of a sample of 10 dwarf ellipticals in the Fornax cluster. New
measurements of metal and hydrogen lines have been combined with available photometric data to discuss the implications for the stellar content of dE’s. Although our conclusions will strictly apply to nuclei, CCD photometry indicates no difference in color between the nuclei and the body of the galaxies (CB87).

Another aim of this paper is to use our measurements of radial velocity to investigate the velocity distribution of dwarf ellipticals in the Fornax cluster together with that of brighter cluster members. In the Nearby Galaxy Catalog (Tully 1988) the Fornax and Virgo clusters and the IC 342 group have the highest galaxy volume density in the Local Supercluster. The IC 342 group is a local group of modest total luminosity, but Fornax has more than twice the central surface density of the Virgo cluster (Ferguson & Sandage 1988). It represents a unique environment for understanding the formation and dynamics of clusters of galaxies.

Recent important contributions to the study of the cluster include an optical study by Jones & Jones (1980), detection of the X-ray gas in the cluster (Killeen & Bicknell 1988), a catalog of dwarf galaxies (Ferguson 1989, hereinafter F89), and a study of the dynamics of the globular cluster system of the central elliptical galaxy, NGC 1399 (Grillmair 1992).

A relatively small number of these galaxies have measured redshifts, however. A purpose of our current program is to begin to remedy this problem and to commence a detailed study of the kinematics of the galaxies in the Fornax cluster.

2. OBSERVATIONS AND REDUCTIONS

2.1 The Program Sample

Since very few dE’s in the Fornax cluster have published spectroscopic data, we just set out to observe all the brightest \((B_T < 16.5)\) nucleated dwarf ellipticals listed by F89 in his study of the luminosity function of galaxies in Fornax. In the following, program objects will be denoted by their number in the F89 catalog. The fact that our sample is biased in
favour of bright, nucleated dE’s must be borne in mind when discussing their statistical properties. Only those galaxies positively identified as dE members of the cluster (”class 1”) were selected. Morphological membership criteria proved to be highly successful. In order to avoid duplicating existing observations, our master list was cross-checked with: (i) a copy of the Huchra’s unpublished ZCAT redshift catalog; (ii) Fornax galaxies collected by Brodie & Huchra (1991). These authors quote radial velocities and discuss metallicities of 10 galaxies in Fornax, 6 of which are dwarfs, from various unpublished sources; (iii) the sample of 5 dwarf galaxies observed and briefly reported by Gregg (1992).

We observed with highest priority all the dE’s in the CB87 list with $B_{nuc} < 21$ (or correspondingly high central surface brightness). Other high central surface brightness candidates for spectroscopy were selected by short-exposure B imaging. Table 1 contains the basic data of our spectroscopic sample of Fornax dwarfs. Photometric data are from Caldwell (1987), CB87, and F89. Although these galaxies are all classified as nucleated dE’s, with the only exception of FCC 261 (dE3pec,N/ImIV), they have rather different surface brightnesses and structure (Table 1).

2.2 Spectroscopy

Spectroscopic observations of nucleated dE’s in the Fornax cluster have been made with the ESO Multi Mode Instrument (EMMI) on the 3.5m NTT telescope of the European Southern Observatory at La Silla, Chile. The EMMI was operated in medium dispersion mode in the blue channel, where the detector was a thinned TEK 1024 $\times$ 1024 CCD (ESO No. 28). CCD read-out was restricted to a 1100 $\times$ 601 region to minimize overhead time, implying a slit length of 3$'$.6. The scale along the direction of the slit was 0".36 per pixel. Long-slit spectra were obtained with a 300 grooves/mm grating blazed at 4000 Å (ESO No. 6), yielding a dispersion of 72 Å mm$^{-1}$ (or 1.73 Å/pixel) over the spectral range $\sim$ 3700 – 5200 Å (the upper limit was set by the EMMI’s blue arm response). With a 1".2
slit, the effective resolution was \( \sim 5.5 \text{ Å} \) (FWHM) \( \sim 3 \) pixels or \( \sim 400 \text{ km s}^{-1} \) at \( \lambda 4000 \text{ Å} \), as measured directly on the final reduced spectra.

Program galaxies were observed on two clear nights of 1-2 December 1991, with typical exposure times 1800–3600s in single exposures (except for the galaxy FCC 207 whose observation was split in two 1800s exposures). This corresponds to \( \sim 800 \) to \( \sim 1500 \) photons per pixel at 4800 Å in most extracted spectra. FCC 85 and FCC 243 are of poorer quality (300–400 photons pixel\(^{-1}\)), which has led to rather uncertain results for these two dwarfs. We also obtained spectra of the Galactic globular clusters NGC 104 (47 Tuc) and NGC 2808, which provide useful reference [Fe/H] values for checking our measurements of dE’s metallicities. As well, these clusters are good radial velocity templates (Webbink 1981). The telescope was nodded in a direction perpendicular to the slit to sample the average population of their centers. Spectra of a few velocity and flux standard stars were also taken in twilight.

Data analysis was carried out with a DEC/5000 workstation at the Bologna Astronomical Observatory using the IRAF \(^2\) package. The data frames were bias-subtracted, and flat-fielded using quartz lamp dome flats for correcting pixel-to-pixel sensitivity variation. The spectra were then extracted using the variance-weighted extraction algorithm of IRAF, which achieved an effective cleaning of cosmic ray hits. Spectra were also visually inspected and a few residual bad pixels interactively interpolated over. Integrated spectra of 47 Tuc and NGC 2808 were obtained by co-adding a \( \sim 25” - 30” \) region across the core, with the sky taken at the edge of the slit farthest from the globular cluster center. Object+sky spectra were also extracted for the dE’s using the same parameters as for the object spectra, aside from sky subtraction. They were used to estimate errors from photon statistics. He-Ar lamp exposures taken before and after each object spectrum were

\(^2\) IRAF is distributed by the National Optical Astronomy Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc. (AURA) under cooperative agreement with the National Science Foundation.
used for wavelength calibration, with a solution error of 0.02–0.07 Å (1.5–5 km s⁻¹, 1σ).

The raw spectra were then rebinned to a linear wavelength scale of 1.5 Å per pixel. For measurement of metallicity indices, we also produced a set of spectra in relative flux units, using observations of a spectrophotometric standard star (L745-46A), and mean extinction coefficients. Since absolute spectrophotometry is beyond the scope of this paper, no attempt was made to put the spectra onto an absolute flux scale.

The wavelength-calibrated spectra of Fornax dE’s and template clusters are shown in Figure 1 on a relative linear flux scale. They are arranged roughly in order of increasing strength of the 4000 Å break (see Section 3.2), and smoothed with a 3-pixel kernel. The absence of Ca II H, K in FCC 85 is attributed to the poor signal.

The IRAF cross-correlation task FXCOR was used to measure the shift in velocity of the dE’s with respect to the velocity standard stars and globular clusters. Internal velocity errors were computed following the precepts of Tonry & Davis (1979). These do not include the contribution of systematic errors, such as the uncertainty in the wavelength calibration of program objects and templates. To evaluate the accuracy of the wavelength scale, we have directly measured template velocities by fitting a Gaussian profile to 6–7 absorption lines in the template spectra. The uncertainty is of the order 20 km s⁻¹ or less, i.e. ~ 1/20 of the resolution element (FWHM). For each galaxy, the velocities obtained from 3 different templates are consistent to within 1/3 of the internal error. Heliocentric velocities are also given in Table 1; they confirm the membership of all of our candidates.

3. ANALYSIS OF THE SPECTRA

3.1 Measurement of Spectral Indices

Line strengths have been measured in Galactic and extragalactic objects by several authors. Brodie & Huchra (1990; hereafter BH) have recently collected and discussed a number of indices defined by Burstein et al. (1984) and Brodie & Hanes (1986), and derived
empirical [Fe/H] calibrations based on the Galactic globulars’ metallicity scale of Zinn & West (1984). The index selection of BH is of special interest for us for two reasons. First, their spectra have resolution very similar to ours, which allows us to retain their bandpass definitions (repeated in Table 2 for convenience). Indices in this first group comprise CH (G band) and $H\beta$ from Burstein et al. (1984), H+K and $\Delta$ (a color measuring the 4000 Å break) from Brodie & Hanes (1986). We note that unfortunately the red cutoff of the blue EMMI spectra prevented measurements of the strong Mg2 feature. Second, we can use Brodie & Huchra’s [Fe/H] calibration of metal line indices to estimate the metallicity of Fornax dwarfs. For this reason we have closely followed all BH reduction procedures. The metallicities derived from our spectra of 47 Tuc and NGC 2808 have provided a useful (although limited) check \textit{a posteriori} of the adopted [Fe/H] scale.

We have also examined indices defined by other authors (Stetson 1984; Rich 1988; Da Costa & Mould 1988; Gregg 1989). Feature and continuum band widths have been adapted to the spectral resolution of our data. Among line indices discussed in the literature, sidebands were chosen to be (i) relatively free from absorption line contamination, and (ii) close to each measured line, to make indices as independent as possible of continuum slope. Our new K, Fe I 4384, Hγ, Hδ, and H8 (Hζ) indices are defined in Table 2. In particular, H8 was defined so as to be little affected by the adjacent CN band with head at 3883 Å. The $\Delta'$ index is similar to $\Delta$ but excludes the noisy region blueward of 3850 Å.

Following BH, line indices were defined as

$$I = -2.5 \times \log_{10} \left( \frac{F_l}{F_c} \right),$$

(1)

where $F_l$ and $F_c$ are the mean fluxes in the line and continuum bandpasses. Pseudo-equivalent widths can be easily calculated from magnitude indices by the relation:

$$W_\lambda = \Delta \lambda \times \left( 1 - 10^{-0.4 \times I} \right),$$

(2)
where $\Delta \lambda$ is the feature bandwidth. The indices were measured by simply integrating the flux within the line and continuum bandpasses in the smoothed, flux-calibrated spectra. (The 3-pixel boxcar smoothing we applied to our spectra has little effect on the indices. In fact, line measurements on the fluxed, unsmoothed spectra yielded the same results at the 1% level).

The bandpasses were suitably redshifted to account for the measured velocities. Where two sidebands are defined, we estimated the continuum at the line center by linearly interpolating the average continuum levels in the sidebands. For the indices with only one continuum bandpass, the average flux in that bandpass was taken.

Extensive tests have shown that these indices are essentially independent of the reduction procedure, or of the intrinsic continuum slope. Only $\Delta$, Ca II K and H8 are somewhat dependent upon the local continuum. The values of the indices are listed in Table 3. Errors in Table 3 were estimated (from read-out noise and photon statistics only) by measuring the auxiliary object+sky spectra in the same bandpasses. Note that indices for the Galactic globulars NGC 2808 and 47 Tuc are probably more uncertain than indicated by their formal errors, which do not take into account inadequate sky subtraction.

Correction of line indices for the effects of internal velocity dispersion ($\sigma_v$), that may be significant for giant ellipticals, should be negligible here, since $\sigma_v$ is expected not to exceed $\sim 50$ km s$^{-1}$ (e.g., Carter & Sadler 1990; Held et al. 1990,1992; Bender et al. 1991; Peterson & Caldwell 1993).

3.2 Metallicities

Given the fairly modest S/N ratio of our spectra of dE's, several indices in Table 3 were combined to produce good estimates of metallicity and hydrogen line strength. The signal-to-noise ratio of our spectra is certainly not sufficient to address the question of relative abundances of light and Fe-peak elements, shown to be variable in giant ellipticals
An Fe deficit (or Mg excess) is not present, however, in weak-line low-luminosity-ellipticals (LLE), showing solar abundance ratios.

Figure 2 shows that the metal-line indices H+K, K, and Fe I correlate quite well with each other and the color ∆, as in Galactic globular clusters. Starred symbols represent the two Galactic globulars. The poor-S/N dE’s FCC 85, FCC 243, and (to a lesser degree) FCC 261 yield the most uncertain indices. The correlation between ∆∗ and ∆, not displayed here, is as good as expected. Errors bars representative of statistical uncertainties in Table 3, are shown for the best and the worst data point. In most cases, we attribute the outliers in these diagrams to the unaccounted errors related to poor sky subtraction, that are certainly most severe, although not easily quantified, for the faintest spectra. We note that the G-band strength is relatively insensitive to metallicity in this range of magnitudes (Burstein et al. 1984, Gorgas et al. 1993). The CH index will not be further discussed here.

The correlations shown in Figure 2 were used to combine all the metal-line indices into an average metallicity index. Straight lines were fitted to the indices in Figure 2, yielding the following relations:

\[ \Delta = 0.146 + 1.162 \times HK \]

\[ HK = 0.058 + 0.507 \times K \]

\[ \Delta = 0.294 + 2.218 \times FeI, \]

also shown as straight lines in Figure 2. A program was used that fits a straight line to data with errors in both variables (based on the Lybanon’s 1984 algorithm, implemented and kindly made available to us by R. Vio). A few outliers were completely excluded from the fit: 4 for H+K vs. ∆; 2 for K vs. H+K; 1 (NGC 2808) for Fe I vs. ∆. This is based on the assumption that indeed metallicity is the factor that drives these correlations. In order to avoid giving too much weight to the globulars on the basis of their (negligible but probably underestimated) formal errors, they were assigned weights equal to those of the
best measured dE’s. Following the approach of Brodie & Hanes (1986), H+K, K, Fe I, and ∆’ were transformed into equivalent ∆ values. Average ∆ indices were then obtained, weighted by the inverse square of the statistical errors; the outliers were discarded, which is almost equivalent to taking the median of the ∆’s. The reason for reducing all indices to an equivalent value of ∆ is that, among the indices in Table 3, ∆ is the only one for which BH provide a metallicity calibration independent of the object type. For H+K, different calibrations have been found for Galactic and M31 globulars, probably due to abundance anomalies (Brodie & Huchra 1991).

The metallicities obtained by applying the Brodie & Huchra’s (1990) ∆–[Fe/H] calibration (for ”All” objects: [Fe/H] = 3.18 * ∆ - 2.43) to our weighted ∆’s are listed in column 3 of Table 4. In column 2 is the number of indices averaged for each object (less than 5 if any discrepant indices were dropped, usually H+K or K of Ca II). Errors were estimated from the (weighted) standard deviation of ∆’s from the average value. They were not divided by the square root of n.[Fe/H]. It should be borne in mind that these errors merely reflect the internal uncertainties affecting the mean ∆ index, and do not account for uncertainties in absolute calibration. Also given in Table 4 are [Fe/H] values obtained from the median of all (five) ∆ values. As expected, the two abundance determinations are in excellent agreement, with the exception of NGC 2808. The errors on the median are simply the standard (unweighted) deviation of all data from the median itself. Therefore they are likely to place an upper limit to the internal uncertainties of our measurements. The errors quoted in column 3 appear more optimistic as a result of weighting.

The metallicity ranking of Table 4 was also checked by eye on the spectra in Figure 1. The metallicities in Table 4 are confirmed, except for FCC 243 that looks much more similar to metal-poor dwarfs (e.g., FCC 188, [Fe/H]~ −1.25) than to metal-rich ones. Its high measured metallicity, reported in Table 4, is likely to be an artifact of the deepness of Ca II H and K lines (Figure 1), for which we could not find any obvious explanation.
In the following, we have adopted for FCC 243 our visual estimate, with the uncertainty quoted in Table 4.

How reliable is our adopted metallicity scale? Since we have closely followed Brodie & Huchra (1990) in measuring the indices, a systematic offset seems unlikely, though it cannot be ruled out a priori. Indeed, the [Fe/H] values obtained for both NGC 2808 and 47 Tuc turn out to be very close to the published values (-1.37 and -0.71, respectively – Zinn & West 1984). Further, the mean Δ indices of the two template globular clusters essentially bracket the range of values for Fornax dE’s, so that we were able to assign metallicities to the dE’s without extrapolation. Thus, while a larger control sample would certainly be desirable, we believe that the metallicity scale presented in Table 4 is basically consistent with Brodie & Huchra’s, within say 0.1–0.2 dex in [Fe/H].

This is confirmed by the agreement between metallicities obtained in this paper and Brodie & Huchra’s (1991) results for Virgo and Fornax dwarf ellipticals. These authors found that (normal and dwarf) elliptical galaxies conform well to the index-metallicity relations defined by globular clusters, and therefore applied their GC metallicity calibration also to galaxies. Their empirical procedure implicitly assumes that stellar populations of galaxies are (at least roughly) similar to those of Galactic and M31 globulars. This is not generally true for dwarf ellipticals, some of which are known to harbour a young or intermediate-age stellar population. The features in the UV-blue spectral region are expected to be sensitive not only to metallicity, but also to the age of the last star formation episode. This is an aspect of the well-known difficulty in distinguishing between the effects of age and metallicity from data in a limited frequency range, for example blue spectra (e.g., Rabin 1982). Recent studies of normal E/S0’s provide circumstantial evidence that some features are indeed sensitive to both metallicity and age. For instance, the 4000 Å break, as well as the Ca II H, K and Fe i 4384 Å lines, which contribute to defining the metallicity ranking of dE’s in this paper, are weak at a given Mg strength in star-forming ellipticals and some S0 disks (Kimble et al. 1989; Gregg 1989). This suggests the
possibility that metallicity measurements of some dE’s from our sample – essentially those with strong Balmer lines – might be subject to similar deviations (cf. Gregg 1992). With these cautionary remarks in mind, we use the Brodie & Huchra’s (1990) [Fe/H] scale as a good approximation to metallicities of dE’s, under the assumption that our indices depend primarily (though not solely) on metal abundance. We shall return to this point in our subsequent discussion.

3.3 Hydrogen Line Strengths

A similar procedure was applied to combine low-S/N Balmer line indices into a mean hydrogen line strength $\langle H_{\beta\gamma\delta} \rangle = \frac{1}{3}(H\beta + H\gamma + H\delta)$, an index also employed in studies of high redshift galaxies. The H$\beta$, H$\gamma$, and H$\delta$ indices were plotted against each other, and regressions obtained using the same techniques as for metallicity. For some dE’s, the H$\beta$, H$\gamma$, and H$\delta$ line strengths are well correlated, so that the three lines were easily averaged. From these data, we also derived scaling relations between the strength of each line and $\langle H_{\beta\gamma\delta} \rangle$.

However, some dE’s have discrepant values of either H$\gamma$ (FCC 296) or H$\delta$ (FCC 85, FCC 207), which are generally attributed to the low S/N of the spectra. Further, FCC 243 and FCC 261 have H$\beta$ too weak for their H$\gamma$ and H$\delta$ (the pseudo-equivalent width of H$\beta$ alone is 0.35 ± 0.85 and 0.43 ± 0.57, respectively). This may indicate the effects of incipient Balmer emission lines, too weak to be detectable as a reversal, yet causing some filling of the H$\beta$ absorption lines. In all these cases, weighted average values were obtained of the two consistent lines, and the result reduced to $\langle H_{\beta\gamma\delta} \rangle$ using the scaling relations described above.

The average H line strengths are listed in column 6 of Table 4. Note that our choice of bandpasses for Balmer lines gives slightly lower (by 20%) pseudo-equivalent widths than other definitions in the literature (e.g., Caldwell et al. 1993). The range of mean H line
strengths of dE’s, 1-3 Å, found here is also typical for spiral galaxies with similar colors. Errors were calculated from both count statistics and the average (weighted) variance of Balmer indices. Only for the globulars 47 Tuc and NGC 2808 is the measured scatter of the indices larger than would be expected from photon statistics. The larger of the two error estimates is given in Table 4.

Caldwell et al. (1993) have recently pointed out that W(H8) is a more reliable indicator of the presence of hot stars than Hδ, since it is less sensitive to filling by Balmer emission (we are grateful to the referee for calling our attention on this diagnostic). The pseudo-equivalent widths of H8 are listed in column 7 of Table 4 along with their statistical errors.

4. DISCUSSION

4.1 Stellar Populations

The present analysis of the spectra of dE’s has the advantage of providing a two-dimensional classification not available from integrated colors, although still semi-qualitative owing to the lack of proper spectral synthesis models with a full grid of ages and metallicities. In a coeval population, hydrogen lines sample the warm stellar component, particularly the temperature distribution on the main-sequence turn-off and the subgiants (e.g., Buzzoni et al. 1993). Figure 3 shows the Balmer line equivalent widths of dwarf ellipticals and Galactic globulars in a (metals, hydrogen) diagram similar to the age-metallicity diagnostic diagram of Rabin (1982). FCC 243 has been plotted using its visually estimated metallicity. The error bars represent the uncertainties quoted in column 4 and 6 of Table 4. In this figure, the average \( \langle H_{\beta \gamma \delta} \rangle \) strengths have been scaled (by a factor 1.2) to the pseudo-equivalent widths of H\( \beta \) alone, to facilitate the comparison with globular cluster data. The reference line in Figure 3 is the locus of Galactic globular clusters, interpreted as a sequence of varying metallicity at constant age. This is defined by the least-squares fit to H\( \beta \) strengths versus Galactic globular cluster metallicities presented in Brodie & Huchra.
(1990). No rescaling or adjustment has been applied. It should be reminded here that the results described in this paper refer to the nuclei of dE’s. Spectroscopy of non-nucleated dE’s, or of the external regions of nucleated dwarfs, is made exceedingly difficult by their extremely low surface brightness.

A number of dwarfs in our sample (FCC 85, FCC 100, FCC 188, and FCC 296) have mean hydrogen line strengths consistent with or marginally weaker than those expected for an old, metal-poor population. In contrast, there are some dE’s showing enhanced hydrogen lines relative to globular clusters of similar metallicity. All the hydrogen lines, except for $H\beta$, are particularly enhanced in FCC 261. The Balmer lines are also moderately strong, $\langle H_{\beta\gamma\delta} \rangle > 1.5$ Å, in FCC 243, FCC 245, FCC 266, and FCC 150 (in order of decreasing intensity). For all of these dwarfs, the equivalent width of H8 is also larger than 3 Å. Hδ is abnormally strong ($\sim 3$ Å) relative to the other H lines in the spectrum of FCC 207. For FCC 207 and FCC 296, the $\langle H_{\beta\gamma\delta} \rangle$ values in Table 4 and Figure 3 are likely to be underestimates of the H line strength, since H8 indicates some hot star content. For FCC 150 and FCC 266, which are relatively metal-rich, the hydrogen line strengths are explained by a relatively blue stellar component. These strong Balmer lines cannot be due to low metallicity. As discussed below, the metallicities of these dwarfs may be, if any, underestimated. The moderate intensity of the hydrogen lines in these two dwarfs suggest the presence of an intermediate-age population, rather than a recent burst of star formation (cf., Bothun & Mould 1988). In the case of FCC 261 and (to a lesser degree) FCC 243 and FCC 245, the hydrogen lines are strong enough to be consistent with the presence of a young stellar component, even in the absence of distorted morphology. In addition, recent star formation in FCC 261 is unambiguously confirmed by a peculiar knotty appearance on blue images.

Hydrogen line strengths are more sensitive to a warm-star component than are integrated colors. For instance, NGC 185 has not abnormally blue $U - V$ color for its luminosity, even with its blue stars. Also, dwarf ellipticals with morphological signatures
of young stars are only 0.1–0.2 mag bluer in $U - V$ than predicted from a color-luminosity relation (Caldwell 1983). In Figure 4 $W_{\text{H}\beta}$ is plotted against $U - B$ for Fornax dwarfs (only 6 dwarfs had their colors measured by CB87). Galactic globular clusters are also plotted for comparison (colors are from Reed et al. 1988, $H\beta$ measurements from Brodie & Huchra 1990). Figure 4 provides further evidence that Balmer lines are stronger in FCC 245 than expected for an old, metal-poor population, and indicates the need for a younger component with respect to globular clusters.

Thus, there is some evidence that young stars or an intermediate-age main-sequence turn-off are relatively common among dE’s, in accord with a suggestion put forth by some authors (Bothun et al. 1985, Zinnecker et al. 1985) that nuclei are the site of recent star formation. The absence of peculiar morphology seems to suggest that residual star formation must have concentrated in the nucleus. An intermediate-age AGB population would also be expected.

Nearby Local Group dwarfs may provide a closer picture and helpful guidelines on understanding the stellar population of dE’s. NGC 205 is known to be experiencing a modest burst of star formation (Wilcots et al. 1990), and asymptotic giant branch stars are observed in the central regions, which implies a significant intermediate-age (0.5–1.5 Gyr) stellar population (Mould et al. 1984; Richer et al. 1984; Davidge 1992). An analogy with Local Group dwarf ellipticals would suggest that an interpretation of Balmer line strengths in terms of coeval stellar populations might not be appropriate. Instead, nucleated dE’s may be forming stars in bursts from the gas recycled from the old population, as proposed by Gallagher & Hunter (1981) for NGC 185 and NGC 205.

4.2 Metallicity

As to metallicity, Figure 3 shows that Fornax dE’s in this study are distributed in a relatively wide range in [Fe/H], from moderately metal-poor ([Fe/H] $\sim -1.4$ dex) to values similar to those of metal-rich globular clusters ($-0.7$ dex). In our limited luminosity range
(MB \sim -15 \pm 0.5 \text{ mag}, adopting a distance modulus 31.0 from Aaronson et al. 1980), we find an apparent scatter of 0.23 dex around a median metallicity [Fe/H] = -1.20, with no apparent correlation between [Fe/H] and luminosity.

[Fe/H] values derived from blue spectra are well correlated with U – B colors from CB87. In Figure 5a, metallicities are plotted against U – B colors for the Fornax dE’s in common with CB87 and the globulars 47 Tuc and NGC 2808. While this relationship is not unexpected, since U–B is sensitive to metallicity through the strength of the 4000 Å blanketing discontinuity, this correlation has important implications. First, it shows that our formal error bars are realistic, and gives confidence in our metallicity measurements. More importantly, this correlation demonstrates that the apparent range in metallicity at a given luminosity is real, i.e. not caused by observational scatter. This conclusion also applies to the range in U – V colors discussed by CB87. Consequently, the general metallicity-luminosity correlation can be studied only statistically, in a wide luminosity range. Metallicity from blue spectra also correlate well with B – V (Figure 5b). There is no shift relative to globular clusters. This correlation is an analog of that between Δ and a spectral gradient in normal elliptical (Kimble et al. 1989), and is driven by the temperature of the main-sequence turn-off. We note that a correlation is also implied between U – B and B – V.

FCC 207 is too blue in U – B (by \sim 0.1 \text{ mag}), and apparently too metal-poor (by 0.15 dex) for its B – V. These effects point towards a young stellar component. Note that U – B colors and [Fe/H] estimates are affected in a similar way, so that FCC 207 lies on the GC relation in Figure 5a. The only other dwarf with strong H lines and published colors, FCC 245, appears quite normal in Figure 5.

In terms of absolute [Fe/H] values, our results are tied to the Brodie & Huchra’s metallicity scale. We note the agreement with the metallicities of the dE companions to M31, NGC 205 and NGC 147, directly obtained from color-magnitude diagrams (Mould et
al. 1984). To use a calibration-independent statement, Fornax dE’s have spectra resembling those of intermediate metallicity to metal-rich globular clusters.

This well established range in spectral characteristic is in good agreement with previous results from blue spectra. Spectroscopy of 3 dE’s by Bothun et al. (1985) suggested that a strong-lined Virgo dwarf, NGC 4472-DW8, is more metal-rich than 47 Tuc (for this object Brodie & Huchra obtained $[\text{Fe/H}] = -1.2 \pm 0.5$, the two results being only marginally consistent). Two other Virgo dwarfs are either moderately metal-poor ($\text{Fe/H} = -1.0$ to $-1.5$, NGC 4472-DW10) or very metal-poor, based on their Ca II line strengths. Bothun et al. (1985) noted that the dE’s form a heterogeneous sample in terms of their spectroscopic properties. In their study of 12 nucleated Virgo dE’s, Bothun & Mould (1988) concluded that blue nuclear spectra resemble those of metal-rich globular clusters, though some dE’s are probably more metal-poor (yet considerably more metal-rich than M92).

Indeed, we note that most of the Virgo dwarfs in the Bothun & Mould’s sample have Ca II K line strengths between those of M79 ($[\text{Fe/H}] = -1.68$) and 47 Tuc. Most recently, Brodie & Huchra (1991) obtained, from 5 blue-visual spectral indices, a mean metallicity of $-1.15$ for Virgo and Fornax dE’s. They pointed out a discrepancy between metallicities derived from optical line strengths and those derived from infrared colors. For example, the $J - K$ colors, which are sensitive to metallicity through giant branch temperatures, indicate metallicities $\sim -0.7$ for Virgo dE’s (Bothun et al. 1985; Thuan 1985).

It would have been of interest to compare our new optical results to IR data. Unfortunately, no infrared photometry has been published in our knowledge for Fornax dE’s. A direct comparison of $J - K$ colors and Ca II K line strengths is however possible for a small sample of Virgo dE’s with IR data (Bothun et al. 1985, Thuan 1985) and spectroscopic data (Bothun & Mould 1988) (Figure 6). These are M87– DW1, DW6, DW11, DW27, and DW31. Note the $\sim 0.1$ mag offset in the $J - K$ colors of Thuan (1985) relative to those of Bothun et al. (1985) and Zinnecker et al. (1985). Figure 6 suggests that $J - K$ colors are
independent of the strength of the Ca II K line. For dE’s with strong Ca II K, infrared colors and spectra are consistent, yielding abundances similar to those of metal-rich globular clusters. For weaker-lined dwarfs, $J - K$ and line strengths in the blue spectra apparently give divergent results, in that $J - K$ colors are redder than expected for an old, moderately metal-poor stellar population. Given the correlation in Figure 5a, this is equivalent to the photometric result that dE’s have bluer $U - B$ colors than globular clusters of the same $J - K$ (CB87). Clearly, it would be important to perform this exercise on a larger sample of dwarfs (including those in this paper) having both accurate IR colors and homogeneous spectroscopy.

To explain this discrepancy, Brodie & Huchra (1991) argued that the IR color-metallicity calibration based on Galactic globular clusters may not be appropriate for dwarf ellipticals. Differences in stellar population mix may be present in dE’s compared to the globulars. In particular, $J - K$ colors could be made redder by a population of AGB stars. Bothun et al. 1985 pointed out a problem with the $H - K$ colors, apparently consistent with those of globular clusters. However, plotting $H - K$ colors against Ca II K for the same sources as in Figure 6, we have found that dE’s have slightly redder $H - K$ than globulars of similar Ca II line strength. Thus we believe AGB stars are a possibility not to be ruled out, but clearly more data are required.

We now examine the alternative possibility that metallicity as derived from blue spectroscopy is biased. CB87 suggested that the range in optical colors of Fornax dE’s could be partly explained by a dispersion in the mean ages. Similarly, perhaps the scatter in [Fe/H] measured from blue spectra is not entirely due to metallicity. As shown in the previous section, it is conceivable that metal line strengths of some dwarfs are diluted by a UV light excess, which potentially leads to an underestimate of metallicity. Indeed, simulations of a recent burst in giant ellipticals by Bica et al. (1990) show that Ca II K is quite sensitive to dilution effects by the UV continuum, even for bursts involving only
0.1 % of the galaxy mass – a result expected to hold at least qualitatively also for metal poorer dwarf ellipticals.

The dwarfs with strong hydrogen lines are the first candidates for such effect, since both Balmer lines and Δ (as well as blue-visual colors) are controlled by the temperature of the main-sequence turn-off. For example, the metallicities of FCC 261 and FCC 245 might be too low by a few tenths of a dex, and ”corrected” data points should be moved to the right (higher metallicities) in Figure 3. As an important consequence, Balmer line strengths would be even more in excess with respect to globular clusters. Evidence for a young or intermediate-age population would be strengthened.

However, the observed metallicity range is unlikely to be entirely explained by dilution effects, for the following reasons: (i) The same range of metallicities as found here is given by Brodie & Huchra (1991) using also indices at longer wavelengths, such as Mg2 or Fe52. The dependence of Mg2 on metallicity is well studied (Mould 1978; Worthey et al. 1992; Buzzoni et al. 1992; and references therein). As regards Fe52, this index mainly reports on the metallicity of the moderately cool stars at the base of the RGB, with little dependence on age (Buzzoni et al. 1993). (ii) Since blue indices are likely to be modified at a different degree, dilution effects should be apparent in index-index plots. In fact, Figure 2 shows that FCC 261, the only case where a blue light excess is evident, has H+K and K indices consistently too strong for its Δ. Further, the G band is too weak (CH is otherwise nearly constant in this abundance range – Burstein et al. 1984). Differential dilution effects are, however, not evident for other objects with strong Balmer lines.

In Figure 7, we have also looked at a possible correlation between metallicity and surface brightness for dE’s (the effect of a threshold gas density for star formation has been discussed, e.g., by Bothun & Mould 1988 and Phillipps et al. 1990). This figure shows no clear correlation between metallicity and effective surface brightness; a similar conclusion is drawn from a plot of [Fe/H] against nuclear magnitude, or the average central surface brightness S3pix (both from CB87). However, we note that the two dwarfs with
the highest surface brightnesses, FCC 150 and FCC 266, also have high metallicities (cf. NGC 4472-DW8 in Bothun et al. 1985).

4.3 Kinematics of the Fornax Cluster

The distribution of the dwarf galaxies in Fornax is shown in Figure 8. In addition to the ten galaxies in Table 1 there are 85 galaxies in ZCAT (Huchra 1990) which satisfy the following criteria:

- Redshift $cz < 2520 \text{ km s}^{-1}$
- Blue magnitude $^3$ known (de Vaucouleurs et al. 1990, F89)
- Location within $5^\circ$ of NGC 1399.

The mean heliocentric velocity of this sample is $1450 \text{ km s}^{-1}$ and the velocity dispersion is $330 \text{ km s}^{-1}$. If the core radius ($r_c$) of the cluster is $0.7^\circ$ (F89) and the distance modulus 31.0 (Aaronson et al. 1980), the crossing time ($r_c/\sigma$) is 0.5 Gyr. Figure 9 shows no evidence for organized motions in the velocity distribution of the sample galaxies, and, in particular, there is no evidence for rotation of the cluster about the minor axis of the distribution in Figure 8 at the level $v/\sigma < 0.07$.

There is a detectable difference, however, between the velocity dispersion of the dwarf galaxies ($B_T > 15 \text{ mag}$) and the rest of the sample. This is indicated in Table 5. Figures 10 (a) and (b) illustrate the normal distribution of the brighter sample and the flatter distribution of the dwarf sample.

The Kolmogorov-Smirnov test rejects the hypothesis that the dwarf sample is drawn from a Gaussian distribution with a dispersion of 300 km s$^{-1}$ at the 75% confidence level. This is not sufficient for us to be able to conclude that there is a difference in the kinematics of the two samples, but it is indicative that there is some probability that this is the case. A similar flatter distribution was seen in a Virgo sample of dwarf galaxies by Bothun &

$^3$ We do not distinguish for present purposes between $B_T$ and $m_B$.
Mould (1988). A larger Fornax sample should be investigated in order to confirm these interesting, but preliminary, results.

It is of interest, nonetheless, to ask how such velocity dispersion differences might physically arise. To discuss this, we recall the relevant timescales. Although cluster virialization may be established in a few crossing-times, and the latter, as indicated above, is short, cluster growth occurs on the infall timescale. The infall timescale for mass shells to turn around and accrete into a cluster is of order 5 Gyrs for the Coma cluster (Gunn & Gott 1972). This collapse timescale scales like the crossing-time, which is similar for the two clusters. The timescale for mass segregation, however, is the relaxation time, which, even in a cluster as dense as Fornax, exceeds the Hubble time by an order of magnitude.

The candidate process, therefore, for velocity dispersion differences in clusters of galaxies, is accretion of galaxies over the lifetime of the cluster. The morphology-density relation (Dressler 1980) would tend produce an initial distribution of galaxies in which dwarf galaxies preferentially occupy the outer halo of the proto-Fornax cluster, while massive early-type galaxies occupy the core. The longer infall timescale of the halo dwarfs would then yield a larger velocity dispersion characteristic of their more recent separation from the Hubble flow.

5. SUMMARY

Spectra of the nuclei of ten dE’s in the Fornax cluster have been obtained, from which radial velocities have been measured and spectral indices derived, related to either metal or hydrogen line strength. Using the empirical Brodie & Huchra’s (1990) calibration based on Galactic and M31 globular clusters, metallicities have been derived for the dwarf ellipticals in our sample. In this paper we have found a large variety of spectral characteristics among the nuclei of dwarf ellipticals, although all targets (except FCC 261) were selected on the basis of a uniform dE,N morphological classification.
1. Blue spectra of dE’s cover a wide range of metallicities, from *metal-rich* ([Fe/H] \sim −0.7) to *intermediate metallicity* globular clusters ([Fe/H] \sim −1.4), with some concentration around [Fe/H] \sim −1.2 and −0.7. This is in agreement with the metallicities derived using color-magnitude diagrams for the dE companions to M31 (NGC 205 and NGC 147) and with previous spectroscopic results for Virgo and Fornax dwarfs. However, it also confirms a discrepancy with metal abundances inferred from infrared colors, at least for the weaker-lined dwarfs. Possible reasons for this discrepancy have been discussed, including contribution of an intermediate-age population to the IR colors, and dilution of spectral features by a blue light excess.

2. A wide range in hydrogen lines strengths is highly suggestive of a complex star formation history in dwarf ellipticals. In particular, a hot stellar population is shown in some (but not all) nucleated dE’s. Some metal-rich dE’s have on average relatively strong H lines, consistent with an intermediate age population, but not as intense as those found in NGC 205, where recent star formation is evident. Other dwarfs (*e.g.*, FCC 245, FCC 261) show stronger H lines, consistent with recent star formation. For FCC 261, this is confirmed by a small-scale structure on blue images. A few relatively metal-poor dE’s have hydrogen lines consistent or perhaps weaker than those of Galactic globulars of comparable metal line strength.

3. There is no clear correlation between metallicity and surface brightness for the dwarf ellipticals having $\mu_B > 23.4$ mag arcsec$^{-2}$. However, FCC 150 and FCC 266, the two dE’s with the highest surface brightness in our sample, are both similar to metal-rich globular clusters. These objects may represent intermediate cases between dE’s and low-luminosity “normal” ellipticals.

4. The radial velocity distribution of Fornax dwarfs looks flatter than that of brighter galaxies. Numbers are small, however. The hypothesis that both samples are drawn from the same parent population can be rejected at the 75% confidence level, which is indicative of (yet does not prove) a difference in the kinematics of the two samples.
These suggestions are important for their implications for stellar populations in dwarf ellipticals. The trends are weak, however, due to the small number of objects, and more data are needed.

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FIGURE CAPTIONS

Figure 1. Flux-calibrated spectra of Fornax nucleated dE’s and two Galactic globular clusters, arranged roughly in order of increasing line strength. The ordinate flux scale was adjusted to approximately reproduce the number of e\(^{-}\) at 4800 Å in the original co-added spectra (units are 100 e\(^{-}\)). Error bars in the upper left corner of each panel give 1 \(\sigma\) errors estimated from photon statistics in object+sky spectra.

Figure 2. Relationship between indices related to metallicity, for Fornax dwarfs (\textit{squares}) and two globular clusters (\textit{starred symbols}). The stronger-lined globular is 47 Tuc. Error bars were computed from photon statistics only. The errors on FCC 150 represent typical uncertainties. Errors are also shown for the 3 dwarfs with poorly defined indices. The regression lines were computed assuming errors on both variables (see text for details).

Figure 3. The mean H\(\beta\) index is plotted against metallicity derived by us for dE’s (\textit{squares}) and two globular clusters (\textit{crosses}). The data point for FCC 243 represents the visually estimated metallicity. The line is the fit to globular cluster of Brodie & Huchra (1990). It represents the locus of old stellar populations of different abundances. Error bars were computed from count statistics.

Figure 4. The equivalent width of H\(\beta\) vs \(U - B\) colors. The squares with error bars denote Fornax dE’s data in Table 4. Colors are from Caldwell & Bothun (1987). The dots represent globular clusters which have H\(\beta\) measured by Brodie & Huchra (1990), and (dereddened) colors from Reed \textit{et al.} (1988).

Figure 5. Correlation between spectroscopically derived [Fe/H] values and \(U - B\) (\textit{a}) and \(B - V\) (\textit{b}), for Fornax dwarfs (\textit{squares}) and 47 Tuc, NGC 2808 (\textit{crosses}). Error bars as in Figure 3.
Figure 6. The $J - K$ color is plotted against the equivalent width of Ca II K for a small sample of Virgo dE’s having both line strengths from Bothun & Mould (1988) and infrared colors from Bothun et al. (1985) (filled squares) and Thuan (1985) (open squares). Color uncertainties in the data are of the order 0.05 mag. Note the magnitude scale offset between different authors. Dots connected by line segments refer to Galactic globular cluster data (Ca II line strength from Da Costa & Mould 1988, infrared colors from Brodie & Huchra 1990).

Figure 7. Metallicity is plotted against mean surface brightness in B inside the effective radius ($<\mu_B>_{eff}$), computed from Ferguson’s (1989) data.

Figure 8. Contours of galaxy surface density in the Fornax cluster from the Ferguson & Sandage (1988) dwarf sample. The contour unit is one galaxy per $[20']^2$. Superposed on the contours are the locations of galaxies brighter than 15th magnitude with redshift less than 2520 km s$^{-1}$ and within 4° of NGC 1399. The bar shown on the figure indicates one degree. North is at the top, east to the right.

Figure 9. A slice of redshift space with Right Ascension the azimuthal coordinate. The radius vectors are 2500 km s$^{-1}$ long and ten degrees of RA apart.

Figure 10. Redshift distribution of Fornax galaxies: (a) dwarf sample, (b) bright sample.