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WASHINGTON PHOTOMETRY OF LOW SURFACE BRIGHTNESS DWARF GALAXIES IN THE FORNAX CLUSTER: CONSTRAINTS ON THEIR STELLAR POPULATIONS

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ABSTRACT

Integrated colors of a sample of low surface brightness (LSB) dwarf galaxies in the Fornax cluster, obtained from CCD images in the Washington system, are analyzed. This system proves useful to, under certain conditions, disentangle the effects of age and metallicity in a color-color diagram. A comparison with synthetic colors of simple stellar systems of known age and metallicity shows that nearly half the dwarfs have colors that can only be reproduced by a mixture of stars including a moderately young ($\simeq 10^8$ yr) population. In particular, one of the galaxies shows evidence of recent or current star formation.

Subject headings: galaxies: photometry — galaxies: stellar content

1. INTRODUCTION

There are several reasons for the interest in the study of the stellar populations in low surface brightness (LSB) dwarf galaxies. First, they are the most common type of galaxy in the universe (Binggeli, Sandage, & Tammann 1985; Ferguson 1989), and consequently they should be taken into account in any cosmological model.

In addition, these are small, and so, at least in principle, simple systems; star formation in dwarf LSB galaxies is then supposed to depend mainly on a few global parameters (depth of general potential well, size), instead of being a more complex process such as in spiral galaxies (see, for example, Larson 1974; Gerola, Seiden, & Schulman 1980).

These two features turn dwarf galaxies into an appropriate set of objects in which current ideas about star formation in stellar systems can be tested. Within this context, it will be particularly important to identify the physical processes (intrinsic and/or environmental) that govern the present rate of star formation, leading to the different types of known LSB dwarfs; quiescent dwarf irregulars (dI's) showing evidence of recent star formation and still having a reservoir of H I, bursting blue compact dwarfs (BCDs), and completely quiet and gas-free dwarf ellipticals (dE's). A variety of evolutive scenarios linking these main three types has been discussed widely in the literature (Kormendy 1985; Thuan 1985; Binggeli, Tarenghi, & Sandage 1990; Bothun et al. 1986; Evans, Davies, & Phillipps 1990; Bothun, Impey, & Malin 1991; Krüger & Fritze-v. Alvensleben 1994); however, our present knowledge of the stellar populations in these galaxies is still too poor to reach any firm conclusion.

Since the mid 1980s, great observational efforts have contributed to the growth of the available data set about stellar populations in LSB dwarfs outside the Local Group; however, the challenge to observers remains very hard to overcome. In particular, the properties of dwarf ellipticals, given their larger number, are better known than those of late-type dwarfs; the following discussion is in consequence mostly restricted to dE's.

Spectroscopic data are still very scarce and limited to the brighter *nucleated* dwarfs (Jones & Jones 1980; Bothun et al. 1985; Bothun & Mould 1988; Brodie & Huchra 1991, hereafter BH; Gregg 1992; Held & Mould 1994, hereafter HM). Photometric data are more abundant, involving both optical (Caldwell 1983; Gallagher & Hunter 1986; Caldwell & Bothun 1987; Bothun, Caldwell, & Schombert 1989; Evans et al. 1990) and infrared (Bothun & Caldwell 1984; Thuan 1985; Bothun et al. 1986) colors. All these works point to a similar conclusion: dE galaxies are old, moderately metal poor systems (i.e., with metallicities between those of intermediate and rich Galactic globular clusters), although some of them show evidences of a younger population. (See also Ferguson & Binggeli 1994 for a recent and comprehensive review on dE's.) There is also evidence for at least a dwarf in the Virgo Cluster showing the signs of very recent or ongoing star formation (Vigroux, Souviron, & Vader 1984).

A similar scenario arises from the study of Local Group dwarfs (which include fainter galaxies than those so far observed in the Virgo and Fornax Clusters). These galaxies are resolved in stars, allowing detailed observations that are not possible for more distant systems. From these studies, it is evident that Local Group dwarfs show different and sometimes complex star formation histories, including that of NGC 205, which is presently forming stars at its center (see Hodge 1989 and Da Costa 1992 for reviews).

In contrast, for dwarfs beyond the Local Group, inte-

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grated light remains the only means to get information about their stellar content. Moreover, there is at the moment no reasonable hope of obtaining spectra of faint and/or nonnucleated dE's, leaving integrated photometry as the unique tool for their study. Many attempts have been made to disentangle age and metallicity effects based on broadband colors alone, leading to a general consensus that many dwarfs must have had recent star formation. However, given the undeniable existence of calibration problems, selection effects, and deficiencies in the population synthesis models used for comparison, this assessment must be made cautiously (Ferguson & Binggeli 1994).

In any case, three-color CCD photometry is a useful technique, since structural parameters and possible color gradients can be studied simultaneously. It is surprising, then, that very few investigators have so far used it (Vigroux et al. 1988); as a result, data of this kind are still very scarce and fragmentary for LSB dwarf galaxies. In a previous paper (Cellone, Forte, & Geisler 1994, hereafter CFG), structural properties and a preliminary color analysis for 15 dwarf LSB galaxies in the Fornax Cluster, obtained from three-band CCD surface photometry, were presented. The quality of those data makes it worthwhile (without forgetting what was said in the previous paragraph) to attempt to discuss the populations of the dwarfs within a quantitative frame. In the present paper, we analyze the integrated colors of the dwarfs in the mentioned sample. These colors are then compared, in a color-color diagram, with observed colors of Galactic globular clusters and synthetic colors of simple stellar populations of known ages and metallicities, showing the capabilities and limitations of this method for the identification of different stellar populations in dwarf galaxies.

2. THE DATA AND PREVIOUS RESULTS

The galaxies in this sample were taken from the Fornax Cluster Catalog (Ferguson 1989), and we retain in this paper the identification numbers given there. All but one of the dwarfs are classified as dE in that work, although a different catalog (Davies et al. 1988) classifies two of the galaxies as dwarf irregulars (dI's). Since no knots and/or irregular features are evident in our images of these two galaxies, we will simply refer to the whole sample as LSB dwarfs, bearing in mind that this may probably be equivalent to calling them dE's, as is usually done in other works (at least while 21 cm observations are not available).

The observations were carried out with the 0.9 and 1.5 m telescopes at CTIO during two runs (1989 October and 1990 November) and were fully described in CFG. However, there are a few points justifying our choice of the observing procedure that we want to emphasize here.

In first place, CCDs are the ideal detectors for this kind of work, adding to their well-known advantages the possibility of obtaining morphological data along with the colors. In this way, CFG concluded that no significative color gradient could be detected in any (except for one; see below) of the dwarfs, and so it should be valid to compute integrated colors.

On the other hand, a main point is the choice of the photometric system. The observations were done in three bands of the Washington system (Canterna 1976): C ($\lambda_{\rm eff}$ = 3910 Å; $\Delta\lambda$ = 1100 Å), M ($\lambda_{\rm eff}$ = 5085 Å; $\Delta\lambda$ = 1050 Å), and T_1 ($\lambda_{\rm eff}$ = 6330 Å; $\Delta\lambda$ = 800 Å). This system was originally developed for the measuring of abundances in giant G and K stars. In practice, its sensitivity to CN abundance, through the C bandpass, has not resulted as expected; however, it has been used successfully as a [Fe/H] calibrator for late-type giant stars (Geisler, Clariá, & Minitti 1991). (See also Paltoglou & Bell 1994 for a complete evaluation of the properties of the Washington system from synthetic spectra.)

This system has also been employed to obtain integrated colors of old stellar systems, including Galactic and extragalactic globular clusters (Harris & Canterna 1977, hereafter HC77). In the case of the dwarf galaxies, given their faintness, observations through the Johnson U band involve prohibitively long exposure times, except that large (~4 m) telescopes are used. Instead, the C band, being midway between the U and B wavelengths and on the sensitivity shoulder of most CCDs (including those with coatings), permits one to obtain information from the ultraviolet region of the spectrum with reasonable exposure times in medium-sized telescopes.

Geisler & Forte (1990) have also shown that the $C - T_1$ index is a sensitive metallicity indicator for Galactic globular clusters, deriving a calibration between [Fe/H] and that color index. Assuming, as a first approach, that the dwarf elliptical galaxies are dominated by an old stellar population, CFG applied that calibration to their $C - T_1$ colors, obtaining a magnitude-metallicity relation in good agreement with that already known for Local Group dwarf spheroidals (Da Costa 1992). However, this relation breaks down if one includes FCC 76, the brightest dE in the sample, because its $C - T_1$ is too blue for its total magnitude. Figure 1 (Plate 5) is a color map of this galaxy, where lighter gray levels correspond to bluer pixels in $C - T_1$. Some very blue (in contrast with the underlying galaxy) concentrations or knots are evident at its center, clearly indicating recent or ongoing star formation taking place there. (The pixels between the knots are red and are depressed with respect to the centerward extrapolated surface brightness profile in all images, suggesting the presence of dust.) This conclusion is supported by the existence of emission lines in its spectrum (Jones & Jones 1980). So it comes out that the relatively blue colors of FCC 76 are not caused by a low metallicity but by a younger mean age compared to the other dwarf galaxies.

A hint for a similar, although surely smaller, effect operating upon the colors of the rest of the dE's was mentioned in CFG, since the scatter in the relation between $C - T_1$ and total magnitude is larger than that expected from observational errors alone. To explore this, we must study how age and metallicity affect the positions in a color-color diagram of the Washington system color indices of simple stellar populations, i.e., closed systems of stars born at the same time and evolving without any further interaction with the external environment. In the following section, we build up a data base of simple stellar populations spanning the appropriate ranges in age and metallicity, for which Washington colors are available or can be derived.

3. THE COLOR-COLOR DIAGRAM

3.1. *Observed Colors of Galactic Globular Clusters*

Galactic globular clusters provide a unique population of objects whose ages and metallicities have been directly measured (via isochrone fitting in color-magnitude diagrams and spectroscopy of individual stars respectively), and, at the same time, integrated colors in the Washington system have been obtained (this is true at least for a large subsample of all the known clusters). HC77 give a $C - M$ versus $M - T_1$ diagram for 43 Milky Way globulars; the same graphic is reproduced in Figure 2, though their metallicities and color excesses have been updated whenever new values were found in the literature (Zinn 1985; Armandroff & Zinn 1988). Also plotted are 12 LSB dwarfs with C, M, and T_1 photometry from our observations. (Three galaxies were excluded from the original sample in CFG: FCC 188, for which we have no M frame, and FCC 82 and FCC 296, whose colors are affected by systematic errors.) A reddening line, corresponding to $E_{(B-V)} = 0.03$ and adopting the ratios given in Harris & Canterna (1979), is also shown.

As HC77 have already pointed out, their sample of globular clusters defines a sequence in this diagram which is determined mainly by metallicity. However, there is a spread in colors along directions roughly parallel to the reddening line for clusters of the same metallicity (linear fits for globulars within the indicated [Fe/H] ranges, and excluding those with $E_{[B-V]} \geq 0.40$, are shown with solid lines in Fig. 2), and they identify three possible causes for this effect:

1. Errors in the color excesses, usually larger for more reddened clusters.
2. Statistical variations in the number of luminous red giants included within the diaphragm, or systematic variations in the spatial distributions of stars of different types within each cluster.
3. Different fractions of stars of various types in the clusters.

Evidences of the first effect can be seen in Figure 3, where, among clusters with similar metallicities, those with greater excesses have colors that are either redder (Fig. 3*a*), or very different from the rest (Fig. 3*b*).

Regarding item 3 above, this is the case of clusters having abnormally red horizontal branches (HBs) for their metallicities, a fact that is widely known as the "second parameter effect," and which is attributed mainly to differences in age (see, for example, Kraft 1980, and references therein), although other parameters like helium content, α-capture element abundances, and mass loss should play an important role in the quantitative timing of HB isochrones (Catelan & de Freitas Pacheco 1993).

Summarizing, the HC77 sample provides the unique set of integrated colors in the Washington system presently available for globular clusters (or any other simple stellar systems), and it defines in the color-color diagram a sequence governed by metallicity, although smaller effects caused by several second-order factors are also evident. Regarding the dwarfs, their locations in Figure 2 suggest metal abundances similar to those of the globulars with intermediate to high metallicities, although some of the galaxies depart noticeably from the sequence defined by the clusters, forming a branch nearly parallel to the lines of constant metallicity. In this case, the existence of an error in the adopted reddening should be discarded, since the mentioned branch extends *blueward* of the sequence defined by the globulars instead of *redward*, as should be the case if our value of $E_{B-V} = 0.03$ were too low; taking a lower value, say $E_{B-V} = 0.00$, does not change anything. (The same reasoning holds against internal reddening as the source of that feature, but we shall return to this point later). Furthermore, a variable extinction in front of, or within, the Fornax

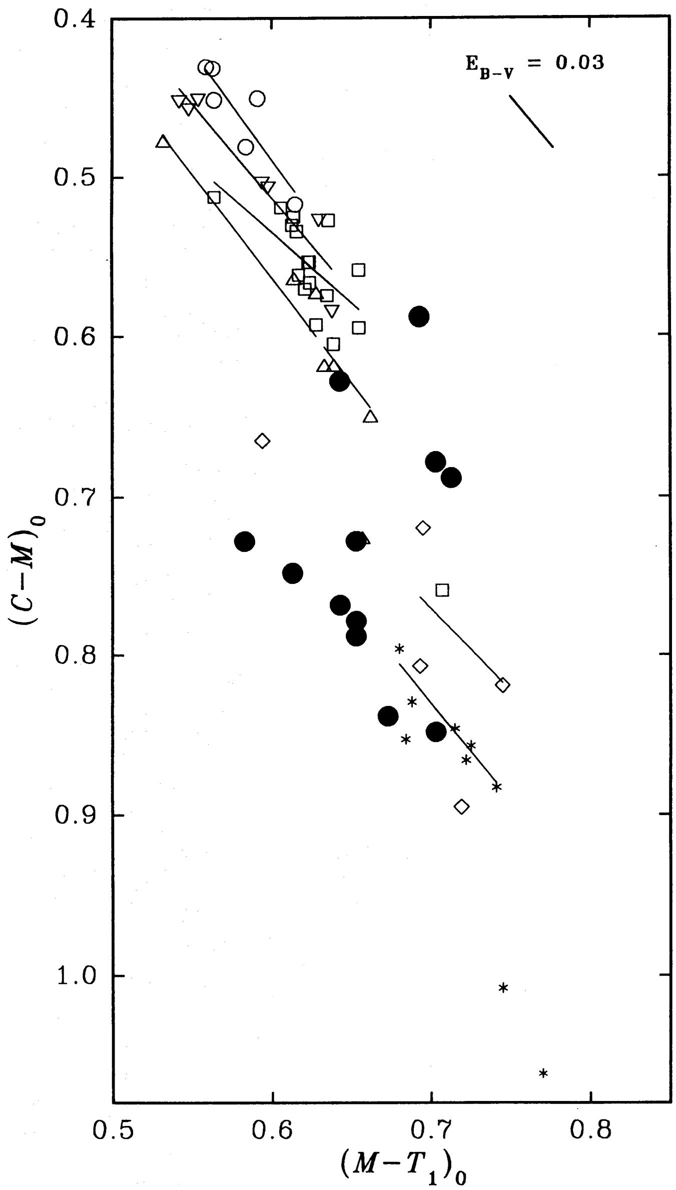

FIG. 2.—$C - M$ vs. $M - T_1$ diagram for the LSB dwarfs (*filled circles*) and Galactic globular clusters. The globulars are divided into six metallicity ranges: *open circles*, $-2.3 \leq$ [Fe/H] < -2.0; *triangles down*, $-2.0 \leq$ [Fe/H] < -1.7; *squares*, $-1.7 \leq$ [Fe/H] < -1.4; *triangles up*, $-1.4 \leq$ [Fe/H] < -1.1; *diamonds*, $-1.1 \leq$ [Fe/H] < -0.8; *asterisks*, $-0.8 \leq$ [Fe/H] < -0.2. For the meaning of straight lines, see text.

Cluster is at variance with observational results (Burstein & Heiles 1982; Ferguson 1993).

Since integrated colors for the dwarfs were derived through the fitting of surface brightness profiles in the different bands instead of employing a diaphragm, and no significative color gradients were found, item 2 above must also be discarded here (and, in any case, as a result of their larger distance compared to Galactic globulars, the dwarfs include a much larger number of red giant stars per unit apparent area, minimizing any statistical variation).

An age effect remains, then, as the most plausible explanation for the deviating branch in Figure 2. Note that within this metallicity range ([Fe/H] $\gtrsim -1.1$) there are no blue HB clusters, and, in any case, the galaxies in the mentioned branch show a spread in colors [$\Delta(C - M) \simeq \Delta(M - T_1) \simeq 0.07$] larger than expected from different HB morphologies alone (see § 4.1). Typical photometric errors

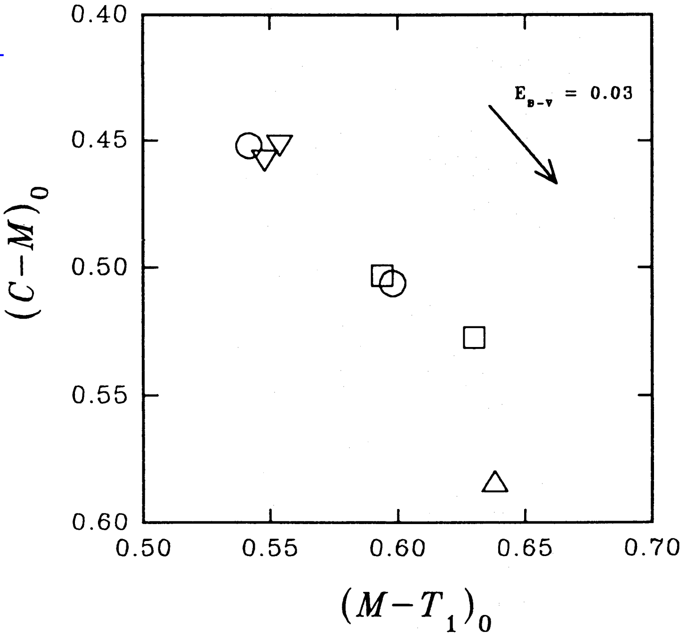

FIG. 3*a*

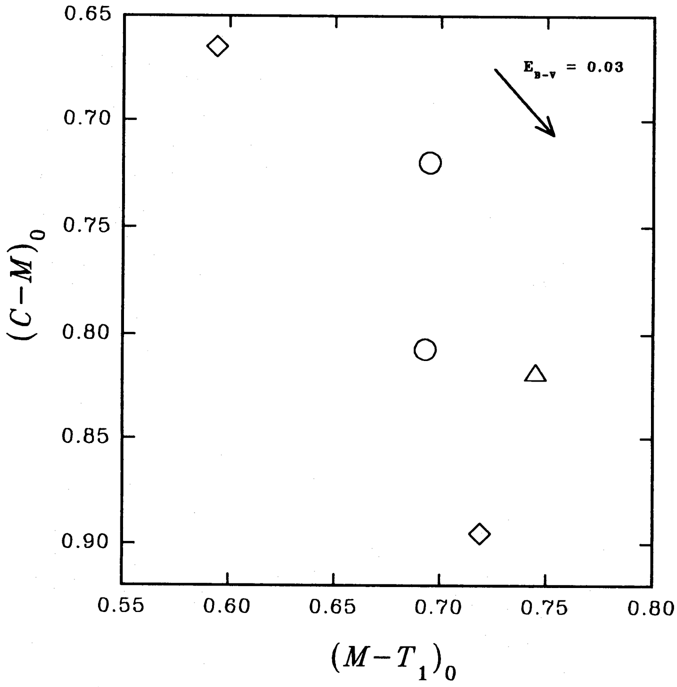

FIG. 3*b*

FIG. 3.—$C - M$ vs. $M - T_1$ diagrams for Galactic globular clusters within two ranges of metallicity: (*a*) $-2.0 \leq$ [Fe/H] < -1.7 and (*b*) $-1.1 \leq$ [Fe/H] < -0.8. Various ranges in reddening are represented with different symbols: *open circles*, $0.0 \leq E_{B-V} < 0.1$; *triangles down*, $0.1 \leq E_{B-V} < 0.2$; *squares*, $0.2 \leq E_{B-V} < 0.3$; *triangles up*, $0.3 \leq E_{B-V} < 0.4$; *diamonds*, $0.4 \leq E_{B-V}$.

TABLE 1

COLOR ERRORS AS A FUNCTION OF LOCAL SURFACE BRIGHTNESS

$S_{(T_1)}$	$\epsilon_{(M-T_1)}$	$\epsilon_{(C-T_1)}$
21.0	0.02	0.02
21.5	0.02	0.03
22.0	0.03	0.03
22.5	0.03	0.03
23.0	0.04	0.03
23.5	0.05	0.05
24.0	0.06	0.07
24.5	0.07	0.09
25.0	0.09	0.12
25.5	0.11	0.16

NOTE.—For these galaxies $B - T_1 \simeq 1.1$; see CFG.

in $M - T_1$ and $C - T_1$ for the dwarfs are given for several isophotal values [$S_{(T_1)}$] in Table 1; the errors in both integrated colors are then expected to be around 0.035 mag. We need then to consider the colors of stellar populations which are younger than those in Galactic globular clusters in order to reproduce the mixes of stars that give the observed colors for the dwarfs.

3.2. *Synthetic Colors*

So far, there is no integrated Washington photometry of stellar systems other than the globulars; to obtain integrated colors of younger stellar populations, we have to synthesize them from observed or theoretical spectra. Each of these alternatives has its own advantages and disadvantages, so we have used them both in a complementary way.

3.2.1. *Theoretical Models*

Evolutionary population synthesis is a commonly used tool in the spectrophotometric study of galaxies. Among the different sets of models now available (see Bruzual 1992 for a recent review), that of Buzzoni (1989, hereafter B89) has several characteristics that make it the most suitable for the present work.

1. Wide spectral coverage, including the four bands (C, M, T_1, T_2) of the Washington system.
2. Metallicities ranging from [Fe/H] $= -2.27$ to [Fe/H] $= 0.23$, and ages between $t = 4 \times 10^9$ and $t = 15 \times 10^9$ yr.
3. Full consideration of all the evolutive stages contributing to the spectra, including HB and post-AGB (asymptotic giant branch) stars.
4. Explicit consideration of different HB morphologies.

B89 computed over 400 models of simple stellar populations (SSPs), although spectral energy distributions are listed for just 10 of them. However, these cover a range in metallicity (although not in age) appropriate for our purpose. Most of the remaining models span similar ranges in [Fe/H] and t, but with different initial mass functions and mass-loss coefficients. The effects on integrated colors of these last two factors are shown to be of second order (Covino et al. 1994), and so we are not involved with them here. Relevant parameters for the selected SSPs are given in Table 2. Columns (1)–(5) are the SSP number, metallicity, helium fraction, age (in units of 10^9 yr), and HB morphology, respectively, taken from Table 7 in B89, while columns (6) and (7) give their $M - T_1$ and $C - T_1$ colors (see § 3.2.3 below).

The fluxes within each bandpass of the Washington system were integrated taking the relative response functions from Canterna & Harris (1979). In order to achieve a homogeneous integration step, the spectra and the response functions were previously interpolated in steps of 1 Å. B89 warns about a UV excess in his spectra, giving an empirical

TABLE 2

PARAMETERS AND COLORS OF SSPs

SSP (1)	[Fe/H] (2)	Y (3)	t (10^9 yr) (4)	HB (5)	$M - T_1$ (6)	$C - T_1$ (7)
1......	−2.27	0.23	15	blue	0.585	1.050
2......	−2.27	0.23	15	intermediate	0.564	1.019
3......	−1.27	0.23	15	intermediate	0.624	1.190
4......	−1.27	0.23	15	red	0.663	1.290
5......	−0.25	0.25	5	red	0.693	1.389
6......	−0.25	0.25	15	red	0.767	1.611
7......	−0.02	0.25	5	red	0.717	1.466
8......	−0.02	0.25	15	red	0.797	1.716
9......	0.23	0.25	5	red	0.734	1.536
10......	0.23	0.25	15	red	0.821	1.811

correction in a subsequent paper (Buzzoni 1995). Since this effect is only relevant for $\lambda < 4000$ Å, it affects the C band, with no effect on either M or T_1. The integrated fluxes within the C band were then corrected in the following way: it was supposed that a constant flux should be subtracted from the spectra for $\lambda < 4000$ Å, and this constant was estimated from the $U - V$ colors listed in B89 and those corrected with the empirical formula in Buzzoni (1995). Typically, the integrated fluxes in C were then ~0.02 mag fainter.

3.2.2. *Observed Spectra*

The main advantage of theoretical spectra is that their input parameters (the relevant ones for this study being metallicity, age, and HB morphology) are well known, allowing one to discriminate their individual effects on integrated colors. However, the set of models here used does not reach ages younger than 5×10^9 yr (see Table 2), while populations as young as $\sim 1 \times 10^9$ yr could be present in some dE's (Thuan 1985), and, as was already noted in § 2, a still younger population is expected in at least one of our galaxies.

Fortunately, this drawback can be overcome. Bica & Alloin (1986) established a base of observed spectra of Galactic open and globular clusters, as well as clusters of different ages in the Magellanic Clouds, covering a considerable area in the age-metallicity plane. The wavelength range of their observations was later enlarged reaching the near-infrared (Bica & Alloin 1987), and, more recently, including the near-ultraviolet (Bica, Alloin, & Schmitt 1994); in this way, the four bands of the Washington system are comprised within this range.

For our purpose of synthesizing broadband colors, it is more convenient to use the template spectra of the groups defined in Bica (1988), instead of individual spectra. Each template is the average of a group of clusters having similar ages and metallicities; their parameters and integrated colors (see § 3.2.3 below) are listed in Table 3, where the designations (col. [1]) G1–G5 correspond to Galactic globular clusters, I1 and I2 are intermediate age populations, and Y1–Y4 are young populations (Galactic open clusters and Magellanic clusters).

Integrated fluxes within the C, M, and T_1 bands were obtained as described in the previous subsection, although obviously no ultraviolet correction was needed in this case.

3.2.3. *Calibration to the Standard System*

The next step is then to calibrate the integrated colors to the standard system. By the time we began this work, only one Washington system standard star, BD +33°2642, had published spectrophotometry available to us (see Oke 1990 for the optical and infrared regions and Bohlin et al. 1990 for the ultraviolet). This is obviously insufficient, so 17 standards with well-determined spectral types and luminosity classes were selected from the lists of Harris & Canterna (1979), and mean spectral energy distributions for stars of the same spectral type and luminosity class were taken from the work of Straižys & Sviderskienė (1972). The spectra of the "mean" stars and that of BD +33°2642 were integrated as described previously, and a slope and a zero point were derived for each color index, $C - M$ and $M - T_1$. The resulting transformation equations are

$$(C - M)_s = (0.235 \pm 0.048) + (0.999 \pm 0.034) \times (C - M)_i , \quad (1a)$$

$$(M - T_1)_s = (1.133 \pm 0.041) + (0.968 \pm 0.021) \times (M - T_1)_i , \quad (1b)$$

where the subindices s and i correspond to "standard" and "integrated," respectively. (HD 2665 was eliminated for the $C - M$ fit.) Table 4 lists the standard stars.

TABLE 3

PARAMETERS AND COLORS OF TEMPLATE SPECTRA

Group (1)	[Fe/H] (2)	t (yr) (3)	$M - T_1$ (4)	$C - T_1$ (5)
Y1........	−0.0	10×10^6	0.571	0.415
Y2........	−0.0	50×10^6	0.302	0.304
Y3a[a]......	−0.0	100×10^6	0.317	0.457
Y3b	−0.0	100×10^6	0.209	0.321
Y4........	−0.0	500×10^6	0.428	0.838
I1........	−0.0	1×10^9	0.694	1.212
I2........	−0.0	3×10^9	0.707	1.464
G1........	+0.0	$>1 \times 10^{10}$	0.817	1.819
G2........	−0.5	$>1 \times 10^{10}$	0.704	1.527
G3........	−1.0	$>1 \times 10^{10}$	0.654	1.274
G4........	−1.5	$>1 \times 10^{10}$	0.624	1.164
G5........	−2.0	$>1 \times 10^{10}$	0.588	1.068

NOTE.—Ages and metallicities are approximate.
[a] Includes contribution from a group of red giants.

TABLE 4

STANDARD STARS

Name	Spectral Type	Luminosity Class
BD +33°2642[a]......	B2	IV
HD 74280	B3	V
HD 4965	A0	V
HD 130109	A0	V
HD 114710..........	G0	V
HD 157881	K7	V
HD 2665	G5	III
SA 92-263	G8	III
SA 102-466	K0	III
HD 104998	K0	III
HD 168322	K0	III
HD 191046	K0	III
SA 98-320	K0	III
SA 114-670	K0	III
SA 96-405	K2	III
HD 97907	K3	III
HD 143107	K3	III
HD 184406	K3	III

[a] Spectrophotometry from Oke 1990 and from Bohlin et al. 1990. The rest are from Straižys & Sviderskienė 1972.

With this calibration, the standard colors of the SSP models and of the template clusters were calculated. However, small systematic differences against the globular clusters colors showed up when placing them in the color-color plot. We compared then the standard colors of groups G1 to G5 with the average colors of sets of clusters with correspondingly similar metallicities, obtaining a good concordance between observed and integrated colors after the corrections $\Delta_{(C-M)} = +0.019$ and $\Delta_{(M-T_1)} = -0.019$ (both well within the expected errors of the fit to the standard system) were added to all the integrated colors.

4. RESULTS

4.1. *Synthesis of the Observed Colors*

So far, we have the colors of the different stellar populations in a homogeneous framework and in coherence with the observations. These colors are listed in columns (6) and (7) of Table 2 for the SSPs, and in columns (4) and (5) of Table 3 for the template clusters. Their location in the $C - T_1$ versus $M - T_1$ diagram, along with that of Galactic globulars and the LSB dwarfs, is shown in Figure 4. (In this figure and in the following one all globular clusters, regardless of their metallicities, are represented with asterisks.) We preferred to use these two color indices (instead of $C - M$ vs. $M - T_1$) for the sake of continuity with CFG, and in order to avoid problems arising from the correlation of errors in the M band (which are usually worse than in T_1).

Figure 4 shows that the 15×10^9 yr old SSP models define a sequence that is determined by metallicity, but which is superimposed to the intermediate age (5×10^9 yr, SSP models 5, 7, and 9) sequence. In this respect, $C - T_1$ and $M - T_1$ are not better than *UBV* colors for disentangling age and metal content effects. The sensitivities of these indices to metallicity and age (within the ranges $[Fe/H] > -0.25$ and $5 \times 10^9 \lesssim t \lesssim 15 \times 10^9$) are $\partial(C - T_1)/\partial[Fe/H] = 0.36$, $\partial(C - T_1)/\partial(\log t) = 0.52$, $\partial(M - T_1)/\partial[Fe/H] = 0.10$, and $\partial(M - T_1)/\partial(\log t) = 0.17$. Therefore, $C - T_1$ and $M - T_1$ are slightly less sensitive, to both metallicity and age, than $U - V$ and $B - V$, respectively (see Buzzoni 1995 for the sensitivity of *UBV* indices).

Besides, it can be seen that, at constant metallicity, HB morphology notably affects the integrated colors. The difference between models SSP 3 (intermediate HB) and SSP 4 (red HB) amounts to 0.10 mag in $C - T_1$ and to 0.04 mag in $M - T_1$, giving again a displacement parallel to the reddening line, in good agreement with the calculations of HC77. It is important to note that the Washington colors of blue-HB models are *redder* than those of intermediate-HB models (see Table 2, SSP 1 and SSP 2). This is the result of a smaller HB contribution to bolometric integrated light from blue-HB clusters compared to red and intermediate-HB ones (B89), and the fact that their contribution is mainly shifted to shorter wavelengths.

Figure 5 repeats the color-color diagram in Figure 4, although limited to the zone occupied by the LSB dwarfs and Galactic globular clusters for clarity. Two features were mentioned in § 3.1:

1. The dwarfs' colors are confined between those of groups G2 and G3.
2. Some of the dwarfs follow the sequence defined by the globulars, but a subset of them forms a divergent branch, toward bluer colors.

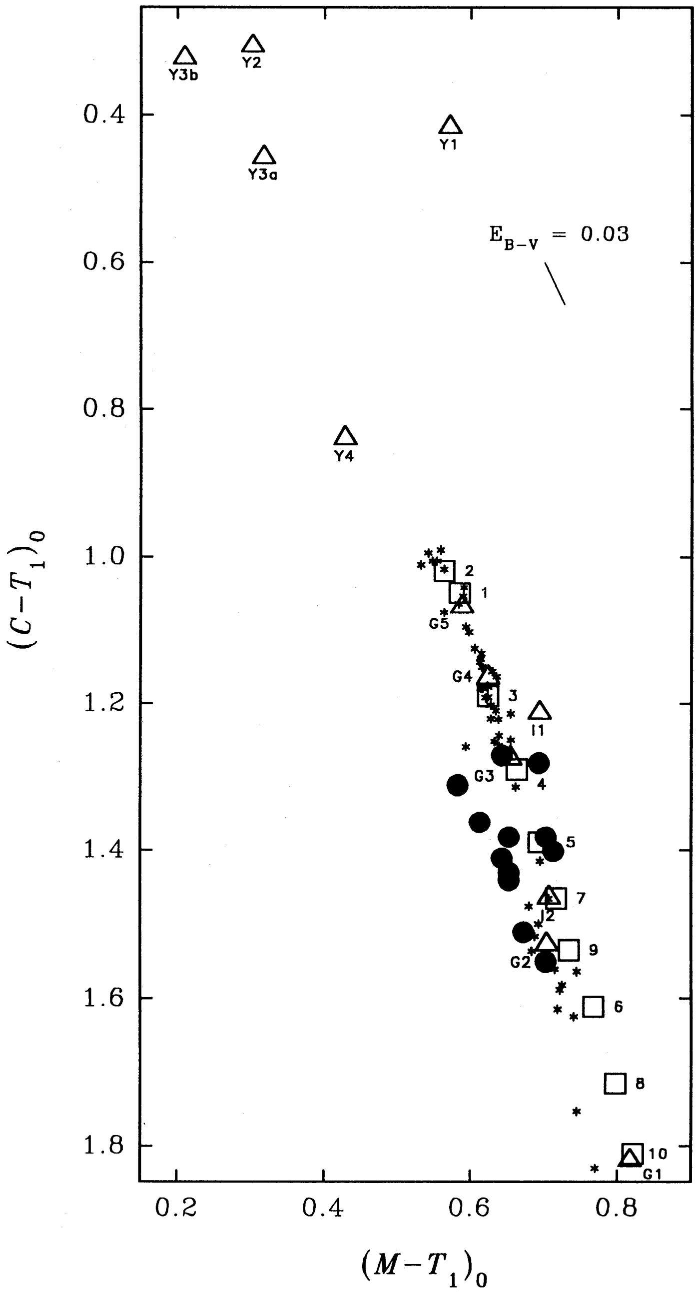

FIG. 4.—$C - T_1$ vs. $M - T_1$ diagram for LSB dwarfs (*filled circles*), Galactic globular clusters (*asterisks*), SSP models (*squares*), and template groups (*triangles*). See Tables 2 and 3 for the identifications of SSP models and template groups, respectively.

The first fact would imply that there are no LSB dwarfs in this sample more metal poor than group G3 ($[Fe/H] \simeq -1.0$). This does not mean that there are no dwarfs poorer than group G3 in Fornax, but, as Figure 13 in CFG suggests, they would be too faint to be included in the present sample. Toward the rich end of the sequence, other factors begin to play. On the one hand, if the metallicity-luminosity relation continues to hold, there should also be a selection effect against the richer (and hence brighter) dwarfs. On the other hand, an object with solar metallicity but with a substantially younger age than the globular clusters should be located in this zone of the diagram (compare the colors of the models SSP 9 and SSP 10, both of solar metallicity, but ages of 15×10^9 and 5×10^9 yr, respectively). However, the available spectroscopic data for the brightest dwarfs in

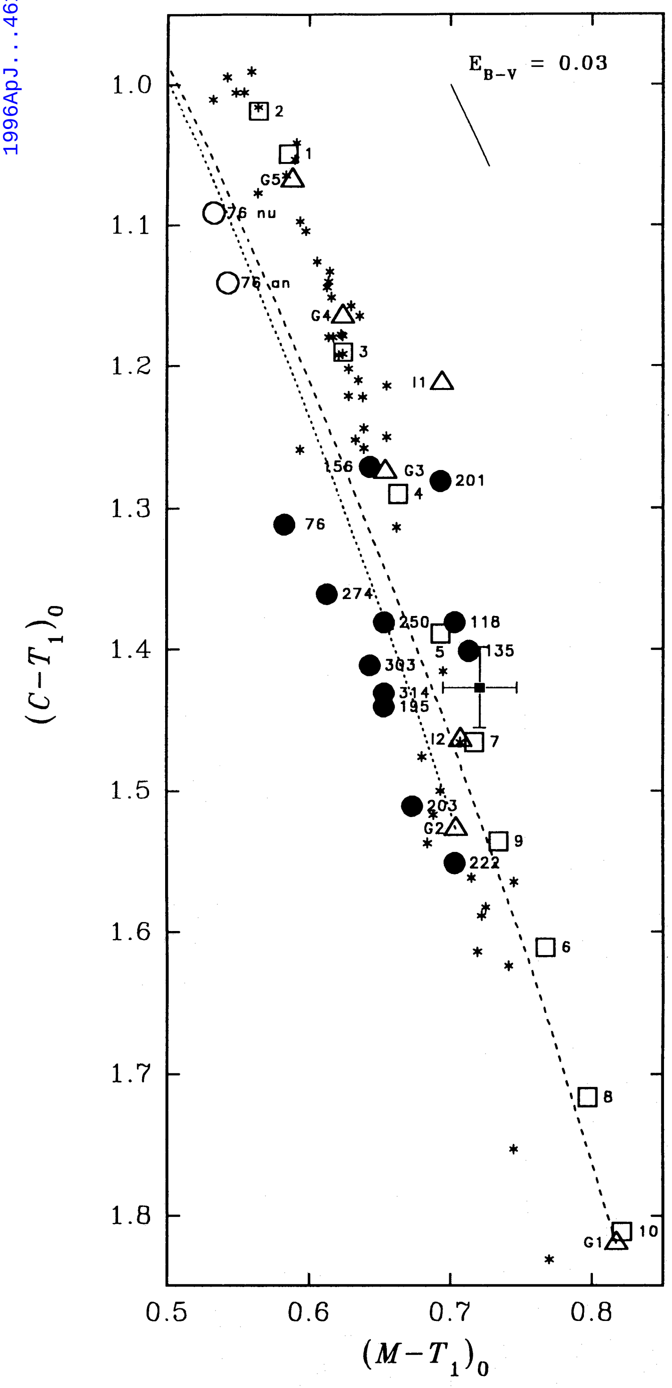

FIG. 5.—Same as Fig. 4, but with a different scale for more clarity. Coding is the same as for Fig. 4, except as follows: open circles are the colors measured in FCC 76 through a central diaphragm ("76 nu") and a surrounding annulus ("76 an"); the small filled square with error bars shows the mean colors (and standard errors of the means) of the outer NGC 1399 globulars. The dwarfs are labeled with their FCC numbers. For the meaning of the dashed and dotted lines, see text.

Fornax completely rule out a solar metallicity (for example, Jones & Jones 1980 obtained moderate metals for FCC 76 and FCC 203, and weak metals for FCC 135 and FCC 222; see also § 4.2 below). Therefore, it can be concluded that the Washington colors of the LSB dwarfs are consistent with a metal content similar to that of moderately rich Galactic globular clusters, in agreement with our first analysis in CFG.

Regarding the deviating branch mentioned above, we said in § 3.1 that a different mean age for each dwarf remains as the most plausible cause for this feature. In order to quantify the effects of a mix of populations of different ages on the integrated colors, we tried to reproduce the observed colors with different combinations of three components: an old population (groups G1–G5), an intermediate population (group I1 and SSPs 5, 7, and 9), and a young population (groups Y1–Y4).

Each of these components was allowed to contribute with a given percent of the monochromatic flux at $\lambda = 5870$ Å (the normalization wavelength for the template spectra). So, starting with a purely old population (say, 100% group G1), the contributions from intermediate and young components were then incremented individually in 10% steps, and the standard colors of each mix were computed. Since the division of the whole metallicity sequence of globular clusters in only five groups prevents a good coverage of the color-color diagram, we interpolated the fluxes for old populations between groups G1 and G2, G2 and G3, etc., and we also used them as the old component in the mixes. We then compared the colors of the LSB dwarf galaxies with those of the different mixes, and, for each galaxy, the mixes whose colors differed by less than a given amount (normally 0.025–0.035 mag, both in $M - T_1$ and in $C - T_1$) from those of the galaxy were selected.

For the dwarfs located on the Galactic globular clusters sequence in Figure 5 (FCC 118, FCC 135, FCC 156, FCC 201, and FCC 250), the results are ambiguous: several hundreds of solutions are possible, although very few of them involve a young population contributing more than 20% in flux. For each of these dwarfs, at least one solution was found with 100% of the flux coming from the old component, or, at worst, with 90% old and 10% intermediate. The natural conclusion is that there are no reasons supporting the existence of a young population in any of these dwarfs.

On the contrary, for the dwarfs located along the blueward diverging sequence, a considerably smaller number of solutions is obtained. All these solutions include an old population comprised between groups G1 and G2 (but always contributing less than 100% for FCC 195, FCC 314, FCC 303, FCC 274, and FCC 76), and, as we move to bluer colors, they have increasing percentages of a young population (always Y4), from 0%–10% for FCC 222 and FCC 203 to 20%–30% for FCC 274 and FCC 76. In particular, the colors measured within a central diaphragm ($r = 4''$) and a surrounding annulus ($4'' < r < 8''$, see CFG) for FCC 76, shown as open circles in Figure 5, need a contribution not lower than 40%–60% and 50% in flux from a young population, respectively. (We are not considering here the effect of the older underlying stellar population included within the diaphragm; note that the knots seen in Fig. 1 are bluer than their surroundings.) These fractions of monochromatic flux can be converted into mass fractions with the equivalences given in Bica, Arimoto, & Alloin (1988). Thus, 10% and 50% contributions in flux at $\lambda = 5870$ Å from a young (Y4) population, correspond to 0.4% and 3.8% in mass fraction, respectively. Therefore, regarding the total mass involved, the dominant population is always that which is $\sim 15 \times 10^9$ yr old.

At this stage, it is useful to remark that we are not pretending to perform any evolutionary model of the dwarfs. The identification of the kind of star formation rate (whether constant or variable, continuous or discontinuous) that has been operating in these galaxies is beyond the scope of this work. We are just showing the presence of a younger population, though we cannot determine its metallicity and therefore whether or not there has been any metal enrichment. This is mainly due to the fact that metallicity effects are less evident in the integrated light of a young population, and so the young and intermediate age groups include a mixture of clusters of different (solar and subsolar) metal content (Bica 1988). This point must be mentioned, since different theoretical models propose the evolution of dwarf galaxies alternatively as closed or as open systems. In the first case, more massive dwarfs should be able to retain part of their enriched interstellar medium after the heating up following the first event of star formation, and subsequent generations of stars can be formed from this material (Larson 1974; Vader 1986). In the second case, slowly moving dwarfs could be accreting intergalactic gas, which had been ejected by the same (or other) dwarf galaxies earlier in the past (Silk, Wyse, & Shields 1987). In this last scenario, the younger population need not be more metal rich than the old one, since its stars may have been formed from gas ejected by a different galaxy.

With this last point in mind, we have drawn in Figure 5 two curves which are obtained by adding increasing fractions of a young population (Y4) to the old populations G1 (*dashes*) and G2 (*dots*), respectively. A rough alignment of the mentioned branch parallel to these curves can be noted. This alignment is quantitatively rather poor, although the difference between observed and synthetic colors is within the expected errors. [It should be noted that if a color excess $E_{(B-V)} = 0.00$ instead of $E_{(B-V)} = 0.03$ is adopted for the Fornax Cluster region, the colors of the dwarfs lie closer to the dotted line, although the fractions of young population needed to reproduce them become smaller.] However, the fact that the colors of the central region of FCC 76, which has independent evidence for a recent burst of star formation, lie at the blue end of the branch strongly supports our conclusion.

Also shown in Figure 5 are the mean colors (error bars correspond to the standard error of the mean for each color) of the outermost globular clusters associated with NGC 1399, the brightest (and almost central) elliptical in Fornax, taken from Ostrov, Geisler, & Forte (1993). Their similarity to the mean colors of the LSB galaxies is remarkable. Note that, as a result of the preceding analysis, the mean colors of the dwarfs' sample become redder if the contribution from the younger population is discounted. In particular, the mean $C - T_1$ values of both populations (the dominant old one in the dwarfs and that of NGC 1399 clusters) are nearly identical. This suggests that both kinds of objects may share a common enrichment history or environmental connection, and it surely deserves further investigation.

4.2. *Comparison with Previous Results*

Our finding of a spread in the mean ages of a sample of LSB dwarf galaxies in Fornax is in qualitative agreement with previous works, which were already mentioned in § 1. However, there is still a quantitative disagreement between spectroscopically derived metallicities and those obtained through the $C - T_1$ calibration used in CFG and this work. CFG pointed out that their [Fe/H] values were higher for two galaxies in common with BH. Two other galaxies have been observed by both CFG and HM: namely, FCC 188 and FCC 296. Again, the abundances derived using several spectral indices are lower than those obtained from our photometry. Unfortunately, these dwarfs are two out of the three that were not included in the present study because of problems with the M images (see § 3.1); however, judging from their $C - T_1$ colors alone, they should lie near FC 222 in Figure 5, i.e., where relatively rich objects with no evidences for a young population are found.

Both HM and BH mention that infrared colors for a sample of Virgo dwarfs are redder than those expected from their spectroscopically derived metallicities, and this fact is tentatively explained with a population of AGB stars in the dwarfs which is not present in the globular clusters used as calibrators. However, should this population exist within our galaxies, it would not strongly affect their $C - T_1$ colors, since its flux contribution blueward of $\lambda \simeq 4000$ Å is negligible compared to the contributions from other stellar components. On the contrary, a prominent AGB occurs only in models with $t \simeq 5$ Gyr which have bluer $C - T_1$ than older (15 Gyr) models with the same metallicity, mainly as a result of a bluer main sequence and a more populated subgiant branch (see B89). In the particular case of carbon stars, it has been shown (Thuan 1985) that Virgo dE's are not as extremely red in $J - H$ as those Magellanic Cloud clusters that do have a population of such red luminous stars.

The metallicities for FCC 188 and FCC 296, according to HM, are [Fe/H] $= -1.20$ and [Fe/H] $= -1.23$ respectively, i.e., intermediate to groups G3 and G4, or close to that of SSPs 3 and 4, while CFG's estimation through the $C - T_1$ calibration gives [Fe/H] $= -0.86$ and [Fe/H] $= -0.79$, respectively. Turning things around, if we accept the lower (spectroscopic) values for the metallicities, these two galaxies are 0.14 mag and 0.18 mag redder in $(C - T_1)_0$, respectively, than expected from the reversion of the mentioned calibration. Note that this difference is too large to be caused purely by a change in HB morphology. Therefore, there is no way of matching the observed $C - T_1$ of FCC 188 and FCC 296 if we accept the [Fe/H] values given in HM, since no stellar mix from our population base can reproduce their colors without increasing the metal abundance.

An appealing alternative is then to speculate that the presence of dust *within* the dwarfs causes their red colors despite their relatively low metallicities. Since the total amount of dust producing this reddening depends strongly on its spatial distribution, a lower limit can be calculated by supposing a foreground layer for each galaxy: this gives $E_{B-V} = 0.07$ and $E_{B-V} = 0.09$ for FCC 188 and FCC 296, respectively, assuming that the reddening ratios for Galactic dust (Harris & Canterna 1979) hold for the interstellar medium (ISM) of the dwarfs. BH observed FCC 303, one of the dwarfs in the blue branch. They obtain [Fe/H] $= -1.23$, close to the CFG value of -1.07, even without considering their large uncertainty (± 0.63). If this galaxy is also affected by an internal reddening similar to the quoted values for FCC 188 and FCC 296, then its new intrinsic colors can now be modeled with a larger fraction of moderately young population ($\sim$30% Y4) superimposed on a slightly poorer old population than that obtained previously in § 4.1. Therefore, our basic conclusions about the presence of relatively young stars in some dE's remain unchanged. We are aware that there is no compelling evidence supporting our assumption of dust within dwarf galaxies; however, it should not be disregarded a priori. We have shown that FCC 76 probably has dust at its center;

again, this galaxy may be an extreme example of the properties shared by other fainter dwarfs.

Finally, we must emphasize that the quoted differences between the metallicities derived by HM and by CFG are within the internal errors of the $C - T_1 - [Fe/H]$ calibration, and in the case of BH's values, the differences are even within their own error margins. What makes the whole effect is the fact that $C - T_1$ gives systematically higher metallicities. In any case, the overlap between the samples is too small to draw any firm conclusions (note also that FCC 188 seems slightly red in $U - B$ for its [Fe/H] in HM's Fig. 5).

4.3. *FCC 76*

This galaxy deserves a few more comments. We have stated in the previous sections that it shows evidence of recent or ongoing star formation at its center. However, though the bluest colors are measured within the central diaphragm, the whole galaxy is still very blue for its total magnitude. This fact indicates that a moderately young population is distributed throughout the whole spheroid. The same is true for the rest of the dwarfs in the blueward diverging branch in Figure 5; the difference with FCC 76 is that (presumably because of its larger mass) it has managed to retain some gas and dust at its center, then sustaining a star formation process.

CFG pointed out that no meaningful gradients could be detected in any of their dwarfs except for the central zone of FCC 76, which gets bluer with decreasing radius. However, a more careful analysis of its color profiles shows that a small gradient could be present also in its outer regions, where the galaxy becomes bluer with increasing radius (see also Fig. 1). Though similar small gradients in other dwarfs are attributed in CFG to observational errors, the relative high signal-to-noise ratio attained in FCC 76 permits one to state with some confidence that such a gradient is real. In this case, the more probable scenario is that the outward blueing of this galaxy is the result of a decrease of metallicity with increasing radius, a feature normally present in bright ellipticals.

An object with similar characteristics to FCC 76 is known in the Local Group: NGC 205, the dE companion to M31. Some 100 O and B stars have been resolved at its center, and H I and a few dust clouds have also been detected, while the underlying distribution of stars corresponds to an old, metal-poor population (Hodge 1989). Peletier (1993) finds color gradients in this galaxy which are qualitatively identical to those we find in FCC 76. The absolute blue magnitude estimated for FCC 76 in CFG is $M_B = -16.6$, while that of NGC 205 is $M_B = -15.6$; NGC 205 is then fainter than FCC 76, though both galaxies are strikingly similar when the distributions of their stellar populations are considered.

In addition, the Virgo dwarf M100-D5 is known to have a blue nucleus (Vigroux et al. 1984). This galaxy is fainter ($M_B = -15.1$) than both NGC 205 and FCC 76; if only more luminous (massive) dwarfs are able to retain sufficient gas and dust in order to go on making stars at their centers, then M100-D5 is setting the lower limit.

5. CONCLUSIONS

Under the assumption that a globular cluster–like stellar population is the dominant component in low surface brightness dwarf galaxies, the Washington indices suggest a range of metallicities between low and moderate values. However, single age populations are not suitable to match the behavior of the whole sample.

In some galaxies the presence of moderately young populations can be inferred from photometric indices but, in others, it is morphologically evident. FCC 76 is a good example of this situation, showing bright blue knots in the nuclear region. If these structures would eventually evolve and transform the galaxy into a *nucleated* object is an open question, however. In any case, it seems that the star-forming process is not constrained to the central region.

A comparison of our photometrically derived metallicities with some (yet scarce) spectroscopic values, however, shows that some discrepancies remain. The color discrepancy is hard to explain with any luminous red giant branch (RGB) or AGB population, or with variations in the HB morphology. The presence of dust (not taken into account in our models) might solve the problem.

From the statistical point of view, it is remarkable that the average $C - T_1$ color of our LSB sample is so similar to the value corresponding to the outer globular cluster population associated with NGC 1399, one of the dominant ellipticals in the Fornax Cluster. This coincidence deserves further attention, as we know that selection effects could be present in the LSB average color as a result of the surface brightness criteria used in conforming the sample, but at first sight, it suggests a similar metallicity enrichment in both populations. Recent results (Grillmair et al. 1994), on the other side, dispute the membership of (at least part of) the globulars in NGC 1399 and point to an association of these systems with the Fornax Cluster (and then with the LSBs) as a whole.

Finally, we want to stress that the results presented in this paper restricted to a small number of objects, justify a larger survey in Fornax oriented toward detecting environmental effects within the cluster and affecting both structural and photometric features.

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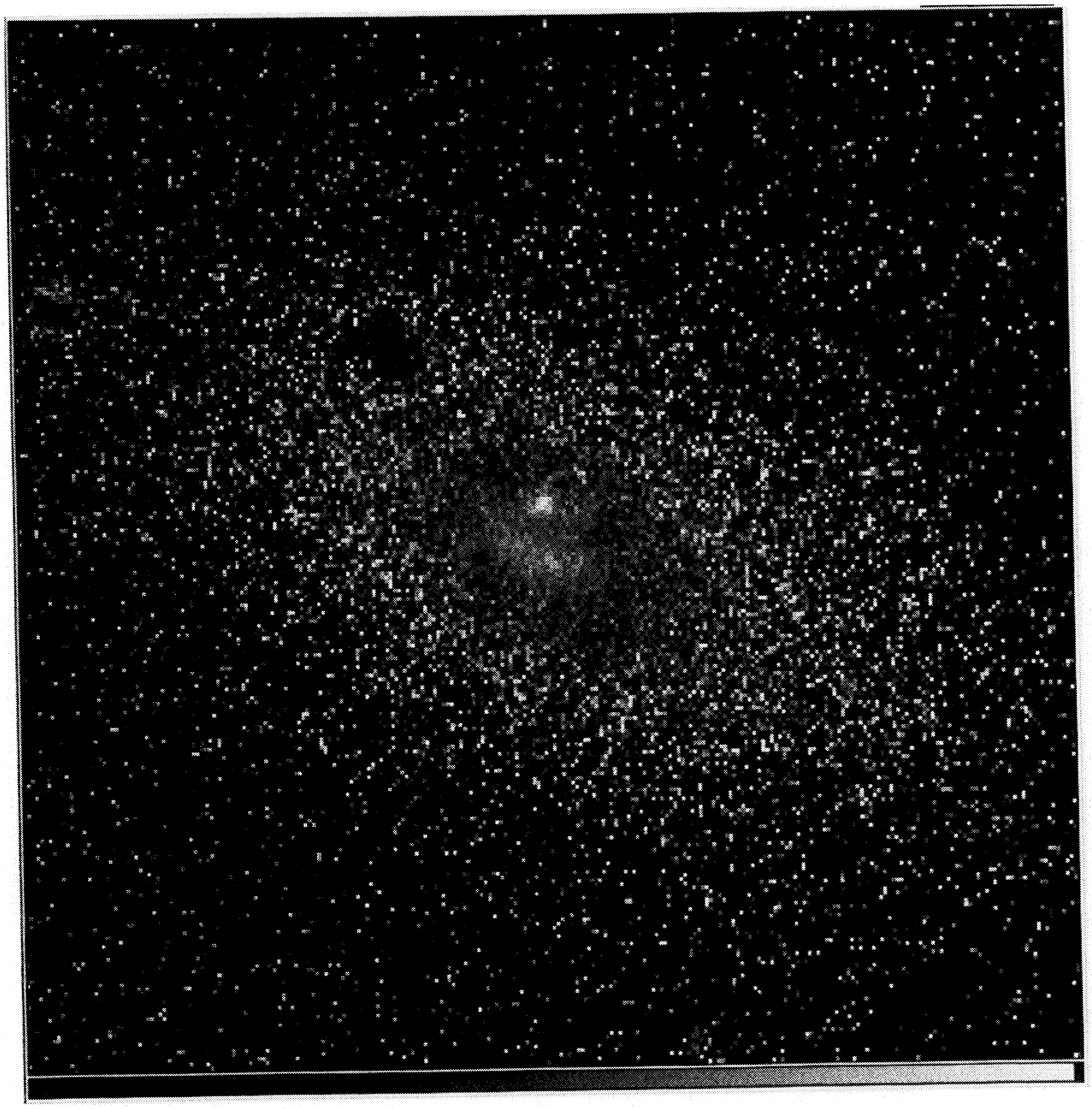

FIG. 1.—$C - T_1$ color map of FCC 76. North is up and east to the left; the field is 2′ on each side. Lighter gray levels correspond to bluer pixels in $C - T_1$.

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