VIRGO CLUSTER EARLY-TYPE DWARF GALAXIES WITH THE SLOAN DIGITAL SKY SURVEY. II. EARLY-TYPE DWARFS WITH CENTRAL STAR FORMATION

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ABSTRACT

Despite the common picture of an early-type dwarf galaxy (dE) as a quiescent galaxy with no star formation and little gas, we identify 23 dEs that have blue central colors caused by recent or ongoing star formation in our sample of 476 Virgo Cluster dEs. In addition, 14 objects that were mostly classified as (candidate) blue compact dwarfs have similar properties. Among the certain cluster members, the dEs with blue centers reach a fraction of more than 15% of the dE population at brighter ($m_B \leq 16$) magnitudes. A spectral analysis of the centers of 16 galaxies reveals in all cases an underlying old population that dominates the mass, with $M_{\text{old}} \geq 90\%$ for all but one object. Therefore, the majority of these galaxies will appear like ordinary dEs within approximately one gigayear or less after the last episode of star formation. Their overall gas content is less than that of dwarf irregular galaxies but higher than that of ordinary dEs. Their flattening distribution suggests the shape of a thick disk, similar to what has been found for dEs with disk features in Paper I of this series. Their projected spatial distribution shows no central clustering, and their distribution with projected local density follows that of irregular galaxies, indicative of an unrelaxed population. This is corroborated by their velocity distribution, which displays two side peaks characteristic of recent infall. We discuss possible formation mechanisms (ram-pressure stripping, tidally induced star formation, and harassment) that might be able to explain both the disk shape and the central star formation of the dEs with blue centers.

Key words: galaxies: clusters: individual (Virgo) — galaxies: dwarf — galaxies: evolution — galaxies: fundamental parameters — galaxies: stellar content — galaxies: structure

Online material: color figure

1. INTRODUCTION

Early-type dwarf galaxies are the most numerous type of galaxy in clusters, suggesting that the vigorous forces acting within a cluster environment might actually be creating them. At least theoretically, this could come about via a morphological transformation of infalling galaxies, such as, e.g., ram pressure stripping of irregular galaxies (Gunn & Gott 1972) or the so-called harassment of late-type spiral galaxies (Moore et al. 1996). While these scenarios would in principle also be able to explain the famous morphology-density relation (e.g., Dressler 1980), unambiguous observational proofs are difficult to obtain. Early-type dwarf galaxies are characterized by their smooth, regular appearance, while any possible progenitor galaxy probably displays a different overall structure, before a morphological transformation occurs. Moreover, early-type dwarf galaxies themselves are not a homogeneous class of objects. In addition to the classical dwarf elliptical galaxies, Sandage & Binggeli (1984) introduced the class of dwarf S0 (dS0) galaxies, which were conjectured to have disk components based on indications like high flattening or a bulge-disk-like profile (Binggeli & Cameron 1991). Following up on the discovery of spiral structure in an early-type dwarf galaxy (Jerjen et al. 2000) and on similar other discoveries, we identified 41 Virgo Cluster early-type dwarf galaxies with disk features in Lisker et al. (2006, hereafter Paper I) and argued that they constitute a population of disk-shaped objects. Furthermore, nucleated and nonnucleated dwarf elliptical galaxies show significantly different clustering properties (Binggeli et al. 1987) and flattening distributions (Ryden & Terndrup 1994; Binggeli & Popescu 1995).

Aside from this structural heterogeneity, color differences have been reported as well (Rakos & Schombert 2004; Lisker et al. 2005), hinting at a range of stellar populations in early-type dwarf galaxies. While the classical dwarf elliptical galaxies are typically considered not to have recent or ongoing star formation and no significant gas or dust content (e.g., Grebel 2001; Conselice et al. 2003), the well-known Local Group galaxy NGC 205 constitutes a prominent example of an early-type dwarf galaxy that does exhibit central star formation, gas, and dust (Hodge 1973). More examples are NGC 185 (Hodge 1963) and the apparently isolated galaxy IC 225 (Gu et al. 2006). Furthermore, Conselice et al. (2003) report a 15% H I detection rate for early-type dwarf galaxies in the Virgo Cluster. All these objects are morphologically early-type dwarf galaxies but form a heterogeneous family of objects, which we assign the common abbreviation “dE,” thereby including galaxies classified as dwarf elliptical or dS0 galaxies.

Based on the general idea of gas removal due to effects like ram pressure stripping, numerous observational studies have focused on comparing the properties of gas-rich dwarf irregular galaxies (dIrrs) and gas-poor dEs and dwarf spheroidal galaxies (dSphs), attempting to confirm or reject a possible evolutionary relationship between them. Thuan (1985) found in his study of optical–near-infrared colors the metallicity ranges of dIrrs and Virgo dEs to be “mutually exclusive.” In their spectroscopic analysis of oxygen abundances of planetary nebulae in Local Group dEs and dSphs, Richer et al. (1998) also found a significant offset to the respective abundances of dIrrs. Similarly, Grebel et al. (2003) recently showed for the Local Group that this metallicity difference exists even when considering only the respective old stellar populations of dIrrs and dSphs, indicative of more intense star formation and enrichment in dSphs. Thuan (1985) and Binggeli (1985) also noted that many Virgo dEs are nucleated, while none of the dIrrs are. Bothun et al. (1986) concluded that Virgo dIrrs would have to fade by $\sim 1.5$ mag in $B$ to fall into the
optical–near-infrared color range of dEs. However, the bulk of faded dIrrs would then have an effective surface brightness \( I_{B,v} > 25 \) mag arcsec\(^{-2}\), substantially lower than the observed values of dEs.

Despite these counterarguments, potential dIrr/dE “transition types” have frequently been discussed (e.g., Ferguson & Binggeli 1994; Johnson et al. 1997; Knezek et al. 1999). Recently, van Zee et al. (2004) pointed out the “remarkable commonality” between dEs and dIrrs with respect to their surface brightness distributions and metallicity-luminosity relations. These authors found significant rotation in several bright dEs, on which they base their discussion about the possibility that these very dEs may have formed via ram pressure stripping of dIrrs. While van Zee et al. (2004) admitted that dEs (in Virgo) might actually form through various processes, they argued that every dE must have been gas-rich and star-forming in the past and would thus inevitably have been classified as dIrr. However, these properties also apply to blue compact dwarf (BCD) galaxies, which have often been discussed in the literature as potential dE progenitors.

An important difference between dIrrs and BCDs was highlighted by Bothun et al. (1986), who characterized dIrrs as an “odd combination of rather blue colors, yet quite low surface brightness,” indicative of a low surface mass density. In contrast, BCDs have a much higher surface brightness, suggesting a higher surface mass density, since they are not bluer than the dIrrs. Whether or not BCDs could indeed be the gas-rich, star-forming progenitors of dEs has been discussed controversially (e.g., Bothun et al. 1986; Drinkwater et al. 1996; Guzman et al. 1996; Papaderos et al. 1996). A glance at the color images \(^1\) of Virgo Cluster galaxies that were classified as (candidate) BCDs reveals what might be one reason for this controversy: these objects do not constitute a homogeneous class but vary strongly in size, (ir)regularity, and the fraction of area dominated by blue light with respect to the total area of the galaxy. It might thus be more promising to simply look for plausible dE progenitors among the BCDs instead of attempting to draw conclusions about this class as a whole.

Interestingly, Bothun et al. (1986) mentioned that the BCDs in their sample look similar to NGC 205. Could dEs with central star formation thus bridge the evolutionary gap from quiescent dEs to potentially star-bursting progenitors? To our knowledge, Vigroux et al. (1984) were the first to identify a central star formation region in a dwarf elliptical galaxy outside the Local Group. Recently, Gu et al. (2006) presented a similar dE with ongoing star formation in its center. In Paper I of this series (Lisker et al. 2006), we identified nine Virgo early-type dwarf galaxies with central irregularities likely to be caused by dust or gas and found that all of them have a blue center. In the present paper we follow up on these objects and systematically search the Virgo Cluster for such dEs with blue centers. This is made possible by the publicly available data of the Sloan Digital Sky Survey (SDSS) Data Release 4 (DR4; Adelman-McCarthy et al. 2006), which covers almost the whole Virgo Cluster with multiband optical imaging and partly with spectroscopy. Our data and sample are described in §§ 2 and 3, respectively. Results from image analysis are presented in § 4, followed by the spectral analysis in § 5. Section 6 focuses on the gas content of our galaxies. The systematic properties of dEs with blue centers are given in § 7. Their evolutionary role is discussed in § 8, followed by a summary and outlook in § 9.

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1 Using the SDSS Image List Tool at http://cas.sdss.org/astro/en/tools/chart/list.asp created by J. Gray et al.
provided by the SDSS, and by the following studies: Binggeli et al. (1985, 1993), de Vaucouleurs et al. (1991), Strauss et al. (1992), Young & Currie (1995), Drinkwater et al. (1996), Grogin et al. (1998), Falco et al. (1999), Gavazzi et al. (2000), van Driel et al. (2000), Conselice et al. (2001), Simien & Prugniel (2002), Caldwell et al. (2003), Geha et al. (2003), and Gavazzi et al. (2004).

Four of these galaxies, however, have velocities above 6000 km s\(^{-1}\) from recent data (SDSS and Conselice et al. 2001). Since the velocities of known Virgo Cluster members are lower by more than a factor of 2, we change the membership status of these galaxies (VCC 0401, VCC 0838, VCC 1111, and VCC 1517) to “possible member.” This leaves us with a subsample of 194 dEs that are certain cluster members and for which radial velocity measurements are available.

3. SAMPLE

3.1. Sample Selection

In Paper I of this series, we put together a sample of Virgo Cluster dEs that comprises all dEs with \(m_B \leq 18.0\) mag that are listed in the VCC, that are covered by the SDSS, and that are certain or possible cluster members according to Binggeli et al. (1985, 1993). While objects with uncertainties were initially included, we then excluded all galaxies that appeared to be possible dIrrs due to asymmetric shapes. Objects classified as “dE/dIrr” were not included. Twenty-five galaxies classified as (candidate) dEs in the VCC are not covered by the SDSS DR4. The resulting sample comprises 476 early-type dwarf galaxies, 410 of which are certain cluster members (see § 2.3). Note that our magnitude limit of \(m_B \leq 18.0\) mag corresponds to the magnitude up to which the VCC was found to be complete (Binggeli et al. 1985). With a distance modulus of \(m - M = 31.0\) mag, this translates into \(M_B \approx -13.0\) mag.

In this sample, we identified several dEs with irregular or clumpy central features likely caused by gas and dust (cf. Fig. 6 of Paper I). By dividing the background-subtracted aligned \(g\) - and \(i\)-band images provided by Paper I, we obtain color maps that are not calibrated yet are useful to look for significant color gradients. Most of the objects just described have a central region whose color is clearly bluer than that of the rest of the galaxy, similar to

![Fig. 1.](image)
the dE recently presented by Gu et al. (2006). Using these color maps, we visually searched all 476 early-type dwarf galaxies that were presented in Paper I for such a blue center. As a complementary check we then examined the radial $g - i$ color profiles (§ 4.1) of the thus-selected galaxies to confirm the presence of a clear color gradient.

Twenty-three out of 476 dEs (16 out of 410 certain cluster members) entered our working sample of galaxies with blue centers (Figs. 1–3). We term these objects "dE(bc)s." Note that the presence of weak color gradients (either negative or positive) in dEs has been reported in the literature (e.g., Gavazzi et al. 2005). Such objects are not the focus of this study; we instead aim at dEs with a blue center, i.e., a significant positive gradient. The distinction between a weak and a significant gradient might appear somewhat arbitrary; however, a detailed and quantitative study of color gradients of our full dE sample is beyond the scope of this paper and will be presented elsewhere. The weakest gradient visually selected by us is that of VCC 0308, with a color

Fig. 2.—Same as Fig. 1.
difference of 0.1 mag between the inner and outer regions (see Fig. 2).

We point out that the dE(bc)s were morphologically classified as dwarf elliptical galaxies or dS0s by Sandage & Binggeli (1984) and were confirmed as early-type dwarf galaxies in our Paper I. While Ferrarese et al. (2006) suggest the reclassification of four dE(bc)s as dE/dIrr based on their blue central colors and irregular isophotal shapes in the center, we do not use color as a criterion for morphological classification. The central irregularities are the reason they were assigned to the class dS0 (Binggeli & Cameron 1991), but their overall appearance is smooth and regular, as can be seen from the combined images (Figs. 1–3). Complementary to these, we show isophotal contours of the dE(bc)s in Figure 4 (see § 4.1). There, the central irregularities in several dE(bc)s can be seen, which are also revealed by the unsharp mask images. Outside of the central region, however, the isophotes are regularly shaped, confirming the early-type dwarf morphology of these galaxies.
Our preselection of dEs relies on the classification given in the VCC and on the subsequent examination of the combined images in Paper I. However, the initial selection was based on photographic plates, which are most sensitive to the blue light. Therefore, if the color distribution of a candidate dE(bc) would be quite asymmetric or if the blue central region would make up for a rather large fraction of the total light, this galaxy might not have been classified as dE in the first place. We thus decided to use the color-combined images provided by the SDSS Image List Tool to search all objects classified as dIrr or BCD (including candidates) for galaxies that look similar to the dE(bc)s, i.e., that have a regular outer shape and a color similar to the dEs while having a blue inner region. We found 12 such objects (10 certain cluster members). Furthermore, two galaxies classified as E/S0 with magnitudes similar to the brighter dEs show the same appearance; both are certain cluster members. Images and color profiles of these additional galaxies are presented in Figures 5 and 6, and their isophotal contours are shown in Figure 7.

2 Note that the dE(bc)s identified above were classified as dE despite having been observed in blue light, in which the light of young stars, if present, dominates.

3 See http://cas.sdss.org/astro/en/tools/chart/list.asp.
To ensure that we are not mixing different types of galaxies, we use separate samples of objects in the course of our study: the main sample comprising the 23 galaxies classified as dE that have a blue center and an additional sample comprising the 14 galaxies classified other than dE that are similar in appearance to the dE(bc)s. Table 1 lists our selected objects along with their classification.

Fig. 5.—Galaxies similar to the dE(bc)s; same as Fig. 1, but for the galaxies of the additional sample, which were not classified as dEs but were chosen by us as being similar. The two left galaxies in the top row were classified as E or S0; the top right galaxy was classified as irregular. All other objects here and in Fig. 6 were classified as (candidate) BCDs and are sorted according to the shape of the color gradient, analogous to Figs. 1–3.

3.2. Presence of Disks

In Paper I we presented a systematic search for disk features in Virgo Cluster dEs, which we detected in 41 out of 476 objects (including candidates). We showed that these galaxies, termed dE(di)s, are not simply dwarf elliptical galaxies that just have an embedded disk component but appear to be instead a population
Fig. 6.—Same as Fig. 5.

Fig. 7.—Isophotal contours of the additional sample; like Fig. 4, but for the galaxies of the additional sample, which are shown in the same order as in Figs. 5 and 6.
of genuine disk galaxies, i.e., flat oblate objects. Among the 23 dE(bc)s of our main sample, five are (candidate) dE(di)s, or 4 out of 16 if only certain cluster members are counted. The fraction of dE(di)s among the full dE sample is roughly about 25% at the median B magnitude of the dE(bc)s (14.86, again counting only certain cluster members). In a randomly chosen sample of 4 out of 16 if only certain cluster members are counted. The fraction of dE(di)s among the full dE sample is roughly about 25% at the median B magnitude of the dE(bc)s (14.86, again counting only certain cluster members). In a randomly chosen sample of 4 out of 16 if only certain cluster members are counted. The fraction of dE(di)s among the full dE sample is roughly about 25% at the median B magnitude of the dE(bc)s (14.86, again counting only certain cluster members).

### 4. IMAGE ANALYSIS

#### 4.1. Techniques

The study presented in Paper I provides us with background-subtracted, aligned $g$, $r$, and $i$-band images; a combined image; unsharp masks; and an elliptical aperture for each object. A detailed description can be found in Paper I. Briefly, combined images were obtained by co-adding the $g$, $r$, and $i$-band images to increase the S/N. From these we produced unsharp masks with various kernel sizes (using IRAF4 *gauss*; Tody 1993), as well as

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**Notes.**—Cluster membership (column “Mem.”) is provided by Binggeli et al. (1985, 1993); M, certain cluster member; P, possible member. Classification is as in the VCC, except for VCC 1488, which has been reclassified as a probable dE by Geha et al. (2003) (former class E6:). VCC 1175 belongs to the M32-like compact elliptical galaxies (Binggeli et al. 1985). Notes in the last column are as follows: D, disk identified in Paper I; D1s, certain disk with spiral arms; D2, probable disk; D3, possible disk; S, useful spectrum available; H, emission; H, detection reported by Boselli et al. (2002) (only given if H, is not detected in the SDSS spectrum or if no spectrum was available). Units of right ascension are hours, minutes, and seconds, and units of declination are degrees, arcminutes, and arcseconds.
isophotal contour diagrams (using IRAF newcont). An elliptical aperture for each galaxy was determined by performing ellipse fits with IRAF ellipse on the combined image and then choosing by eye one of the outer elliptical isophotes to best trace the outer shape of the galaxy. This isophote was usually between 1 and 2 half-light radii.

The SDSS flux calibration was applied to the aligned \( g \) and \( i \)-band images for each source, following the instructions on the SDSS Web site.\(^6\) These images were then divided by each other, converted into magnitudes, and corrected for Galactic extinction (Schlegel et al. 1998), yielding proper \( g - i \) color maps. From the same images we obtained radial intensity profiles by azimuthally averaging over elliptical annuli with IRAF ellipse. We used geometric steps (i.e., steps that increase by a constant factor) and a fixed position angle, ellipticity, center, and semimajor axis. The ratio of the \( g \) and \( i \)-band fluxes was then converted into magnitudes, yielding radial \( g - i \) color profiles, where radius is calculated from semimajor \((a)\) and semiminor \((b)\) axes as \((ab)^{1/2}\). Disturbing foreground stars and background galaxies were masked prior to profile calculation.

4.2. Results from the Image Analysis

In Figures 1–3, 5, and 6 we present for each galaxy the radial color profile, the combined image, the unsharp mask created with a Gaussian filter with \( \sigma = 4 \) pixels, and the color map. The color profiles contain two types of errors: the black error bars give the uncertainty calculated from the S/N only, whereas the gray error bars represent the azimuthal variation of the color at the respective radius (which, of course, includes S/N effects). A color distribution that is not symmetric with respect to the galaxy center (e.g., in VCC 1617; see Fig. 2) or is somewhat irregular (e.g., in VCC 0170; see Fig. 1) leads to an azimuthal variation of color significantly larger than the uncertainty from S/N only.

In many cases the unsharp masks reveal central irregularities likely caused by gas and dust features or by asymmetric star-forming regions. On average, the central irregularities are stronger and the blue central regions are larger for galaxies of the additional sample as compared to those of the main sample.

Obviously, some galaxies have a relatively constant outer color and abruptly start to become bluer when going inward (e.g., VCC 0173), while others display a gradual color change from the outer regions to the center (e.g., VCC 1501). Although it is not always unambiguous which of the two cases applies to an object, we attempted to sort the \( \delta \text{E}(bc)\)s in Figures 1–3, as well as the (candidate) BCDs of the additional sample in Figures 5 and 6, according to the color profile shape, starting with those that have a constant outer color until a steep gradient sets in abruptly, to those with a smooth gradient. We found no correlations of this profile shape with either magnitude, radius, or surface brightness.

In order to compare the \( g - i \) colors of the \( \delta \text{E}(bc)\)s with those of “ordinary” \( \delta \text{Es}, \) we make use of the colors computed by Lisker et al. (2005) for 228 galaxies of our full \( \delta \text{E} \) sample, excluding \( \delta \text{E}(bc)\). Those colors were derived from aperture photometry on the SDSS images, using circular apertures with a radius equaling the half-light radius. We performed a linear fit to the color-magnitude relation of \( B \) magnitude versus \( g - i \) color, yielding an average \( \delta \text{E} \) color for each magnitude with a standard deviation of 0.06 mag. These values are shown in Figures 1–3, 5, and 6 for each galaxy: the gray-shaded bands enclose the 2 \( \sigma \) range of color at each galaxy’s magnitude. For most galaxies, the outer color is still bluer than the typical \( \delta \text{E} \) color; for several objects it is even bluer than the 2 \( \sigma \) range. Note that the above fit has been performed on \( \delta \text{Es} \) computed within the half-light radius; however, no strong gradient is to be expected, since all \( \delta \text{E}(bc)\)s have been excluded from the fit. Thus, the relatively blue outer colors of the \( \delta \text{E}(bc)\)s could hint at a younger age of the \( \delta \text{E}(bc)\)s as a whole, a lower metallicity, or a shorter time since the last star formation activity in the outer regions as compared to ordinary \( \delta \text{Es} \). A spectroscopic examination of the stellar content of the \( \delta \text{E}(bc)\)s is possible, at least for the centers of several galaxies, as presented in § 5.

5. SPECTRAL ANALYSIS

In order to explore the stellar content of our objects, we examine integrated spectra from the SDSS DR4 as described in § 2.2. These are taken with fibers of diameter 3′, corresponding to a physical size of 231 pc at a distance \( d = 15.85 \) Mpc. Ten such spectra are available for the main \( \delta \text{E}(bc) \) sample, one of which (VCC 0046) proved too noisy for a stellar population analysis. Seven spectra are available for the additional sample. These 16 galaxies are labeled in the last column of Table 1 with “S.” Six \( \delta \text{E}(bc)\)s of the main sample and six galaxies of the additional sample display Balmer line emission (see Table 1). One more \( \delta \text{E}(bc) \) of the main sample and three galaxies of the additional sample are fitted to synthetic composite stellar populations’ spectra. Sim-ilar methods have already been employed by Cid Fernandes et al. (2003), Kong et al. (2003), Westera et al. (2004), and Gu et al. (2006); the latter describe a \( \delta \text{E} \) with a blue center very similar to our objects.

5.1. Synthetic Stellar Populations

The synthetic composite stellar populations were composed using simple stellar population (SSP) spectra from three different libraries of SSPs. The first SSP library (hereafter the BC99 library) was produced using the Galaxy Isochrone Spectral Evolution Library (GISSEL) code (Charlot & Bruzual 1991; Bruzual & Charlot 1993; A. G. Bruzual & S. Charlot 2000, private communication), implementing the Padova 2000 isochrones (Girardi et al. 2000) combined with the BaSeL 3.1 “Padova 2000” stellar library (Westera et al. 2002; Westera 2001, p. 378). The second SSP library, “Starburst,” consists of spectra from the Starburst99 data package (Leitherer et al. 1999) including nebular continuum emission (Fig. 1 on the Starburst99 Web site).\(^6\) It implements the BaSeL 2.2 library (Lejeune et al. 1997, 1998), and for stars with strong mass loss it also takes into account extended model atmospheres by Schmutz et al. (1992) combined with the Geneva isochrones (Meynet et al. 1994; Schaller et al. 1992; Schaerer et al. 1993a, 1993b; Charbonnel et al. 1993). For old populations, the BC99 spectrum was used, since the Starburst99 data package only contains spectra up to 900 Myr. In addition to these two libraries, we also used a library with higher spectral resolution, the BC03 library, produced by employing the 2003 version of the GISSEL code (Bruzual & Charlot 2003) and the Padova 1995 isochrones (Fagotto et al. 1994;...
Girardi et al. (1996) combined with the STELIB (Le Borgne et al. 2003) stellar library. The nebular continuum emission was also added to the spectra in the BC99 and BC03 libraries, in the same way as described by Leitherer et al. (1999).

5.2. Fit to Model Spectra: Procedure

The spectra cover a wavelength range of around 3820–9200 Å, but the wavelength region above 8570 Å is too much affected by telluric lines, so we fit the full spectra from 3820 to 8570 Å, except for those various parts of the spectra showing “contamination” from different emission and/or telluric line sources. Table 2 lists all the regions that were omitted.

We corrected the spectra for redshift and for Galactic foreground extinction using the values from Schlegel et al. (1998) and the extinction law of Fluks et al. (1994). In the eight cases with Hα and Hβ emission we also corrected for internal gas extinction, again using the Fluks et al. extinction law. The extinction constants $E(B-V) = A_V/3.266$ were estimated from the Hα/Hβ Balmer decrements following Torres-Peimbert et al. (1989), adopting intrinsic ratios of the emission-line fluxes $I_{Hα}/I_{Hβ} = 2.87$ (Osterbrock 1989). In order to properly determine the emission-line strengths, we first had to remove the contribution from the absorption lines of the underlying stellar populations. This was done by making a first fit to the spectra employing the method described in the following paragraph, using the highest resolution library (BC03; see above) and then subtracting the best-fit spectra from the observed spectra as illustrated in Figure 8. The so-found values for $E(B-V)$ were multiplied by a factor of 0.44 to correct for systematic differential extinction between the stellar populations and the gas (Calzetti et al. 2000). In the cases in which the spectrum displays only Hα but no Hβ emission, we assume the internal extinction to be negligible: in all of these spectra the emission is much weaker than in the cases with both Hα and Hβ emission, in which the lowest value for $E(B-V)$ is already close to zero $[E(B-V) = 0.02]$. The average value for internal extinction of the eight galaxies with Hα and Hβ emission is $E(B-V) = 0.10$. Note that the problem of apparent truncation of strong emission lines in SDSS spectra reported by Kniazev et al. (2004) does not occur in any of our spectra.

We modeled the actual population as being composed of an old (≥1 Gyr), an intermediate-age (10 Myr to 1 Gyr), and a young (<10 Myr) stellar population. While there is no standard definition for this age terminology, these age ranges are chosen to reflect the significant changes in the spectrum of an SSP with increasing age. Similar values were used, e.g., by Cid Fernandes et al. (2003), Maraston (2005), and Gu et al. (2006). The characteristics and free parameters of the three populations are summarized in Table 3. In order to confine the parameter space to as few dimensions as possible and to focus on the relative fractions of the populations, we fixed the age of the old population at 5 Gyr and the metallicity of all populations at [Fe/H] = −0.3. These values equal the best-fitting mean age and metallicity found by Geha et al. (2003) in a study of Lick/IDS absorption-line indices for dEs. Moreover, the spectra of SSPs of various ages do not differ much at ages of several gigayears and above (e.g., Bruzual & Charlot 2003).

The best-fitting population was found by a $\chi^2$ algorithm. In order to be able to calculate the $\chi^2$ estimator, the observed and theoretical spectra have to be on the same wavelength grid (at least in the range used for the fit). This was done by rebinning the

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![Image](https://example.com/image.png)

**TABLE 2**

WAVELENGTH RANGES THAT WERE NOT USED FOR THE SPECTRAL FIT

| Range (Å) | Contamination Source |
|-----------|----------------------|
| 3885–3900 | H8                   |
| 3965–3980 | H+ [Ne ii] I4367     |
| 4100–4110 | H6                   |
| 4335–4345 | H2+ [O ii] I4363     |
| 4855–4870 | Hβ                  |
| 4955–4965 | [O ii] I4959         |
| 5000–5015 | [O ii] I5007         |
| 5535–5590 | Telluric lines      |
| 5860–5905 | He i I5876           |
| 6245–6320 | [O i] I6300+[S ii] I6312 |
| 6520–6600 | Hα+[N ii]           |
| 6700–6740 | [S ii] I6717, 6731   |
| 7130–7145 | [Ar iii] I7136       |
| 7500–7600 | Telluric lines      |
| 7700–8100 | Telluric lines      |
| 8250–8480 | Telluric lines      |

**TABLE 3**

POSSIBLE VALUES OF THE POPULATION PARAMETERS

| Parameter | Possible Values |
|-----------|-----------------|
| (Mz + My) : M0 | 0, 1, 1:100, 1:30, 1:10, 1:3, 1:1, 3:1, 10:1, 1:0 |
| Mz : M0 | 0, 1, 1:30, 1:10, 1:3, 1:1, 3:1, 10:1, 30:1, 1:0 |
| Agez | 1, 2, 3, 4, 5, 6, 7, 8, 9 Myr |
| Agey | 10, 20, 50, 100, 200, 500 Myr |
| Agei | Fixed at 5 Gyr |
| [Fe/H] | Fixed at −0.3 |
| [Fe/H] | Fixed at −0.3 |

**Notes.—** The young population is denoted by index $y$, the intermediate-age one by $i$, and the old one by $o$; $M_i$ is the mass fraction of the respective population.
observed spectra to the resolution of the theoretical spectra using a Gaussian kernel function with a full width at half-maximum corresponding to the resolution of the theoretical spectra (20 Å for BC99 and Starburst and 1 Å for BC03). The same was done with the “signal-to-noise spectra,” i.e., the S/N as a function of wavelength provided along with the actual spectra. The \( \chi^2 \) estimator was calculated with wavelength-dependent weighting, giving higher weight to the regions with a higher S/N. Figure 9 shows an example of an observed spectrum and the resulting composite model spectra, as well as the individual spectra of the three assumed subpopulations.

5.3. Fit to Model Spectra: Results

The best-fitting population parameters for the fits with the different libraries can be found in columns (2)–(6) of Tables 4–6. In all dE(bc)s of the main sample and all but one (VCC 1499) of the additional sample, the old population makes up 90% or more of the total mass, even though its contribution to the total light is rather small (spectra \( f_o \) in Fig. 9). The young population, on the other hand, usually contributes less than 1% to the mass but often dominates the light (\( f_y \) in Fig. 9), whereas the intermediate-age population usually makes up a few percent of the stellar mass. However, all three populations are doubtlessly present, from which we conclude that these galaxies have been forming stars until the present day. We remind the reader again that the spectra cover only the very central part of our objects and do not allow us to draw direct conclusions about the surrounding regions.

Typically, the parameter space of such spectral fits is full of degeneracies. For example, a change of the ratio of the mass fractions of young and intermediate-age populations has a similar effect on the composite spectrum as varying one of the ages of these populations. Therefore, the parameter values given in Tables 4–6 for individual galaxies should be taken with a grain of salt. However, the excellent agreement between the solutions found with the different libraries, and the similarities in the solutions for the different galaxies, suggest that the general trends in the derived parameters reflect the real properties of the dE(bc)s, within the simplified framework of our three-population models. We emphasize that our approach of approximating the SDSS spectra with synthetic populations composed of three SSPs is not meant to represent the detailed star formation history of our target galaxies but only to demonstrate the range of ages during which star formation must have occurred. Whether stars were formed by short starbursts or by extended episodes of star formation can typically not be decided for galaxies only observable in integrated light (e.g., Lilly & Fritze-v. Alvensleben 2003).
Notes.—$M_y$ and age$_y$ give the mass fraction and age of the young population, respectively. $M_i$ and age$_i$ are the same parameters for the intermediate-age population. The age of the old population was fixed at 5 Gyr; $M_o$ gives its resulting mass fraction.

TABLE 4

| VCC  | $M_y$ | Age$_y$ (Myr) | $M_i$ | Age$_i$ (Myr) | $M_o$ |
|------|-------|---------------|-------|---------------|-------|
| (1)  | (2)   | (3)           | (4)   | (5)           |
| Main Sample | | | | | |
| 0021 | 0.0029 | 9 | 0.0880 | 509 | 0.9091 |
| 0281 | 0.0029 | 1 | 0.0293 | 203 | 0.9677 |
| 0781 | 0.0003 | 2 | 0.0096 | 203 | 0.9901 |
| 0870 | 0.0029 | 7 | 0.0293 | 102 | 0.9677 |
| 0951 | 0.0010 | 1 | 0.0312 | 203 | 0.9677 |
| 0953 | 0.0010 | 7 | 0.0312 | 203 | 0.9677 |
| 1078 | 0.0029 | 1 | 0.0880 | 509 | 0.9901 |
| 1488 | 0.0010 | 7 | 0.0312 | 203 | 0.9677 |
| 1684 | 0.0000 | . . | 0.0909 | 203 | 0.9091 |

Table continued...

Notes.—$M_y$ and age$_y$ give the mass fraction and age of the young population, respectively. $M_i$ and age$_i$ are the same parameters for the intermediate-age population. The age of the old population was fixed at 5 Gyr; $M_o$ gives its resulting mass fraction.

TABLE 5

| VCC  | $M_y$ | Age$_y$ (Myr) | $M_i$ | Age$_i$ (Myr) | $M_o$ |
|------|-------|---------------|-------|---------------|-------|
| (1)  | (2)   | (3)           | (4)   | (5)           |
| Main Sample | | | | | |
| 0024 | 0.0029 | 1 | 0.0293 | 102 | 0.9677 |
| 0135 | 0.0010 | 3 | 0.0312 | 102 | 0.9677 |
| 0340 | 0.0074 | 1 | 0.0025 | 509 | 0.9901 |
| 1175 | 0.0050 | 1 | 0.0050 | 509 | 0.9901 |
| 1273 | 0.0025 | 2 | 0.0074 | 203 | 0.9901 |
| 1437 | 0.0161 | 8 | 0.0161 | 509 | 0.9901 |
| 1499 | 0.0081 | 9 | 0.2419 | 203 | 0.7500 |

Table continued...

Notes.—$M_y$ and age$_y$ give the mass fraction and age of the young population, respectively. $M_i$ and age$_i$ are the same parameters for the intermediate-age population. The age of the old population was fixed at 5 Gyr; $M_o$ gives its resulting mass fraction.

TABLE 6

| VCC  | $M_y$ | Age$_y$ (Myr) | $M_i$ | Age$_i$ (Myr) | $M_o$ |
|------|-------|---------------|-------|---------------|-------|
| (1)  | (2)   | (3)           | (4)   | (5)           |
| Main Sample | | | | | |
| 0021 | 0.0029 | 9 | 0.0880 | 509 | 0.9091 |
| 0281 | 0.0029 | 1 | 0.0293 | 509 | 0.9091 |
| 0781 | 0.0003 | 1 | 0.0096 | 509 | 0.9901 |
| 0870 | 0.0029 | 6 | 0.0293 | 203 | 0.9677 |
| 0951 | 0.0010 | 6 | 0.0312 | 203 | 0.9677 |
| 0953 | 0.0010 | 7 | 0.0312 | 203 | 0.9677 |
| 1078 | 0.0029 | 1 | 0.0880 | 509 | 0.9091 |
| 1488 | 0.0010 | 7 | 0.0312 | 203 | 0.9677 |
| 1684 | 0.0029 | 6 | 0.0880 | 509 | 0.9091 |

Table continued...

Notes.—$M_y$ and age$_y$ give the mass fraction and age of the young population, respectively. $M_i$ and age$_i$ are the same parameters for the intermediate-age population. The age of the old population was fixed at 5 Gyr; $M_o$ gives its resulting mass fraction.

5.4. Evolution of $g - i$ Color

Finally, we would like to know for how long after the last star formation phase integrated spectral properties can be distinguished from those of a pure old population. We focus on the $g - i$ color, since it was used for the actual selection of our objects. For this purpose, we produced synthetic composite populations using the three SSP libraries and calculated the total $g - i$ color as a function of the age of the youngest partial population as these composite populations evolve.

The simplest case is that of two populations: a young one turning into an intermediate-age one, on top of the old one. If we assume the mass of the young population to have one-hundredth of the mass of the old one, the color of the mixture evolves as shown by the solid line in Figure 10 (top). In this scenario, it takes a few hundred Myr until the $g - i$ color of the composite population differs by less than 0.1 mag from a pure old population (dotted line) and thus becomes difficult to distinguish from the latter. The colors shown in Figure 10 are the ones using the BC99 library, but the results hold true for all three libraries.

Now we take instead a composite population like one of the typical solutions from Tables 4–6, that is, $(M_y + M_i):M_o = 1:10; M_y: M_i: M_o = 1:30$, the intermediate-age population being around 500 Myr older than the young one. $M_y, M_i$, and $M_o$ denote the mass fractions of the young, intermediate-age, and old population, respectively. The color of this mixture evolves like the solid line in the lower panel of Figure 10. Again, the dotted line shows the color of only an old population. In this scenario, the mixture is still distinguishable from a pure old population 500 Myr after the birth of the youngest one. However, this parameter combination is the one with the smallest mass fraction of the old population among the results for the main sample. By using the values of the other typical solutions from Tables 4–6,
The age of the old population is fixed at 5 Gyr, and the metallicity of all populations is fixed at [Fe/H] = −0.3. Top: Composite population made out of a young and an old population. The young population makes up 1% of the total mass. Bottom: Composite population made out of a young, an intermediate-age, and an old population, similar to the best-fit results derived for the dE(bc)s. The curve represents a population with $(M_y + M_{i}) : M_o = 1 : 10$, $M_y : M_i = 1 : 30$, with $M_{i, o}$ denoting the mass fractions of the young, intermediate-age, and old populations, respectively. The intermediate-age population is chosen to be ~500 Myr older than the young one. The circles mark the color of this mixture after 500 Myr (top circle), as well as that of two other mixtures: $(M_y + M_i) : M_o = 1 : 30$, $M_y : M_i = 1 : 30$ (middle circle); and $(M_y + M_i) : M_o = 1 : 100$, $M_y : M_i = 1 : 10$ (bottom circle).

$(M_y + M_i) : M_o = 1 : 30$, $M_y : M_i = 1 : 30$ or $(M_y + M_i) : M_o = 1 : 100$, $M_y : M_i = 1 : 10$, the $g - i$ color after 500 Myr is much more similar to the pure old population color (circles in the bottom panel of Fig. 10). Therefore, after the end of star formation it will take less than approximately a gigayear for the (strong) color gradient to disappear, and in many cases only approximately half a gigayear depending on the mass fraction of the young and intermediate-age population. This also demonstrates the need for a thorough study of both strong and weak color gradients in early-type dwarf galaxies, in order to draw conclusions about evolutionary histories. Whether or not star formation will cease soon, or has ceased already in some objects, depends on the amount (and state) of leftover gas, which is the subject of § 6.

### 6. GAS CONTENT

Dwarf elliptical galaxies are commonly considered to be systems that have lost their (cold) gas (e.g., Ferguson & Binggeli 1994; Conselice et al. 2003). On the other hand, Conselice et al. (2003) reported “credible” H i detections for seven Virgo dEs from their own study, as well as from other literature, translating into a 15% H i detection rate for dEs. The GOLDMine database (Gavazzi et al. 2003) reports detections for six more early-type dwarf galaxies. From the SDSS spectra presented above, we know that the dE(bc)s show clear signs of either ongoing or very recent star formation, suggesting the presence of a certain amount of gas. It would thus be interesting to know whether we can expect more episodes of star formation in the near future, requiring a significant cold gas content, or whether star formation is likely to cease soon due to the lack of leftover gas.

Two dE(bc)s of the main sample are detected in H i, while for eight others at least upper limits are available. Ten objects of the additional sample are detected in H i, and upper limits are available for three further galaxies. See Table 7 for H i masses and upper limits on our objects, along with the corresponding references to the literature. Two objects have values from more than one publication; these agree well within the errors.

We now seek to derive an estimate for the ratio of the gas mass to the total baryonic mass, $M_H/M_{bary}$. For this purpose we use V-band mass-to-light ratios between 3 and 6, as given by Geha et al. (2003), and assume no dark matter content, again following Geha et al. (2003). We calculate the total V-band absolute magnitude from the $g$- and $i$-band flux within an elliptical aperture with 1.5 times the estimated semimajor axis from Binggeli et al. (1985) (at $\mu_{gi} = 25.5$ mag arcsec$^{-2}$), using the transformation of Smith et al. (2002). The resulting gas-to-baryonic mass fractions or upper limits for mass-to-light ratios of 3, 4.5, and 6 are listed in Table 7.

Of the dE(bc)s in the main sample, three objects have a very low gas content, with $M_H/M_{bary}$ values of 1% or below (VCC 0170, VCC 0951, and VCC 0953). Of the remaining galaxies, one has an H i content with a resulting fraction of 3%–6% (depending on the adopted mass-to-light ratio). The others have upper limits of several percent, up to 7%–13% for VCC 1488. In contrast, most of the galaxies in the additional sample have a much higher gas fraction. Of the 10 detected galaxies, 7 reach up to more than 10%, with values up to 38%–55%. However, for one object (VCC 0135) the upper limit lies below 1%.

A comparison with average H i–to–total mass ratios for Local Group dwarf galaxies shows that at least some dE(bc)s of the main sample have a larger gas fraction than the 0.2% ± 0.4% of an ordinary dE, while it is mostly lower than the 30% ± 24% of dIrrs (Conselice et al. 2003). If the detected gas was centrally concentrated, at least some of the dE(bc)s of the main sample might still continue to form stars there for a significant amount of time. In contrast, most objects of the additional sample fall in the

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7 Two of these, however, were not classified as early-type dwarf galaxies in the VCC, and they appear to us as at least doubtful dE candidates from visual inspection of the SDSS images.

8 Three of these (VCC 0170, VCC 0227, and VCC 0281) are listed as S0 or late-type spiral galaxies in NED and are listed similarly in Gavazzi et al. (2005), who reported their H i detections, although they were classified as early-type dwarf galaxies in the VCC and confirmed as such by Paper I.
range of the Local Group dIrrs, suggesting that a longer duration of star formation is possible. See § 8 for further discussion.

7. SYSTEMATIC PROPERTIES

We have shown so far that the dE(bc)s, which were classified morphologically as early-type dwarf galaxies, are dominated by an old stellar population. Given their moderate amount of cold gas and the lack of any (significant) star formation activity beyond their central regions, the dE(bc)s will evolve into ordinary-looking dEs in the future. However, up to this point we have mainly focused on the appearance and the composition of the dE(bc)s, but we have not yet compared the statistical properties of the sample of dE(bc)s with those of the sample of dEs and dE(di)s (dEs with disks; see § 3.2). As demonstrated in Paper I, the luminosity function, the projected spatial distribution, and the flattening distribution are important tools to investigate differences between types of galaxies and to judge whether they constitute separate populations. We present and analyze these distributions for the dE(bc)s in §§ 7.1–7.5.

7.1. Luminosity Function

Figure 11 shows the distribution of dE(bc)s, dE(di)s, and the remaining dEs with respect to their $B$-band magnitude provided by the VCC. With the assumption that all galaxies are located at roughly the same distance from us, this distribution represents their luminosity function. Our data are presented as a running histogram with a bin width of 1.0 mag (i.e., ±0.5 mag). Only galaxies with certain cluster membership are taken into account, i.e., 16 dE(bc)s in the main sample whose distribution is given by the dark-gray shaded area. The dE(di)s are represented by the medium-gray shaded area, and the full dE sample with dE(bc)s and dE(di)s excluded is given by the light-gray shaded area. The fraction of dE(bc)s among the full dE sample is shown as a black line. The white line shows the distribution of the 12 certain cluster members of the additional sample, which by construction are not included in the dE sample.

The luminosity function of the full dE sample is shown as a gray dashed line. It has a conspicuous bump at brighter magnitudes, which we explained in Paper I with the superposition of dE(di)s and ordinary dEs, implying that they were two different populations of objects. However, as can be seen in the figure, this bump might at least partly be explained by the superposition of dE(bc)s, dE(di)s, and the remaining dEs. On the other hand, it has been shown in Paper I that we missed ~50% of the dE(di)s due to issues of S/N. Therefore, we have now subtracted the dE(bc)s and 1.5 times the number of dE(di)s from the full sample as a further test (not shown). Still, there is no obvious oversubtraction of the bump (which would result in a dip), so the data are consistent with the estimated number of missed dE(di)s.

### Table 7: H I Detections

| VCC (1) | $\log (M_{\text{HI}}/M_\odot)$ (2) | $M_{\text{HI}}/M_{\text{bary}}(M/L = 3)$ (3) | $M_{\text{HI}}/M_{\text{bary}}(M/L = 4.5)$ (4) | $M_{\text{HI}}/M_{\text{bary}}(M/L = 6)$ (5) | Reference (6) |
|--------|-------------------------------|----------------------------------|----------------------------------|----------------------------------|--------------|
| 0021... | <7.78                         | <0.048                           | <0.032                           | <0.024                           | 1            |
| 0170... | 7.39                          | 0.014                            | 0.009                            | 0.007                            | 2            |
| 0281... | 7.52                          | 0.055                            | 0.037                            | 0.028                            | 2            |
| 0781... | <7.92                         | <0.094                           | <0.065                           | <0.049                           | 1            |
| 0951... | <6.84                         | <0.055                           | <0.038                           | <0.028                           | 1            |
| 0953... | <6.54                         | <0.009                           | <0.002                           | <0.001                           | 1            |
| 1488... | <8.27                         | <0.134                           | <0.093                           | <0.072                           | 1            |
| 1779... | <7.72                         | <0.041                           | <0.027                           | <0.021                           | 1            |
| 1912... | <7.44                         | <0.031                           | <0.021                           | <0.016                           | 1            |
| 0024... | 8.90                          | 0.546                            | 0.445                            | 0.376                            | 2            |
| 0135... | <7.13                         | <0.009                           | <0.006                           | <0.004                           | 2            |
| 0334... | 7.89                          | 0.339                            | 0.255                            | 0.204                            | 2            |
| 0340... | 8.76                          | 0.547                            | 0.446                            | 0.377                            | 2            |
| 0446... | 7.62                          | 0.284                            | 0.209                            | 0.166                            | 2            |
| 0841... | 7.55                          | 0.270                            | 0.198                            | 0.156                            | 2            |
| 0890... | 7.27                          | 0.106                            | 0.073                            | 0.056                            | 2            |
| 1273... | <7.10                         | <0.064                           | <0.044                           | <0.033                           | 2            |
| 1437... | 8.17                          | 0.311                            | 0.232                            | 0.184                            | 2            |
| 1499... | <8.53                         | <0.256                           | <0.186                           | <0.147                           | 4            |
| 1555... | 7.66                          | 0.047                            | 0.032                            | 0.024                            | 2            |
| 2007... | 7.31                          | 0.218                            | 0.157                            | 0.122                            | 2            |
| 2033... | 7.39                          | 0.045                            | 0.031                            | 0.023                            | 2            |

Notes.—H I masses and upper limits are given for our adopted Virgo Cluster distance of $d = 15.85$ Mpc. In cols. (3)–(5) we list the ratios of the gas mass to the total baryonic mass, using different mass-to-light ratios as given in the column header; for details, see text. References.—(1) GOLDMine database (Gavazzi et al. 2003; http://goldmine.mib.infn.it); (2) Gavazzi et al. 2005; (3) Huchtmeier & Richter 1989; (4) Huchtmeier & Richter 1986.
The fraction of dE(bc)s among all dEs reaches up to more than 15% for the main sample at brighter magnitudes and declines to almost zero at \( m_B \geq 16 \). Thus, the dE(bc)s are not a negligible population of objects, but instead constitute a significant fraction of the bright dEs. To investigate whether the decline of the dE(bc) fraction at fainter magnitudes is real or whether it is due to S/N effects, we artificially dimmed all 11 dE(bc)s of the main sample with 14 \( \leq m_B < 15 \) by 1 and 2 mag. This was done by adding Gaussian noise to the images such that the rms of the total noise was increased by 1 and 2 mag. Color maps and radial color profiles were then constructed as described above and were examined for whether they would have been selected as dE(bc)s by us. When dimmed by 1 mag, 9 of the 11 objects would still have been selected, whereas at 2 mag fainter only 5 would have been recognized as dE(bc)s. Thus, if the true dE(bc) fraction would be constant at 17% (the average value within the interval 14 \( \leq m_B < 15 \)) independent of magnitude, we would expect to observe a fraction of 14% at magnitudes in the range 15 \( \leq m_B < 16 \) and 8% in the range 16 \( \leq m_B < 17 \). Within these magnitude ranges, we should thus find 9.4 \( \pm \) 2.8 and 8.2 \( \pm \) 2.8 dE(bc)s, respectively, for a binomial distribution. However, we found only 4 and 0 dE(bc)s, which lie within 1.9 and 3.0 standard deviations, respectively. It is thus very likely that the decline of the number fraction of dE(bc)s is real.

Since we are using B-band magnitudes, it is an obvious question how much fainter the dE(bc)s will become after their star formation has ceased. From our spectral analysis, we expect a decrease of the B-band flux of the central 3' to one-third of the current flux (median value 0.32) for the main sample dE(bc)s. To obtain this estimate we compared the total spectrum of each galaxy with the model spectrum of the old population only, as a conservative estimate. Since our galaxies show a color gradient (Figs. 1–3), which we interpret as a decrease of the fraction of young stars when going outward, we now assume that the above ratio of faded and current flux linearly increases to 1 up to the B-band half-light radius. This leads to an estimated fading of the total galaxy flux in the B band of 0.2 mag for all dE(bc)s. Therefore, we do not expect significant evolution of the dE(bc) luminosity function after the cessation of star formation.

For the galaxies in the additional sample, Figures 5 and 6 show that the blue regions are more extended. We therefore assume the linear increase of the ratio of faded and current flux (see above) to extend to 2 half-light radii. This leads to an estimated fading of 0.4–0.5 mag. On average, these galaxies are already slightly fainter than the dE(bc)s of the main sample (see Fig. 11). This difference would thus become more pronounced after their star formation has ceased. On the other hand, one might expect from their gas content that a significant amount of stars could still be formed in these objects, which would counteract the fading to some extent.

7.2. Flattening Distribution

The flattening distribution of the dE(bc)s is presented in Figure 12, along with that of the dE(di)s from Paper I. The axial ratios were derived from the elliptical apertures provided by Paper I (see § 4.1). Again, only galaxies with certain cluster membership are considered. The distributions are presented as running histograms with a bin width of 0.1. Only galaxies with certain cluster membership are considered. Beyond the last data point on each side, the histograms are plotted with dotted instead of solid lines. The bottom right panel shows theoretically expected curves for intrinsic oblate (black) and prolate (gray) shapes, assuming randomly distributed inclinations and intrinsic axial ratios that are described by the following Gaussian distributions: oblate with mean \( \mu = 0.4 \) and \( \sigma = 0.07 \) (black solid line), \( \sigma = 0.04 \) (black dashed line), and \( \sigma = 0.02 \) (black dotted line); prolate with \( \mu = 0.65 \) and \( \sigma = 0.2 \) (gray solid line), \( \sigma = 0.15 \) (gray dashed line), and \( \sigma = 0.1 \) (gray dotted line).
In Paper I we deduced that dE(di)s are consistent with being flat oblate objects. Here we find that the dE(bc)s of the main sample are similarly distributed, with slightly larger axial ratios than the dE(di)s. A comparison with the theoretical curves demonstrates that, despite the small sample size, their distribution is hardly consistent with dE(bc)s being spheroidal objects and instead suggests the shape of a relatively thick disk. The galaxies of the additional sample are rounder, although not spheroidal. This is another point, besides the overall gas content, strength of emission lines, and size of star-forming regions, in which the dE(bc)s of the main sample and the additional galaxies are not alike.

7.3. Spatial Distribution

In Paper I we found that while ordinary dEs are more strongly clustered toward the Virgo Cluster center, dE(di)s basically show no clustering at all, another indication of them being a different population of galaxies. The dE(bc)s of the main sample also show no central clustering (Fig. 13, top), similar to the dE(di)s. The same applies to the objects of the additional sample (Fig. 13, bottom). While the number of dE(bc)s is relatively small and does not allow statistically secure statements, their distribution is hardly consistent with a centrally concentrated population.

7.4. Morphology-Density Relation

In Figure 14 we present the cumulative distributions of projected local densities, calculated as in Dressler (1980) and Binggeli (1987). We define a circular area around each VCC galaxy that includes its 10 nearest neighbors (independent of galaxy type), yielding a projected density (number of galaxies per square degree). Only galaxies with certain cluster membership are taken into account. Top: The dE(bc)s of the main sample (solid black line), the galaxies of the additional sample (dashed black line), the dE(di)s from Paper I (solid gray line), and ordinary dEs [excluding dE(bc)s and dE(di)s; dashed gray line]. Bottom: The dE(bc)s of the main sample (black line) compared to various Hubble types.
et al. (1987), for the dE(bc)s, the galaxies of the additional sample, the dE(di)s, and the remaining, ordinary dEs (top panel). We also compare these with the distributions of standard Hubble types (bottom panel), i.e., with the well-known morphology-density relation.

The dE(bc)s and the objects of the additional sample are preferentially found in regions of moderate to lower density and are distributed similarly to the irregular galaxies. This implies that they, as a population, are far from being virialized, corroborating the indications from the spatial distribution (§ 7.3). The dE(di)s show a similar distribution, which follows that of the spiral galaxies. Ordinary dEs, however, are preferentially found in higher density regions. Their location in the morphology-density diagram is intermediate between E/S0 and spiral galaxies.

7.5. Velocity Distribution

Heliocentric velocities are available for 194 early-type dwarf galaxies of our full dE sample that are certain Virgo Cluster members (see § 2.3). We present these data in Figure 15 for the dE(bc)s, the dE(di)s, and the remaining dEs [i.e., dE(bc)s and dE(di)s excluded]. Each panel shows a running histogram with a bin width of 366 km s$^{-1}$, which corresponds to the semi-interquartile range of all 194 velocities. Their median value, $v_{\text{helio}} = 1248$ km s$^{-1}$, is given as a dotted vertical line in each panel for comparison.

The dE(bc)s of the main sample show a relatively large deviation from the overall median value: their median velocity is only $v_{\text{helio}} = 802$ km s$^{-1}$. However, since the semi-interquartile range is large ($\Delta v_{\text{helio}} = 463$ km s$^{-1}$) and only 15 objects are included in this sample, we cannot state whether this constitutes a significant difference. Instead, it might be more promising to compare the shapes of the distributions. The sample of ordinary dEs shows a close-to-symmetric distribution, which would be expected for a relaxed population. In contrast, the distributions of dE(bc)s and dE(di)s are asymmetric and less smooth. Both display side peaks, indicative of an infalling population (Tully & Shaya 1984; Conselice et al. 2001). This would be consistent with their spatial distribution, which shows no central concentration within the cluster, and with their distribution with projected local density, which follows that of the irregular cluster galaxies.

8. DISCUSSION

The SDSS enables for the first time a systematic study of several hundred dEs in the Virgo Cluster with optical imaging and partly with spectroscopy. These data provide the basis for this series of papers, which aims at disentangling the various subpopulations of early-type dwarf galaxies and uncovering their evolutionary histories. In Paper I we found that dEs with disk features [dE(di)s] constitute a disk-shaped, unrelaxed dE population that is clearly different from classical dwarf elliptical galaxies. In the current paper we focus on another conspicuous feature that is common to several dEs: a blue center caused by recent or ongoing central star formation. We have shown that these dE(bc)s constitute a significant fraction (more than 15%) of bright dEs in the Virgo Cluster. This number declines to almost zero beyond $m_B > 16$, which is most likely a real decline and is not mainly due to S/N effects.

Two dE(bc)s of the main sample are detected in H$\alpha$, with gas-to-baryonic mass fractions of 1% and 3%–6%, respectively. These values and the upper limits for several other dE(bc)s suggest an average gas content larger than that of ordinary dEs but lower than that of dIrrs. Note that we do not know where in the galaxies the gas is located; if it were concentrated in the central region, it would probably be able to fuel star formation for a longer time than if the gas were distributed homogeneously.

As soon as star formation has ceased, each dE(bc)’s color, which provided the basis of its selection, will become indistinguishable from that of an ordinary dE within approximately a gigayear or less (see § 5.4). However, the statistical properties of the dE(bc) population are unlike those of ordinary dEs: the projected spatial distribution and the flattening distribution of the dE(bc)s are similar to those of the dE(di)s and are different from those of dEs that have no blue centers or disk features. Both the dE(bc) and dE(di) population show no central clustering, which, along with the side peaks of their velocity distributions, hints toward fairly recent infall. How long ago this infall could have taken place depends on relaxation timescales. Conselice et al. (2001) derived a two-body relaxation time for the Virgo dEs of much more than a Hubble time. Even violent relaxation, which might only apply for the case of merging groups or subclusters, would take at least a few crossing times $t_{\text{cr}}$, with $t_{\text{cr}} \approx 1.7$ Gyr for the Virgo Cluster (Boselli & Gavazzi 2006). Thus, a dE population built out of infalling galaxies remains in an unrelaxed, nonvirialized state for many gigayears. We conclude that the dE(bc)s most likely formed through infall of progenitor galaxies.

The shape of the dE(bc)s, as deduced from their flattening distribution, is hardly consistent with their being spheroidal objects and instead implies that the dE(bc)s are rather thick disks, i.e., oblate-shaped objects with intrinsic axial ratios around $\sim 0.4$. This is only somewhat thicker than the dE(di)s, for which we derived an axial ratio of $\sim 0.35$ in Paper I. How could these disk-shaped dEs be produced?

8.1. Formation Scenarios

In the galaxy harassment scenario (Moore et al. 1996), an infalling late-type disk galaxy gets transformed into a dE through high-speed encounters with massive cluster galaxies. This obviously leads to an increase in the axial ratio during the transformation process, since a disk is converted into a spheroid. However, a
thick stellar disk may survive and lead to lenticular systems (Moore et al. 1996; Mastropietro et al. 2005). These may form a bar and spiral features and retain them for some time, depending on the tidal heating of the galaxy (Mastropietro et al. 2005). Galaxy harassment thus appears to be a plausible scenario to explain the formation of disk-shaped dEs and of dE(di)s in particular. Moreover, it predicts that gas will be funneled to the center and form a density excess there (Moore et al. 1998). While Moore et al. compare this to the presence of a nucleus in many dEs, they admit that their simulations “were not designed to probe the inner 200 pc.” The radii of many of the blue central regions of the dE(bc)s are only slightly larger than this value (see Figs. 1–3); consequently, the central gas density excess could well explain the blue centers. The harassment scenario thus describes a possible evolution of an infalling late-type disk galaxy to a dE(bc) and to a dE(di).

Another mechanism to form disk-shaped dEs could be ram pressure stripping (e.g., Gunn & Gott 1972) of dllrs. Depending on galaxy mass, the gas might be significantly removed except around the central region (Mori & Burkert 2000), which would seem to be consistent with the central star formation of the dE(bc)s. As shown by van Zee et al. (2004), several dEs have significant rotation and could thus be the descendants of dllrs, which are also known to be mostly rotationally supported, at least at the luminosities considered here. However, apart from the problems with this scenario discussed in § 1, like the metallicity offset between dEs and dllrs or the too-strong fading of dllrs, the flattening distribution of dllrs shown by Binggeli & Popescu (1995) is not quite like that of our dE(bc)s. Instead, dllrs have a (primary) axial ratio \( \geq 0.5 \). On the other hand, significant mass loss due to stripped gas would be expected to also affect the stellar configuration of the galaxies and could thus possibly account for the difference.

As outlined in § 1, several studies claimed that BCDs might be progenitors of dEs. Their flattening distribution, as analyzed by Binggeli & Popescu (1995), is somewhat more like that of our dE(bc)s, although still slightly rounder. These BCDs behave similarly to the galaxies of our additional sample, which were mostly classified as (candidate) BCDs but were selected only if their appearance was similar to the dE(bc)s. Overall, they have more extended blue regions, stronger emission lines, and a clearly higher gas content than the dE(bc)s of the main sample. They are also dominated by an underlying old population—only one out of seven has \( M_{\text{bul}} < 90\% \)—and they have fairly regular outer shapes. Their spatial distribution also hints at an unrelaxed population, and their velocity distribution is asymmetric.

Tidally induced star formation in dllrs (Davies & Phillipps 1988) might be able to link BCDs and dEs and could at the same time overcome the problems of the ram pressure stripping scenario. The initially lower metallicity and surface brightness of a dlr is increased by several bursts of star formation, during which the galaxy appears as a BCD. After that, it fades to become a dE. The last star formation burst might occur in the central region of the dwarf (Davies & Phillipps 1988), consistent with the appearance of the dE(bc). The fraction of nucleated galaxies among the dE(bc)s is 7 out of 16 (44%), which is based on the VCC classification and has been verified by us through visual inspection of images and unsharp masks. We find one more dE(bc) to have “multiple nuclei” (VCC 0021) and one to have a possible nucleus (VCC 1512). If those two objects were counted as being nucleated, the fraction would increase to 56%. Among the dE(di)s, 26 out of 36 galaxies are nucleated (72%). Ordinary dEs [i.e., excluding dE(bc)s and dE(di)s] also have a nucleated fraction of 72% among the brighter objects (\( M_g \leq 16 \)), which is the magnitude range of most dE(di)s and all but one dE(bc). If we assumed a 72% nucleated fraction for the dE(bc)s as well, we would expect to find 11.5 nucleated dE(bc)s among our 16 objects, with a standard deviation \( \sigma = 1.8 \). Our observed number thus lies within 1.4 \( \sigma \) of the expected value if dE(bc)s had the same nucleated fraction as dEs and dE(di)s and if the two uncertain objects were counted as nucleated. Thus, there is no significant difference between dE(bc)s, dE(di)s, and the other dEs with respect to the presence or absence of a nucleus.

Still, the somewhat smaller number of nuclei in dE(bc)s could be a hint that nuclei are indeed forming in their centers. Of the galaxies in the additional sample, none displays a nucleus, but the significant amount of central gas and dust might leave the possibility of a hidden nucleus or of a nucleus just being formed.

We point out that the ACS Virgo Cluster Survey (Côté et al. 2004) finds a much higher frequency of compact stellar nuclei in early-type galaxies than Binggeli et al. (1985) did, primarily due to the much higher resolution of space-based studies as compared to ground-based ones (Côté 2005). However, if we took into account these results, a dE classified as nucleated in the VCC would then simply be termed a dE with a nucleus bright enough to have been detected by Binggeli et al. (1985).

8.3. Presence of dE(bc)s in Less Dense Environments

Early-type dwarf galaxies with blue centers are not only present in the Virgo Cluster. NGC 205, with its central region of young stars and central dust clouds (Hodge 1973), is a well-known local example of what we term a dE(bc); the same applies to NGC 185 (Hodge 1963). On one hand, NGC 205 might be considered a special case due to its clear signs of tidal interaction with M31 (Mateo 1998). On the other hand, tidal interaction might not be something special but instead something very common and even required for the formation of dEs and of dE(bc)s in particular. While galaxy harassment is negligible in groups (Mayer et al. 2001b), a similar mechanism is provided there by the so-called tidal-stirring scenario (Mayer et al. 2001a), in which a dlr that suffers repeated tidal shocks is transformed into a dE or a dSph. In this model, the galaxies with higher surface brightness can reach a central gas density excess like that described above for harassment. Tidal stirring might thus provide a consistent explanation for dE(bc)s in groups.

Contrary to the above interpretation of NGC 185 and NGC 205 as possible results of tidal stirring, Gu et al. (2006) recently presented an apparently isolated dwarf elliptical galaxy with a blue center (IC 225) at a distance of 20.6 Mpc. Its spectrum displays Balmer line emission, and based on its appearance it would doubtlessly enter our dE(bc) sample. The authors base their conclusion about the galaxy’s isolation on their failure to find a potential companion within 30′, using NED. This angular search radius corresponds to 180 kpc at their given distance. We increased the search radius and found the small galaxy group USGC U124 (Ramella et al. 2002) to lie at the same distance as IC 225 (within 25 km s\(^{-1}\) in radial velocity) and at an angular separation of 145′, or 870 kpc. The brightest group member (NGC 0936) is an early-type spiral galaxy with \( M_g \approx -20.5 \). Since 870 kpc would
seem a rather large distance for IC 225 to be a bound companion, we test whether a single interaction could have occurred in the past. As an example, if the relative velocity was 100 km s\(^{-1}\) the encounter would have occurred 8.5 Gyr ago, much too long for the current star formation to have been triggered by it.

While the tidal forces of smaller galaxies closer to IC 225 could possibly affect the galaxy’s gas distribution, Brosch et al. (2004) argued that tidal interactions might not be necessary for activating star formation and that instead the dynamics of gas masses in a dark matter gravitational potential could be the primary trigger. Nevertheless, the main problem would be to explain how an isolated dE could have formed at all. Therefore, if IC 225 is indeed a truly isolated galaxy, one has to think of other mechanisms for dE formation than those we have discussed. It also demonstrates, along with NGC 185 and NGC 205, that central star formation does not only occur in cluster dEs and that, consequently, the mechanisms for dE formation might be similar in different environments. In fact, in the Local Group, where we can study galaxies at the highest angular resolution, many dSphs show star formation histories that extend over many gigayears. In all of these cases, the younger populations are more centrally concentrated than the old ones (Harbeck et al. 2001). Apart from interactions, this may also be a consequence of longer lived gas reservoirs at the centers of these galaxies’ potential wells.

Finally, we caution against calling the dE(bc)s “de/dfr transition types”: this would suggest that every dE(bc) has a dfr progenitor, which might not be the case, as discussed above. Similarly, Grebel et al. (2003) argued for Local Group dwarf galaxies that the so-called dfr/dSph transition types are plausible progenitors of dSphs, while dfrs themselves seem less likely.

9. SUMMARY AND OUTLOOK

We have presented a study of Virgo Cluster early-type dwarf galaxies (dEs) with central star-forming regions, based on photometric and spectroscopic data from the SDSS DR4. These “dE(bc)s” are not rare objects, but they reach a fraction of more than 15% among the bright \((m_B < 16)\) dEs. Their spatial distribution and their distribution with projected local density suggest that they are an unrelaxed population. Their flattening distribution is consistent with them being disk-shaped objects like the dEs with disk substructure [dEd(d)ls] identified in Paper I. Even in the very center, where their colors are bluest, 90% or more of their mass belongs to an old stellar population. Thus, they will appear like ordinary dEs within about 1 Gyr after the end of their star formation. The gas content of the dE(bc)s is lower than in dfrs but probably somewhat higher than in classical dEs, implying that at least in some dE(bc)s star formation might still continue for some time. Plausible formation mechanisms that could explain both the disk shape and the central star formation of the dE(bc)s are galaxy harassment (Moore et al. 1996), which describes the transformation of infalling late-type disk galaxies into dEs; tidally induced star formation in dfrs (Davies & Phillipps 1988); and possibly also ram pressure stripping (Gunn & Gott 1972) of dfrs and star formation induced by gas compression due to ram pressure.

We have started our series of papers on Virgo early-type dwarf galaxies by describing two sorts of dEs with “special features,” i.e., dEs with a blue center (this study) and dEs with disk substructure (Paper I). It is important to stress that we are not looking at a single population of dEs, with those features just being some extra “flavor,” but that these dE subtypes constitute populations with distinct properties that differ from the rest of the dEs. To complicate the issue even more, ordinary dEs [i.e., excluding dE(bc)s and dEd(d)ls] are probably not a homogeneous population either, since, e.g., the clustering properties of nucleated and nonnucleated dEs differ significantly (Binggeli et al. 1987). Whether all of these dE subtypes simply reflect different evolutionary stages of one single class of galaxy or they are indeed different classes of early-type dwarf galaxies will be discussed in detail in a forthcoming paper.

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