Colors of Dwarf Ellipticals from GALEX to WISE

James M. Schombert

Department of Physics, University of Oregon, Eugene, OR 97403, USA; jschombe@uoregon.edu

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Abstract

Multicolor photometry is presented for a sample of 60 dwarf ellipticals (dE’s) selected by morphology. The sample uses data from GALEX, SDSS, and WISE to investigate the colors in the NUV, ugri, and W1 (3.4 µm) filters. We confirm the blueward shift in the color–magnitude relation (CMR) for dE’s, compared to the CMR for bright ellipticals, as seen in previous studies. However, we find that the deviation in color across the UV to near-IR for dE’s is a strong signal of a younger age for dE’s, one that indicates decreasing mean age with lower stellar mass. Lower mass dE’s are found to have mean ages of 4 Gyr and mean [Fe/H] values of −1.2. Age and metallicity increase to the most massive dE’s, with mean ages similar to normal ellipticals (12 Gyr) and their lowest metallicities ([Fe/H] = −0.3). Deduced initial star formation rates for dE’s, combined with their current metallicities and central stellar densities, suggest a connection between field low surface brightness (LSB) dwarfs and cluster dE’s, where the cluster environment halts star formation for dE’s, triggering a separate evolutionary path.

Key words: galaxies: dwarf – galaxies: elliptical and lenticular, cD – galaxies: evolution

1. Introduction

Ellipticals represent one of the most carefully studied type of galaxy with respect to stellar populations. They exhibit the simplest morphological as well as internal kinematics and, thus, are well-modeled as a single stellar population rather than the kinematically distinct components found in disk galaxies. They have the highest masses (i.e., luminosities) of all galaxy types and, therefore, are the clearest signposts at high redshift. Studies of galaxy evolution often focus on ellipticals owing to early indications that their spectrophotometric changes are the simplest to model and trace, reliably, through cosmic time (the so-called passive evolution). In addition, ellipticals are the only morphological type that inhabits every galaxy environment from the richest clusters to the field, and present a coherent appearance from the dwarf ellipticals (dE’s) to the brightest cluster members.

The study of stellar populations in ellipticals has historically taken three different routes. The first is the use of optical and near-IR colors to interpret the integrated light of the underlying stellar population. The discovery of the color–magnitude relation (CMR; Sandage & Visvanathan 1978) and the separation by color of morphology types (Tojeiro et al. 2013) and different galaxy components (e.g., core versus envelope; Head et al. 2014) were often our earliest explorations into the stellar populations and the meaning of color with respect to the star formation history of galaxies (Tinsley 1978). Technological improvements in the 1980s led to a second, and obvious, extension of multicolor work through the higher resolution of the spectroenergy distribution (SED) of galaxies with the focus on various spectral indices related to the different types of stars found in a stellar population. This type of investigation reached a peak with the development of the Lick/IDS line-strength system (Worthey et al. 1994; Trager et al. 2000), where a set of specific spectral features was shown to correlate with the two primary characteristics of a stellar population, its age and mean metallicity. Guided by SED models of the Lick/IDS line-strength system (see Graves & Schiavon 2008), these spectral indices became the observable of choice to study nearby and distant galaxy stellar populations. Lastly, with the launch of HST, space imaging provides the best study of a stellar population by direct examination of their color–magnitude diagrams (CMDs). The number of pure ellipticals open to HST CMD imaging is limited to the nearby universe and, therefore, for a majority of stellar population studies, the Lick/IDS line-strength system is the method of choice.

The use of optical and near-IR colors to investigate stellar populations still has an important role to play even in the spectroscopic era. For example, higher signal-to-noise ratio is acquired for faint, distant galaxies using colors. Large areal surveys, such as those obtained by wide-field cameras using well-chosen filter sets, provide numerically superior data sets to spectroscopic surveys. In the 1990s, Rakos & Schombert pioneered the use of narrowband filters selected to cover age/metallicity features around the 4000Å break as a fast and efficient system to study cluster galaxies with direct imaging (see Rakos & Schombert 1995). The results from those studies confirmed the passive evolution of the stellar populations in cluster ellipticals but were in sharp disagreement with the results from spectroscopic surveys that found much younger ages and lower metallicities for the same objects (Trager et al. 2000; Graves et al. 2009; Conroy et al. 2014). Larger SDSS samples (Bernardi et al. 2005; Gallazzi et al. 2005; Graves et al. 2010) presented a more diverse range of ages and metallicities, and more sophisticated analysis techniques (see Johansson et al. 2012; Conroy et al. 2014; Worthey et al. 2014), all of which reinforced the conclusion of younger ages and lower metallicities with decreasing luminosity and stellar mass for bright ellipticals.

One deficiency in the spectroscopic surveys is that they are less able to explore the low-luminosity/mass realm of ellipticals, the dE’s. Their combined low absolute luminosities and depressed central surface brightnesses made spectroscopic observations of dE’s a particular challenge even for nearby clusters and, in practice, impossible for high-redshift systems. Given the various scenarios where bright ellipticals are constructed from low-mass systems through hierarchical mergers (Driver 2010), a deficiency in accurate stellar population values (e.g., age and metallicity) for dE’s is a continuing problem in comparing observations with theory.
This paper attempts to extend our knowledge of stellar populations in low-mass systems by presenting a comprehensive analysis of dE colors using archival data from the near-UV (GALEX NUV) to the far-IR (WISE 3.4 μm) in an effort to extend our estimates of age and metallicity to the low-mass realm. This study is an extension of the color analysis of bright ellipticals ($M_e < -20$) from Schombert (2016) that focuses on presenting a large sample of morphologically classified dwarf ellipticals (class dE) and bridging the gap between normal and dwarf ellipticals (the luminosity range between $-18$ and $-20$). As demonstrated in Schombert (2017), this gap is populated by a rare class of faint ellipticals with power-law surface brightness profiles, in the same structural family as normal ellipticals. The family of dE’s have profiles structurally distinct from normal ellipticals, yet appear to transition coherently in color with normal ellipticals (Caldwell 1983).

This study will provide a detailed comparison of dE’s with previous color studies and will also examine the differences between various photometric relationships. The colors presented herein will anchor the zero point of bright and dwarf elliptical colors for use in high-redshift studies. In addition, these colors will also provide a window into the stellar populations of ellipticals by comparing with simple and multimetallicity population models, where the wide wavelength coverage offers an avenue to break the age–metallicity degeneracy that plagues optical colors (Worthey 1994).

2. Sample

The bright elliptical data for this study ($M_e < -20$) were based on the sample defined by Schombert & Smith (2012), a purely morphological sample of ellipticals selected from either the Revised Shapley-Ames (RSA; a catalog selected by luminosity) catalog of the Uppsala Galaxy Catalog (an angular limit catalog). The sample was restricted to large angular-sized ($D > 2$ arcmin) galaxies and required having been imaged by the 2MASS project (we used $J$ magnitudes as our baseline). In addition, the sample had to satisfy a criterion of isolation from foreground or background objects (i.e., there are no nearby bright stars or companion galaxies that would distort the surface brightness isophotes).

The resulting $JHK$ surface photometry was presented in Schombert & Smith (2012), and the final sample consisted of 436 bright ellipticals. That sample was then cross-correlated with the Galaxy Evolution Explorer (GALEX; Martin & GALEX Team 2005), SDSS, and Spitzer image libraries for existing data from 226.7 nm (GALEX NUV) to 3.6 μm (channel 1, Spitzer). Using automated scripts to browse the various mission Web sites resulted in 2925 image files from the four missions. Overall, there were 436 ellipticals in the 2MASS sample, of which 149 had GALEX data, 252 had matching SDSS images, and 149 with archived Spitzer 3.6 μm images. These numbers were primarily determined by the varying sky completeness of each mission.

In the original sample, only 5% of the galaxies were fainter than $M_e = -20$, which sharply degrades the ability to study the CMR to low stellar masses. To extend the elliptical sequence, we collected 60 more ellipticals from the recent early-type catalog of Dabringhausen & Fellhauer (2016; hereafter the DF catalog) specifically for low absolute magnitudes. Again, pure elliptical morphology and isolation were the requirements, plus the target had to be in the SDSS DR13 image library. In addition to these faint ellipticals (classed E in the DF catalog), 62 dE’s were also selected from the dE sample of Lisker et al. (2008) for study. Of this 62, 49 are classed dE(N), eight are classed dE(nN), and five as dE(bc) based on the Lisker scheme. A majority of these galaxies are in the Virgo cluster. The Virgo sample was combined with a sample of group dE from the DF catalog, for a total dwarf sample of 62 galaxies. The combined sample (bright, faint, and dwarf) contains 374 ellipticals with, at least, photometry from SDSS ugr images.

Each object in the total sample was also inspected for evidence of emission lines (excluding AGN features), dust, or other signatures of recent star formation when spectroscopic data were available in the SDSS archive. The idea here was to find a sample of ellipticals that was as similar in terms of morphology and star formation history as possible. While some contamination of the inner colors due to low-level AGN activity was acceptable, their effects had to be restricted to inside the various mission’s PSF, or the galaxy was rejected from the sample. All of the images were ellipse-subtracted to look for asymmetric features that might be a signature of recent mergers or dust lanes. Although the usual selection of boxy-like and disk-like residuals was observed, there were no obvious linear features. In addition, color-subtracted frames were examined for evidence of dust lanes, but none were detected in the UV and optical images.

2.1. Data Reduction

The data reduction of the flattened, calibrated images from each mission was performed with the galaxy photometry package ARCHANGEL (Schombert 2007). These routines, mostly written in Python, have their origins in disk galaxy photometry from the late 1980s and are blended with the GASP package from that era (Cawson et al. 1987). The ARCH-ANGEL package has four core algorithms that (1) aggressively clean and mask images, (2) fit elliptical isophotes, (3) repair masked regions then perform elliptical aperture photometry, and (4) determine aperture colors and asymptotic magnitudes from curves of growth as well as accurate errors based on image characteristics, such as the quality of the sky value.

The photometric analysis of galaxies branches into four areas: (1) isophotal analysis (the shape of the isophotes), (2) surface brightness determination and fitting (2D images reduced to 1D luminosity profiles), (3) aperture luminosities (typically using masked and repaired images and elliptical apertures), and (4) asymptotic or total magnitudes (using curves of growth guided by surface brightness data for the halos; see Schombert et al. 2011). Ellipticals are the simplest galaxies to reduce from 2D images to 1D luminosity profiles since, to first order, they have uniformly elliptical-shaped isophotes (Jedrzejewski 1987). As many ellipticals display disky or boxy isophotal shapes (Kormendy & Bender 1996), this deviation is at the few percent level and has a negligible effect on the surface brightness profile, aperture luminosities, or color values (Schombert 2013).

Surface brightness determination and fitting consume a large fraction of the processing time for ellipticals. Accurate surface brightness profiles require detailed masking to remove foreground stars, fainter background galaxies, and image artifacts. While cleaning an elliptical galaxy’s image is simplified by the lack of H II regions, dust lanes, or other irregular features, the final accuracy of the profile will be highly dependent on the quality of the data image, in particular the flatness of the image...
and knowledge of the true sky value. The smooth elliptical shape of early-type galaxies results in very low dispersions in intensity around each isophote that, in turn, makes the removal of stellar and small background galaxies an iterative task.

Following the prescription outlined in Schombert & Smith (2012), we processed all of the mission images in the same manner. Despite the differing plate scales (i.e., arcsec per pixel), orientations on the sky, and flux calibrations, the GALEX, SDSS, 2MASS, and Spitzer missions all provide well-flattened final data products, usually free of any obvious artifacts. Very little image preparation was required, other than confirming that the targets in the images were, in fact, the correct galaxy (galaxy misidentification in the archive servers was not uncommon). This was accomplished by comparison with the PSS-II J images at STScI/MAST and crude luminosity estimates compared to the RC3 magnitudes (de Vaucouleurs et al. 1991).

Isophotal fitting on each image begins with a quick visual inspection of the field to manually suppress the artifacts and to mark the center of the galaxy. Then, an iterative ellipse-fitting routine begins outside the core region, moving outward and fitting the best least-squares ellipse to each radius until the isophote intensity drops below 1% of the sky. The routine then returns to the core to finish the inner pixels in a like manner. During the ellipse fitting, pixels greater than (or less than) 3σ from the mean intensity are masked and removed using a 50% growth radius. The resulting fits are output as the mean intensity and dispersion around the ellipse, major axis, eccentricity, position angle (and errors), plus the first four intensity moments. The conversion to surface brightness profiles uses the generalized radius, the square root of the major times minor axis ($\sqrt{ab}$). All spatial parameters will be quoted using the generalized radii.

The resulting elliptical isophotes are calibrated (intensity and pixel size) using the standard pipeline calibrations provided by the missions, then processed into surface brightness profiles. Various fitting functions have been applied to elliptical surface brightness profiles over the years. A full discussion of their various strengths and weaknesses can be found in Schombert (2013). In brief, the Sérsic $r^{1/n}$ provides the best fits over the full range of surface brightnesses, but suffers from coupling between its shape and characteristic radii parameters that reduce its usefulness. Templates are a stronger match to the shape of elliptical profiles (Schombert 2015), but are only parametrized by luminosity and do not provide any structural metrics. In the end, we found that empirically determined parameters, such as the half-light radius ($r_h$) and mean surface brightness ($\langle \mu \rangle$), are the parameters most strongly correlated with luminosity or stellar mass.

As this study is primarily concerned with colors, the determination of luminosity in a consistent and accurate manner from the data sets is of the highest priority. Aperture luminosities are calculated using the ellipses determined by the isophote routines. Care was taken to make sure that the same eccentricities and position angles were used across the various mission images. None of the sample galaxies display any variation in eccentricity or position angle at the 2% level from the near-UV to the far-IR. Thus, the aperture values were, in effect, determined using fixed radii in kiloparsecs.

The total luminosity of a galaxy is a much more problematic value to determine. The procedure used here is outlined in Schombert et al. (2011), where elliptical apertures are determined using a partial pixel routine from the masked images, where the masked regions have been filled by the local mean isophote. Although it seems obvious that masked regions would reduce the calculated flux inside an aperture, in fact, this effect is rarely more than 5%–10% of the total flux of an elliptical. However, this effect is also unlike Poisson noise in that it always works to reduce the measured luminosity. The cleaned images are then integrated as a function of radius to produce curves of growth. An added feature is that as the outer apertures are integrated, their fluxes are corrected by the mean isophotal intensity as given by either the raw surface brightness profile or the Sérsic $r^{1/n}$ fit to the profile. This reduces the noise in the outer apertures and often produces a smoother convergence to a stable total flux.

The half-light luminosity, and radius, used in our bright elliptical sample was found to be unstable for the dE’s. Their smaller angular size and exponential profiles introduce an unacceptable error in the determination of the half-light radius. Instead, for this paper, we used the Holmberg radius, which is the radius where the $g$ surface brightness profile reaches 25 mag arcsec$^{-2}$. The Holmberg luminosity is the aperture luminosity calculated inside this radius and, typically, results in 92% of total of the total luminosity (although this varies slightly with filter choice; Schombert 2016). While this choice has little impact on the measured colors (color gradients are the dominant source of color variation), for relationships that compare the total luminosity (a proxy for total stellar mass) with color (e.g., the CMR), the aperture luminosity is corrected for the missing 8% to bring the luminosities in alignment with the half-light values from Schombert (2016).

In a majority of the missions, the error quoted in the archives for the total and aperture magnitudes severely underestimate the actual error found in this study (see Schombert 2016, Sections 2.2, 2.3, 2.4, and 2.5). This is due to the fact that their error calculations focus, primarily, on the Poisson noise that is proportional to device sensitivity and exposure time. However, for large extended sources ($D > 2$ arcmin) or ones that are low in mean surface brightness (i.e., dwarfs), the primary source of noise is uncertainty in the sky value and the variation of sky across the image. The sky for this study was determined using two separate algorithms. The first is the manual section of between 10 and 20 sky boxes (typically 20 by 20 pixels in size) in regions surrounding the target (outside its halo), but separate from other galaxies or bright star halos. The dispersion of the mean from the averages in each sky box provides the best value for the uncertainty in the sky value (Schombert 2013). The total errors quoted in this paper are then calculated as $3\sigma$ from the mean sky value applied to the sum of the pixels in each aperture. As a check of the correct sky value, the elliptical isophotes are fixed in shape and tabulated beyond the galaxy radius to the edge of the frames. These outer ellipse intensity values should converge on the sky value determined from the sky boxes. In the few cases where the two values disagree, the ellipse sky value was used, but the error estimates continued to use the dispersion between the sky boxes.

Full surface brightness analysis is performed on all filter images. Thus, a second determination of color is possible by examining color as measured from the difference in the surface brightness profiles directly. While any particular color surface brightness isophote contains much more error than the comparable aperture color at the same radius, at large radii this method can be more informative as the number of pixels
used is large compared to the sky error. Of course, color gradients are the primary use for multilayer surface brightness profiles. And, again, with the regularity of the shape of ellipticals, the run of color with radius is a direct measure of the projected 2D distribution of stellar populations. The best measure of the core color of an elliptical is the interpolation of the color surface brightness profiles to zero radius.

Apparent uncorrected luminosities are designated by lowercase letters (e.g., \(m_{\text{NUV}}\) for raw GALEX NUV luminosities). Absolute luminosities, radii, and colors are corrected for Galactic extinction following the prescription of Cardelli et al. (1989) and the \(E(B-V)\) values from NED. Magnitude units varied between the missions; GALEX, SDSS, and WISE used the AB/Vega system (NUV, \(u, \ g, \ r, \ i, \ W1, \ 3.6\), and 2MASS used the Johnson system (\(J, \ H, \ K\)). We have noted in our discussions when the various units were used the 3K CMB distances using the benchmark model values for the standard cosmological constants (in particular, \(H_0 = 75 \text{ km s}^{-1} \text{Mpc}^{-1}\)). A majority of the dE’s were located in the Virgo cluster, and a distance modulus of 31.09 was assumed. As none of the galaxies in this sample have redshifts greater than 0.04, no \(k\)-corrections were applied to the data. The final data products are too extensive to be listed in this publication. Instead, the author maintains all of the data, reduction scripts, and log files at his Web site (http://abyss.uoregon.edu/~js). We follow the philosophy of presenting all of the reduction techniques as user-enabled scripts, rather than a detailed description of the various steps leading from raw images to final luminosities and colors.

2.2. True Internal Colors

One point about galaxy colors that is often unspoken and assumed to be known to the reader is that a color quoted for a particular region in a galaxy does not represent the color of the stellar population at that 3D coordinate, but rather a pencil beam average of the stellar population colors between the observer and infinity. Thus, the measured color at a particular elliptical annulus traced by an elliptical fit of radius, \(r_{\text{in}}\), is, in fact, the luminosity-weighted sum of colors of all the isophotes at radii \(r > r_{\text{in}}\). This effect will be greater for small radii, where the pencil beam crosses through all the isophotes in the galaxy profile, and less for outer radii, where the pencil beam passes through a fewer number of isophotes with colors similar to the starting radii (for typical color gradients). Negative color gradients (decreasing color with radius) will result in underestimating the true color of a position with more significance for stronger gradients and steeper profiles.

Some information on this effect can be extracted if the run of the surface brightness and color with radius is known. For example, one can bootstrap backwards for each position, iterating on cells of luminosity perpendicular to the surface brightness profile using the annulus luminosity density as an estimate of the cells in the pencil beam (see Figure 1). Then, the colors from the radial gradient are assigned to each cell, weighted by cell size and luminosity, and then summed. This value is compared to the integrated color for that radius and iterated until they agree. The resulting color of the inner cell represents the true internal color at that radius; in particular, the extrapolation to the galaxy center then represents the true color at the core. The calculations depend on the assumed 3D shape that the pencil beam is passing through. However, numerically, for extreme prolate or oblate shapes, this is only a 5% correction, which is typically much less than the outer color errors, and this correction decreases toward the center.

An example of this impact on color gradients is shown in Figure 2. The raw color gradient is shown by the black data points with the true internal-corrected colors shown by the red line. The blue line is the total color of the galaxy from elliptical apertures. Note that the total color is lower than the mean color from the surface photometry due to the negative color gradient producing bluer colors in the outer isophotes, which contain more integrated flux, than in the inner core pixels. The true color is typically 0.01–0.02 redder for intermediate radii, but rises to 0.08 redder in \(g - r\) in the central regions. A true core color will be significantly redder (or bluer depending on slope of the color gradient) than a total or halo color. This will be considered in the discussion section (see Section 3.3).

2.3. WISE

As opposed to the photometry of normal ellipticals in Schombert (2016), we have added archival data from the WISE mission to the whole data set, mostly to offset the lack of 2MASS photometry for the dE’s in the sample due to the survey’s low limiting magnitude. The WISE MIDEX mission (Wright et al. 2010) was a cryogenically cooled 40 cm telescope equipped with a camera containing four mid-IR focal plane array detectors that simultaneously imaged the same \(47 \times 47\) arcmin field of view. The entire sky was imaged at
3.4, 4.6, 12, and 22 μm (labeled as the W1, W2, W3, and W4 filters) using a HgCdTe 1024 × 1024 array with 2.76 arcsec per pixel plate scale for the W1 filter. Processed images, obtained from IRSA, are flattened, sky-subtracted, calibrated frames with plate scales of 1.375 arcsec per pixel and a resolution of 8.5 arcsec PSF. The PSF is poor, compared to our other data sets, but adequate to obtain Holmberg magnitudes and colors.

The dE’s in this sample were all too faint to be detected in 2MASS K images, and very few were targeted by Spitzer. Thus, comparison to the bright elliptical sample was problematic in the near-IR. Instead, the WISE archive was searched for the dE’s in our samples (as well as the bright and faint elliptical samples) with GALEX and SDSS coverage. In total, 60 dE’s from the DF catalog met these criteria and have a full range of wavelength coverage. All of the ellipticals in the bright (252) and faint (60) samples had WISE coverage. Figure 3 displays two colors that cover all three major data sets (GALEX NUV, SDSS ugr, and WISE W1) and for the three components of our sample (bright ellipticals at \( M_K > -20 \), faint ellipticals between \(-20 > M_K > -16 \), and the dE’s selected by morphology). The dispersion is not due to photometric errors but rather to the well-known CMR, which is more evident at long wavelengths than at short (Bouquin et al. 2015). The dE’s notably distinguish themselves in visual appearance, and surface brightness profile shape and color.

It is worth exploring the behavior of the three near-IR filters from 2MASS, WISE, and Spitzer (K, W1, and 3.6 μm) since most SED models produce K colors and, hopefully, can be easily converted to W1 or 3.6 μm. These filters have wavelength centers at 2.16 μm (2MASS K), 3.35 μm (WISE W1), and 3.55 μm (Spitzer 3.6). The bandwidths are 0.26, 0.66, and 0.75 μm, where 2MASS K is in the Johnson system, and W1 and 3.6 μm are in the AB magnitude system. The sample of ellipticals with K, W1, and 3.6 μm observations were culled from the main sample. There were 253 ellipticals with \( K-W1 \) colors, and 80 ellipticals with \( W1-3.6 \) colors. The sample was taken as a whole, and mean colors were deduced using a jackknife average. Then, the sample was divided into two subsets at the midpoint in luminosity, one brighter than \( M_K = -21 \), the other fainter. The resulting values plus dispersions are listed in Table 1.

The small change in the near-IR colors is unsurprising given that each filter is close to each other in central wavelength, plus the SED of an old stellar population peaks at around 3 μm, and each filter is basically sampling a flat portion of a galaxy’s SED with little dependence on the metallicity of the galaxies. There is a slight change in color with absolute luminosity for \( K-W1 \) and \( K-3.6 \) (0.016 and 0.019, respectively), but this change is barely significant, and formal fits to the near-IR CMR produce a correlation coefficient of less than 0.15.

There is also very little evidence of a color term in the two-color diagrams, where \( K-W1, W1-3.6, \) or \( K-3.6 \) is on one axis. For example, in \( u-i \) versus the near-IR colors, there is a range from 2.0 to 3.4 in \( u-i \), but the mean \( K-W1 \) color only varies from 0.055 to 0.070, with a dispersion of 0.085. Any color variation is minor compared to the internal errors on the aperture colors. With respect to correcting the \( K \) magnitudes and colors from the SED models to \( W1 \), we have adopted a \( K-W1 \) color of 0.070, with the caveat that for the bluest dE’s, an additional correction of 0.010 could be applied and limits the interpretation of age and metallicity by that amount.

3. Discussion

The analysis of the colors of dE’s follows the procedure outlined in Schombert (2016) for bright ellipticals: the
empirical two-color relationships for all optical and near-IR filters, comparison to multimetallicity population models, and the CMR. For clarity, we divide the discussion of the two-color relations into those defined by filters close in wavelength (near colors) and those whose filters are widely separated in wavelength (far colors).

3.1. Near Colors

The colors of the new faint and dwarf ellipticals in our sample extend the relations found in Schombert (2016) by six more magnitudes in luminosity. The near colors are defined by the near-UV and optical filters (GALEX NUV, SDSS ugr). Four of these two-color relations, between neighbor filters, are shown in Figure 4 along with the Milky Way (MW) and M31 globular cluster colors from Galleti et al. (2009) and Peacock et al. (2010). The mean error bars for each of the samples are also shown. In general, the colors from each of the samples are coherent, meaning that galaxies that are blue (or red) in one color set are also blue (or red) in other filter combinations. The exception are NUV colors, which display a turnover at the reddest colors. As discussed in Schombert (2016), this behavior is well-modeled by the single abundance scenario proposed by Yi et al. (1998) and underlies the importance of a small metal-poor population to colors even in massive ellipticals dominated by metal-rich stars (see Rakos et al. 2008).

Also shown for the SDSS colors (ugri) are the stellar population models for 12 and 5 Gyr for varying mean metallicities. Again, as discussed in Schombert (2016), the bluer colors (u - g versus g - r) indicate that an internal metallicity distribution is required to match the global colors (the so-called multimetallicity models; Schombert & Rakos 2009); the bluer u - g colors are influenced by a small metal-poor population (also seen in the NUV colors), presumably a population of between 5% and 10% of the total stellar mass that is composed of the first generation of stars with near globular

Table 1

| $M_g$ | $K - W1$ | N  | $W1 - 3.6$ | N  | $K - 3.6$ | N  |
|-------|----------|----|-----------|----|-----------|----|
| < -21 | 0.075 ± 0.067 | 160 | 0.089 ± 0.028 | 39 | 0.177 ± 0.074 | 42 |
| > -21 | 0.059 ± 0.077 | 93  | 0.081 ± 0.072 | 41 | 0.148 ± 0.056 | 40 |
| Total  | 0.070 ± 0.073 | 253 | 0.086 ± 0.029 | 80 | 0.162 ± 0.066 | 82 |

Figure 4. Two-color relations for GALEX and SDSS near colors (NUV - u, u - g, g - r, r - i). Red symbols are bright ellipticals ($M_g < -20$), green symbols are faint ellipticals ($M_g > -20$), blue symbols are dwarf ellipticals (dE’s), and black crosses are M31 and MW globular clusters. All colors are based on Holmberg aperture luminosity values (the Holmberg radius determined in the g frames and applied to the other filters). Typical error bars as shown on the right side of every panel. The solid black line is a 12 Gyr SSP model; the dashed line is a 5 Gyr model (varying from $[\text{Fe}/\text{H}] = -2.5$ to +0.3). The magenta line shows the average colors of the 1850 globulars in the Virgo cluster (Powalka et al. 2016). The green line is the locus of RC3 Sb-Sm galaxies, i.e., a locus of star-forming colors.
cluster metallicities. The multimetallicity models (shown in Schombert 2016) follow the colors of the bright ellipticals to a greater degree than those of the single-metallicity models (SSP; see Schombert 2016).

The SDSS colors display the well-known degeneracy between age and metallicity. The 12 and 5 Gyr SSP tracks are indistinguishable in two-color space, although the 5 Gyr models require extremely high metallicities ([Fe/H] > 0.6) to match the colors of the brightest ellipticals. In a single two-color comparison, it is impossible to separate the possibility of very young stellar populations with high metallicities versus older stellar populations with low metallicities. Separation can be achieved with a longer wavelength baseline in color due to the fact that age and metallicity, while still coupled at all optical and near-IR colors, have varying contributions to color as one goes to longer wavelengths (see Section 3.3).

As noted by Schombert (2016), the trend for positively correlated colors is seen in all colors except for NUV − u. Elliptical colors are, in general, coherent from filter to filter (i.e., red galaxies are red in all filters). In addition, outliers are usually outliers across all of their colors, with the probable explanation that some contamination is in the galaxy itself or from undetected strong emission lines or simply a flaw in the calibration and/or reduction pipeline. Their rarity does not warrant extensive investigation as they are not relevant to the averaged results. Correlations between colors have the lowest scatter for widely spaced filters, mostly because filters close in wavelength have less dynamic range (the slope of the galaxy SED varies little over small changes in wavelength except near the 4000 Å break), and photometric errors play an increasing role.

A criterion for recent star formation in bright ellipticals was a NUV − r cutoff at 5.5 (Schawinski et al. 2007) of which 93% obey this selection. However, for luminosities fainter than −20, only 40% had redder colors and, for the dE sample, only 3% have redder colors. This probably does not reflect a steep increase in recent SF for lower mass ellipticals but, rather, is the effect of decreasing metallicity where colors bluer than NUV − r = 5.5 are typical for old stellar populations with mean [Fe/H] < −0.5 (Schombert 2016). A younger mean age is not ruled out in dE’s based solely on NUV colors; however, UV colors, by themselves, cannot conclusively demonstrate younger age. The locus of late-type RC3 galaxies is shown in the upper-right panel of Figure 4. At the blue end of this sequence are galaxies with current star formation rates (SFRs) between 0.10 and 1 M☉ per year. Only a handful of dE’s approach this color realm.

With respect to the three groups of ellipticals (bright, faint, and dwarf), the trend for bluer colors in all filters is evident. Where the bright ellipticals defined an extrapolation of the globular cluster colors in all filters, the faint ellipticals clearly overlap with the reddest globulars, and the dE’s are consistent with the mean globular clusters, leaving only the most metal-poor globulars at the extreme end in color. If color maps directly onto [Fe/H] (which is probably not the case for dE’s; see Section 3.4), then the faint ellipticals have [Fe/H] values slightly less than solar, and dE’s range from −1.5 to −0.5 in average metallicity. This is consistent with the CMR (see Section 3.3).

There is some tendency for the dE’s to be slightly bluer, on average, than the globulars in the bluest colors (NUV − g and u − g). However, they are in agreement for the redder colors (g − r and r − i). Any deduction of [Fe/H] from the colors, as in Schombert (2016), assumes a 12 Gyr age and agreement across the optical and near-IR colors with the bright ellipticals whose metallicity calibration is set by the globular clusters’ two-color relations. We will explore this discrepancy as it impacts the estimate of the mean age and metallicity for dE’s in Section 3.4.

We also note the recently published SDSS and K colors for a broad sample of Virgo globular clusters (Powalka et al. 2016), shown in Figure 4 by a magenta line. This line represents a moving average in color space of 1850 globulars. The trend in two-color space is identical to that for MW and M31 globulars, although there is a tendency toward slightly redder blue colors at the high metallicity end of the Virgo globulars sequence. Whether this signals a break in the age–metallicity relation for globulars in Virgo, compared to the MW and M31, or a shift in the color calibration at redder colors is unclear. We will continue to use the MW/M31 sequence to define the 12 Gyr locus and calibration of [Fe/H] for ellipticals as outlined in Schombert (2016).

3.2. Far Colors

The similarity between normal ellipticals and dE’s, and globular clusters, continues in the colors with the largest wavelength separation shown in Figure 5. Here, the WISE filter W1 replaces the 2MASS K filter from Schombert (2016) with only a nominal correction to stellar population models to jump from K colors to W1 colors. Again, the trends from Schombert (2016) are reproduced, now with a greater range of galaxy luminosities (i.e., bluer colors). The optical to near-IR colors display high uniformity from bright to dwarf ellipticals. This would rule out a strong AGB contribution from dE’s compared to normal ellipticals as this would be signaled by a sharp change in the slope of the optical to near-IR two-color diagrams (see Schombert & McGaugh 2014). A lack of AGB colors, in turn, rules out a strong star formation in the last few gigayears.

As with the near colors in Figure 4, the far colors also display the behavior of the dE’s overlapping with the intermediate-metallicity globular clusters ([Fe/H] between −1.5 and −0.5). SSP models for the far colors have very little separation by age, tracking parallel to color–color sequences with only the metallicity providing the sole variation in color. Thus, these individual colors, by themselves do not distinguish between a subsolar dE population of 12 Gyr or a near-solar metallicity dE population with ages less than a Gyr.

However, there is a subtle change as one goes from u − W1 to i − W1. While the bright and faint normal ellipticals maintain their relative distributions with respect to globular cluster colors, the dE’s become increasingly redder with respect to the mean globular color. This can be seen by using the mean color of the globular clusters and bright ellipticals as an anchor to the reddest and bluest colors from u to W1. The mean color of the faint elliptical sample lies at 0.71, 0.69, 0.69, and 0.68 in the fraction of this interval for u − W1, g − W1, r − W1, and i − W1. On the other hand, the mean dE sample color lies at 0.26, 0.19, 0.16, and 0.12 for the same colors and interval. In other words, the mean color for dE’s decreases, with respect to normal ellipticals, as we go from u − W1 to i − W1.

This behavior is unexpected since the color of normal ellipticals with respect to the globular clusters was extremely consistent from GALEX to Spitzer (Schombert 2016). In fact, assigning a metallicity value, just from a normal elliptical’s color using globulars as a calibration, produced a consistent and robust measure even if the scatter in an individual color
was high. This procedure will fail for dE’s as using colors closer in wavelength will result in increasing low [Fe/H] values. The most obvious explanation for this type of color behavior is an age effect, which was first indicated with narrowband colors (Rakos & Schombert 2004), and will be discussed in Section 3.4.

3.3. Color–Magnitude Relation

It was demonstrated in Schombert (2016) that the CMR is primarily a relationship between stellar luminosity (a proxy for total galaxy stellar mass) and mean metallicity. Although limited age and recent star formation effects cannot be completely excluded (e.g., Faber et al. 1995), these effects are at the 5% level for colors (although may have a larger contribution for spectral index studies). The slopes for the CMR, found in Table 3 of Schombert (2016), are identical to the slopes from other CMR studies (Bernardi et al. 2003; Chang et al. 2006). Changes in the slope of the CMR with redshift is an interesting measure of galaxy chemical evolution, so accurate slope values for zero redshift samples are an important parameter.

The CMRs for near and far colors are shown in Figures 6 and 7. There is no evidence that the new sample of faint ellipticals deviates from the CMR slopes fit to the bright ellipticals (shown in each figure by the green symbols). This makes a solid statement that power-law-shaped ellipticals, which define the bright and faint elliptical sample (Schombert 2017), also obey the same structural and stellar population relationships. This will be somewhat of a challenge to many hierarchical models of galaxy formation, which predict extended epochs of star formation that vary significantly with mass (Naab et al. 2007). However, age determination with colors allows for a great deal of flexibility with respect to the first epoch of star formation and its initial duration (for example, a shorter duration at a later epoch will mimic a long duration SF event at early epochs; see below).

There is no evidence in any color combination that normal ellipticals are composed of a significant stellar population with ages less than 12 Gyr (Rakos et al. 2008; Schombert 2016; although see a dissenting view in Graves et al. 2010). And, thus, the slopes of the various CMRs are consistent, across all of the wavelengths, with a pure metallicity interpretation in a generally old stellar population. Even small variations in mean age (greater than 4 Gyr) would result in different slopes between blue and near-IR colors (if age varied with stellar mass; see Schombert & Smith 2012; Eigenthaler & Zeilinger 2013). As demonstrated in Schombert (2016), there is no indication of an age effect in the CMR, and the new sample of fainter ellipticals supports this conclusion. This implies that the CMR is, in fact, purely a metallicity relationship, presumably between the stellar mass that produces metals and, later, produces the galactic winds that remove the remaining gas and halt star formation and chemical enrichment (see Matteucci 2007).
The identical CMR slopes for bright and faint ellipticals implies that we can use the same techniques of assigning a mean metallicity to the new, low-luminosity sample as we did the brighter ellipticals in Schombert (2016). As outlined in Schombert (2016), each color can be assigned a metallicity–color relation as guided by the predictions from multimetallicity population models (Schombert & Rakos 2009) tied to globular cluster [Fe/H] values. A guide to the accuracy of this method is to compare the spread in [Fe/H] as deduced from colors. This technique produced a mean dispersion of 0.15 dex in metallicity for both the bright and faint elliptical samples. Mapped onto the CMR, this results in [Fe/H] values of 0.5 for the brightest ellipticals, decreasing to −0.2 for ellipticals around −19.

The behavior of the colors for dE’s differs from that of the normal ellipticals in that a majority (varying between 60% and 80%) have colors bluer than expected for their luminosities based on a linear extrapolation of the CMR. Small number statistics make it impossible to determine if the dE’s form their own sequence or are a nonlinear extension to the normal elliptical sequence. We can only state that the brightest dE’s have colors near the CMR, and the deviation becomes greater at lower luminosities. And, while most of the dE’s in the sample have colors that place them below an extrapolation of the CMR from normal ellipticals, that deviation is greatest at the longest wavelengths. From the near-IR colors, there is a clear indication that dE’s deviate from normal ellipticals with decreasing luminosity to a greater extent than is seen in the optical colors.

If one assumes that metallicity is still the primary driver for the CMR in dE’s and one applies the same metallicity–color relations for normal ellipticals to dE’s, then the CMR for dE’s implies [Fe/H] values near −0.2 for the brightest dE’s, decreasing to −1.0 for the faintest dE’s in our sample. However, this is not consistent between the colors. For example, the u and W1 colors derive [Fe/H] values near −1.5 for the faintest dE’s, while the gri colors derive much higher values near −0.5 for the same galaxies. This type of behavior, not found in normal ellipticals, suggests that another parameter, the most obvious being age, is in play (although one could entertain extreme IMF and extinction values).

### 3.4. Younger Age for Dwarf Ellipticals

It is possible to estimate the magnitude of an age effect on the complete sample of dE’s without assigning a specific age to each galaxy. The technique follows the prescription outlined in Schombert (2016) with respect to bright ellipticals. A metallicity can be assigned to each color combination based on a procedure of taking SSP models and convolving them to a multimetallicity framework (one that assumes an underlying metallicity distribution based on high-resolution studies of nearby ellipticals; see Monachesi et al. 2011). The zero point to these multimetallicity models is set by the globular cluster colors (both MW and M31 samples), the mean [Fe/H] values...
of which are determined directly from their CMDs. As discussed in Schombert (2016), single-population models are a poor description of bright elliptical colors, whereas multi-metallicity predictions reproduce the mean colors and CMRs of bright ellipticals without any need to introduce a younger component to a pure 12 Gyr population.

Using these colors in metallicity models, and assuming a 12 Gyr age, each color predicts an [Fe/H] value. Any systematic deviations from a mean [Fe/H] based on an average of all the colors would signal a problem for the technique, such as a second parameter other than metallicity (e.g., age or IMF variations) as the main determinant in the continuum shape of galaxy spectra (i.e., colors). None were seen in the faint plus bright elliptical samples, and the scatter in the deduced [Fe/H] values were solely owing to error in the colors.

We can now apply those metallicity calibrations to the dE colors, again with the assumption of a solely metallicity-driven continuum and a mean age of 12 Gyr. As expected from the deviations in the CMR, this procedure fails. The colors for faint ellipticals are in line with those of the bright ellipticals (see Figure 8), and even the brightest dE’s are consistent from color to color. But a majority of the dE’s do not produce consistent [Fe/H] values. Typically, they overestimate the [Fe/H] for blue colors and underestimate the [Fe/H] for red and near-IR colors. One such color combination is shown in Figure 8 for the metallicity deduced from g − r versus the metallicity deduced from g − W1. The normal ellipticals display a good one-to-one correspondence between the calculated [Fe/H] values. However, the dE’s begin to deviate below metallicities of −0.3, and a majority have near-IR calculated [Fe/H] values 0.5 dex below those calculated from optical colors.

If one relaxes the age requirement of 12 Gyr, for example assuming a mean age of 5 Gyr, then one gets the resulting metallicity track as shown in Figure 8 (green dotted track). The deviation in color is well-matched to an age effect, but now the deduced [Fe/H] values become non-unique as there is a wide range of possible age and metallicity combinations that produce the observed colors. This range can be narrowed down using multi-age tracks across several color combinations. The result of this numerical experiment is that dE’s seem to range in age from 12 to 6 Gyr in age, and −0.3 and −1.4 in [Fe/H]. There is a clear trend of decreasing metallicity and decreasing age with luminosity (stellar mass). The positions of the Local Group and Fornax dE’s, with CMD-determined ages and metallicities, are indicated using the model predictions. Their positions agree well with the general trend of the dE sample.

4. Conclusions

A difference in the CMRs for normal and dwarf ellipticals can be traced back to Caldwell (1983). His Figure 3 displays the U − V colors for a small sample of Virgo bright ellipticals plus a sample of 19 dE’s. While the bright end of the CMR is ill-defined, the dE’s clearly lie blueward of a linear extrapolation of the bright elliptical trend. Interpretation at that time focused on recent star formation in dE’s, but concluded that massive stars were missing and that the bluer colors were due to a younger mean age.

Some curvature in the optical CMR, at high and low luminosities, was detected by Bernardi et al. (2011). They covered a range of −18 to −24 in SDSS r, compared to the range in our study of −15 to −24. We do not, statistically, detect an upturn at high luminosities in our sample, but the amount they claim is within our errors. An upward turn at high luminosities is interpreted by Bernardi et al. as a signal of major mergers in the history of bright ellipticals. Our data do not confirm or falsify this conclusion. The shape of the CMR at the bright end appears to be independent of environment (De Propris et al. 2013), supporting our old age, pure metallicity interpretation as the internal process of chemical enrichment dominates. The downturn they find at low luminosities is at the same luminosity that we find in our dwarf sample (first seen by Janz & Lisker 2009), thus they agree with our general observations of the low-mass end. Another example of a blueward trend in the CMR at low luminosities is found in Agulli et al. (2016), who detect a blueward downturn for red sequence cluster members of Hercules (A2151). While they cannot separate out galaxies by morphological type, there is a clear trend for the red sequence members of their spectroscopic survey to display bluer colors at luminosities fainter than −18 with respect to the expectation from a linear fit to the bright end of the CMR (see their Figure 1).

By contrast, Roediger et al. (2017), who studied the CMR in Virgo down to $M_r = -9$, do not identify a downward trend for dE’s, but instead find a surprising flattening of color for galaxies fainter than −14, well below our sample limit. It is difficult to make a comparison with our sample as their sample numbers are very low for ellipticals brighter than −18 (i.e., the normal elliptical CMR is ill-defined for their sample), and we have no ellipticals fainter than −14 in our sample. Their conclusion, that very low-mass galaxies quench in star formation at the same epoch to produce similar colors, does

Figure 8. Example of [Fe/H] deduced from colors, calibrated to the MW/M31 globular cluster metallicities (Schombert 2016). Bright and faint ellipticals produce coherent [Fe/H] values from color to color ($\tau = +0.15$ dex). However, the dwarf elliptical sample deviates from the line of unity in a systematic fashion with color, indicating an age effect. A 5 Gyr model is placed in the same color–color space which deviates downward for metallicities deduced from near-IR colors, dE’s range from 2 to 8 Gyr younger than normal ellipticals, with mean age decreasing with decreasing dwarf mass. Also, the positions for three dE’s in the Local Group (M32, NGC 147, and NGC 185) plus one Fornax dE (NGC 1396) are indicated using their CMD-determined age and metallicities with respect to the models.
not seem to apply to our dE’s. A similar problem is found for a test of the linearity of the CMR in Virgo by Smith Castelli et al. (2013). In that study, the focus was on the $g - z$ CMR of Virgo ellipticals between $-16$ and $-20$. Again, the CMR is ill-defined, with few bright ellipticals to stabilize the fitting of the high-luminosity end. However, there was no evidence of a blueward trend between ellipticals brighter than $-18$ and those fainter than this demarcation.

Regardless of the filter combination, we confirm the main conclusion first expressed by Janz & Lisker (2009) that normal and dwarf ellipticals do not follow one, linear CMR. With the assumption that the deviation from a normal elliptical CMR for dwarfs is real and systematic across the colors from GALEX to WISE, we present an interpretation based on a younger age for low-mass ellipticals. We base this conclusion on the fact that the dE’s deviate from the metallicity–color relations, defined by normal ellipticals, in a coherent fashion for each color combination, a trend that is predicted by SSP models, calibrated to globular cluster ages and metallicities, and indicates that the mean age of the stellar population in dE’s is younger than normal ellipticals by between 2 and 8 Gyr (younger with decreasing luminosity). With these younger ages, the deduced metallicities range from $-0.5$ on the high-mass side to $-1.5$ for the lower mass dwarfs, in agreement with the metallicities deduced from dE RGB CMDs (Caldwell 2006).

A younger mean age for dE’s comes as no surprise given the detailed star formation history (SFH) results for M32, our nearest dE (Monachesi et al. 2011). To summarize the CMD results for M32, they find a mean metallicity of the RGB of $-0.2$, but with a wide spread ranging from $-1.0$ to solar. Analysis of the red clump gives a mean age of $8–10$ Gyr (i.e., 2 Gyr younger than normal ellipticals), but the detection of AGB stars above the RGB indicates some component of a 5 Gyr intermediate-age population. Using a mass-weighted analysis, Monachesi et al. (2012) find that 40% of the stellar population in M32 has an age between 2 and 5 Gyr, with the remaining stars being older than 5 Gyr for an average age of 7 Gyr for all the stars. For the mean metallicity, this age agrees well with the color trend in Figure 8 where the dE’s with [Fe/H] values between $-0.5$ and solar have only slightly younger ages than normal ellipticals (in the 8 Gyr range).

In a similar analysis, Mentz et al. (2016) find the age and metallicity of NGC 1396 (a well-studied Fornax dE) to be 6 Gyr and $-0.4$, respectively. Geha et al. (2015) find values of 10 Gyr and $-1.0$ for NGC 185, and 6 Gyr and $-0.5$ for NGC 147, the other two dE companions to M31. These values, and those for M32, are shown in Figure 8 and are consistent with the trend of luminosity and age for the entire dE sample. In addition, Rakos & Schombert (2004) found dE’s are 3–4 Gyr younger than bright ellipticals in Coma using narrowband continuum colors between 3500 and 5500 Å. Thus, a different age for stellar populations in dE’s, compared to bright ellipticals, is well-established.

Lastly, Sybilska et al. (2017) find, using SAURON results for 12 Virgo dE’s, that their sample galaxies contain two stellar populations: an old (12 Gyr) population and a younger (age < 5 Gyr) population with varying degrees of dominance. They conclude that the two populations are due to either extended SF (longer duration) or a second burst, leaning toward an extended SF interpretation. The range of ages presented by Sybilska et al. agrees well with our colors, although the [Fe/H] values are much lower than those we deduce from our multimetallicity models.

It is important to note that assigning a mean age by color to dE’s does not distinguish between a scenario where the initial epoch of star formation is at lower redshifts than normal ellipticals, or if that initial epoch was extended in duration such that the distribution of stellar ages peaks at the mean age value. In fact, the proposal by Thomas et al. (2005) based on spectral indices (particularly the $\alpha$/Fe ratio) is that lower mass normal ellipticals have increasing SF duration times. Here, the scenario is that all ellipticals have a common (and early) initial stage of SF, but lower mass normal ellipticals peak in star formation at later epochs (typically 2–3 Gyr later than the most massive ellipticals). Given the information gleaned from a handful of nearby dE’s that have high-resolution CMD imaging, it appears that the latter scenario is more probable as a majority of these nearby dwarfs have a significant fraction of their stars in resolved old populations with ages greater than 10 Gyr. Duration versus a later epoch of SF can be tested by color models; however, the $\alpha$/Fe index is a more sensitive indicator of duration, at least for the first few Gyr before SN I begin to enrich a galaxy with Fe.

In addition, there is no strong motivation to presume that the SFH of dE’s resembles that of normal ellipticals. Aside from their lack of visible structure (i.e., spiral arms) and no SF features (i.e., H II regions), the family of dE’s has little else in common with normal ellipticals as they are structurally and kinematically distinct from the normal elliptical sequence (Schombert 2017). It also seems difficult to understand how normal ellipticals can be built from small objects like dE’s or dIrr’s given the differences in their stellar populations, unless this construction occurs at redshifts before the initial SF epoch. The fact that the mean age of dE’s appears to approach the mean age of normal ellipticals at higher luminosities, in a smooth and uniform fashion (see Figure 8), suggests that an independent process guides the SFH of dE’s separate from the SFH process of ellipticals, but ends with similar patterns of SF at the highest dwarf masses.

The most commonly accepted evolutionary scenario for all types of galaxies since $z = 1$ is the so-called downsizing scenario (Cowie et al. 1996; Gavazzi & Boselli 1996), with massive galaxies forming the bulk of their stars in short, high-SFR periods at earlier epochs, whereas less massive galaxies have delayed SFHs which are extended over a longer time period (Gavazzi & Boselli 1996; Nelan et al. 2005; Thomas et al. 2005; Jimenez et al. 2007; Fontanot et al. 2009). In that limited context, the colors of dE’s presented herein agree with that scenario. However, there is no evidence that normal ellipticals display any variation in age (although it is nearly impossible to distinguish an age change of less than 2–3 Gyr from an old 12 Gyr population). Recchi et al. (2012) find that the $\alpha$/Fe index varies uniformly with stellar mass and also interpret this relationship as smaller galaxies forming over longer timescales (downsizing), allowing a larger amount of Fe (mostly produced by SN Ia) to be released and incorporated into newly forming stars. In addition, Fontana et al. (2004) find that the typical M/L ratio of massive ellipticals is larger than that of less massive ones, suggesting that their stellar population formed at redshifts higher than those of dE’s (see also Cappellari et al. 2013).

The mechanisms for halting star formation typical falls into two categories: quenching (Bundy et al. 2006) and exhaustion
For normal ellipticals, which appear to have a majority of their stars in the form of an old, metal-rich population, their $\alpha$/Fe ratios argue for an exhaustion process to dominate, presumably where the exhaustion is triggered by the removal of large quantities of gas by galactic winds (Matteucci 2004). For dE’s, since their existence is strongly tied to a cluster environment (there are very few dE’s in the field; Sandage et al. 1985), a quenching mechanism due to ram pressure stripping is implied. If the trend from Figure 8 is generic, then lower mass dE’s have longer durations of initial SF and, therefore, younger mean ages than higher mass dE’s, the age and [Fe/H] values of which continue the pure metallicity sequence of normal ellipticals. The age difference detected in dE colors is similar to the trend of age/metallicity seen in the Peng et al. (2015) study of SDSS galaxies.

The dilemma with a longer duration of SF for lower mass dE’s is that longer timescales should produce higher metallicities; where the opposite is seen, the lowest mass dE’s have the lowest metallicities. This presumes an SFR that is similar in mass. We can use the stellar mass–SFR correlation for low surface brightness (LSB) dwarfs from the SPARC data set (Lelli et al. 2016) as a crude indicator of initial SFR. The so-called main sequence for LSB galaxies has a slope of unity with a typical SFR of 0.0003 $M_\odot$ per yr$^{-1}$ for stellar masses of $10^9$ $M_\odot$, rising to 0.04 at a stellar mass of $10^{10}$ $M_\odot$ (McGaugh et al. 2017). Over durations of 8–2 Gyr with increasing dE mass, this corresponds to between 10% and 25% of the needed mass to make a present-day dE. Thus, the initial SFRs would need to be only increased by a factor of 5 at early epochs to produce the objects we see today as quiescent dE’s. These low rates of star formation would inhibit chemical enrichment, and the deduced [Fe/H] values for the dE’s in this sample are only slightly metal richer than present-day LSB dwarfs of similar stellar mass (Schombert & McGaugh 2015).

The last remaining question is what kind of galaxy, in terms of structure, would be produced from a history of early, but low-level SF, which is halted suddenly by infall into the cluster environment? The presumption here is that LSB dwarfs and young dE’s follow the same style of star formation at similar rates during the era of galaxy formation. The gas is converted into stars until the gas supply is exhausted (which has yet to happen for LSB dwarfs) or the gas supply is removed by tidal stripping (the probable event for cluster dE’s to halt star formation). In this scenario, the stellar densities between LSB dwarfs and dE’s should be similar, with slightly higher central densities expected for dE’s owing to a slightly higher SFR expected. Figure 9 displays this comparison using the central surface brightness of dwarf galaxies based on exponential fits. The LSB galaxies are taken from the SPARC sample (where 3.6 $\mu$m mag are converted to W1 mag) and follow the same trend as dE’s for absolute luminosity versus central surface brightness. The dE’s are about 0.5 mag higher in central surface brightness compared to SPARC LSB’s, but have similar central densities compared to the higher SFR sample from 11HUGS (Lee et al. 2007) and James et al. (2004). A KS test rejects the hypothesis that the dE and LSB samples are similar (the $p$-value was below 1%). Thus, the scenario proposed herein is that cluster dE’s are cousins to field LSB dwarfs rather than high-SFR BCD’s or dIrr’s. Their evolution was slightly faster in the past than the current values for LSB galaxies, an evolution that was presumably cut short by the entrance into a disruptive cluster environment where the gas supply was stripped and SF was halted. This scenario makes it difficult to assemble normal ellipticals from dE’s, as their stellar populations have very different components, and will be a challenge for galaxy formation scenarios that depend on dry mergers.

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Figure 9. Relationship between total luminosity (i.e., total stellar mass at W1) and central surface brightness ($\mu_W$) based on exponential fits to the W1 surface brightness profiles. The blue symbols are gas-rich LSB dwarfs from the SPARC database. Red symbols are the dwarf ellipticals from this study. The green line is a moving average of the 11HUGS and James et al. data set for 462 late-type galaxies. The dashed lines are the moving average for the SPARC and dE samples. The dE’s overlap the highSFR Irr sample of 11HUGS and are slightly higher in density than present-day LSB galaxies. The interpretation is that dE’s had slightly higher SFRs than present-day LSBs, resulting in slightly higher central stellar densities. However, the SF history of dE’s would have been remarkably similar to present-day LSBs, i.e., slow, inhibited SF, until the cluster environment quenched the SF and removed the remaining gas. The low stellar densities and similar [Fe/H] values to present-day LSB’s suggests a common star formation history.
