INTERNAL DYNAMICS, STRUCTURE, AND FORMATION OF DWARF ELLIPTICAL GALAXIES. II. ROTATING VERSUS NONROTATING DWARFS

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ABSTRACT

We present spatially resolved internal kinematics and stellar chemical abundances for a sample of dwarf elliptical (dE) galaxies in the Virgo Cluster observed with the Keck telescope and Echelle Spectrograph and Imager. In combination with previous measurements, we find that four out of 17 dE’s have major-axis rotation velocities consistent with rotational flattening, while the remaining dE’s have no detectable major-axis rotation. Despite this difference in internal kinematics, rotating and nonrotating dE’s are remarkably similar in terms of their position in the fundamental plane, morphological details, stellar populations, and local environment. We present evidence for (or confirm the presence of) faint underlying disks and/or weak substructure in a fraction of both rotating and nonrotating dE’s, but a comparable number of counterexamples exist for both types that show no evidence of such structure. Absorption line strengths were determined based on the Lick/IDS system (Hβ, Mg b, Fe5270, and Fe5335) for the central region of each galaxy. We find no difference in the line-strength indices, and hence stellar populations, between rotating and nonrotating dE galaxies. The best-fitting mean age and metallicity for our sample of 17 dE’s are 5 Gyr and [Fe/H] = −0.3 dex, respectively, with rms spreads of 3 Gyr and 0.1 dex. The majority of dE’s are consistent with solar [α/Fe] abundance ratios. By contrast, the stellar populations of classical elliptical galaxies are, on average, older, more metal-rich, and α-enhanced relative to our dE sample. The line strengths of our dE’s are consistent with the extrapolation of the line strength versus velocity dispersion trend seen in classical elliptical galaxies. Finally, the local environments of both rotating and nonrotating dE’s appear to be diverse in terms of their proximity to larger galaxies in real or velocity space within the Virgo Cluster. Thus, rotating and nonrotating dE’s are remarkably similar in terms of their structure, stellar content, and local environments, presenting a significant challenge to theoretical models of their formation.

Key words: galaxies: abundances — galaxies: dwarf — galaxies: kinematics and dynamics

1. INTRODUCTION

Dwarf elliptical (dE) galaxies are the dominant galaxy type in nearby galaxy clusters, accounting for more than 75% of all objects in these regions down to a limiting magnitude of \(M_V = -14\) (Bingelli, Sandage, & Tammann 1988; Trentham & Tully 2002). They are characterized by low effective surface brightness \(\mu_{e, eff} < 22\) mag arcsec\(^{-2}\) and faint luminosities \(M_V \geq -18\) (for a review, see Ferguson & Binggeli 1994). Unlike classical elliptical galaxies whose surface brightness profiles tend to be well fitted by the de Vaucouleurs’ \(r^{1/4}\) law (de Vaucouleurs 1948), dE’s have brightness profiles that are characterized by Sérsic profiles (Sérsic 1968) with indices ranging between \(n = 1\) and \(3\) (where \(n = 1\) corresponds to an exponential law and \(n = 4\) to an \(r^{1/4}\) law), making them appear more diffuse than classical elliptical galaxies of the same total magnitude. A direct illustration of this is the discontinuity in surface brightness between dE’s and the low-luminosity end of classical elliptical galaxy sequence (Kormendy 1985; Bender, Burstein, & Faber 1992; however, see Graham & Guzmán 2003).

Detailed studies of the internal dynamics of Local Group dE’s have been carried out over the past two decades (e.g., Bender, Paquet, & Nieto 1991), but, until recently, only integrated measurements were available for more distant dE’s (Peterson & Caldwell 1993). The number of dE’s outside the Local Group with spatially resolved measurements of internal kinematics has increased dramatically in the last few years (De Rijcke et al. 2001; Geha, Guhathakurta, & van der Marel 2002; Pedraz et al. 2002; Simien & Prugniel 2002). These observations have revealed an intriguing diversity of properties: several dE’s in the Virgo and Fornax clusters appear to be roughly consistent with rotational flattening, while others have no detectable rotation similar to their Local Group counterparts (Bender et al. 1991). This range in rotation velocities is a newly found feature of cluster dE’s that must be explained by theoretical models of their formation.

1 Data presented herein were obtained at the W. M. Keck Observatory, which is operated as a scientific partnership among the California Institute of Technology, the University of California, and the National Aeronautics and Space Administration. The Observatory was made possible by the generous financial support of the W. M. Keck Foundation.

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Formation scenarios for dE galaxies fall into two broad categories: (1) dE’s are old, primordial objects, and (2) dE’s have recently evolved or transformed from a progenitor galaxy population. Two independent lines of observational evidence favor the latter category. Primordial dwarf galaxies are expected to be less strongly clustered than massive galaxies in the context of hierarchical structure formation theories, whereas the dE-to-giant galaxy ratio is observed to be higher in regions of higher galaxy density (Ferguson & Sandage 1991). The radial velocity distribution of galaxies in the Virgo Cluster suggests that dE’s may be a recently accreted population (Bothun & Mould 1988; Conselice, Gallagher, & Wyse 2001).

From simulations, Moore, Lake, & Katz (1998) suggest that galaxy harassment in clusters can morphologically transform a spiral galaxy into a dE. Recent observations of embedded disks in a handful of Virgo and Fornax dE’s support this model (Jerjen, Kalnajs, & Binggeli 2000; Barazza, Binggeli, & Jerjen 2002; De Rijcke et al. 2003). Galaxy harassment partially disrupts the rotational motion of the progenitor galaxy while increasing velocity dispersions, and is expected to result in a range of rotational velocities. It is yet unclear whether this scenario can reproduce the large fraction of dE’s with extremely low rotational velocities (Geha et al. 2002). Another model suggests that gas-rich dwarf irregular and/or small spiral galaxies are transformed into dE’s through the process of ram pressure stripping (Faber & Lin 1983). In this case, dE’s would be expected to largely retain the rotational properties of their progenitors. The degree of rotational support present in dE galaxies is thus a strong constraint on formation models.

We investigate whether or not dE properties such as morphology, stellar population, and local environment are correlated with the degree of internal rotation. A sample of 17 dE’s in the Virgo Cluster forms the basis of this study. In § 2, we present Keck spectroscopy and imaging for 11 dE’s and combine these observations with the six additional dE’s previously presented in Geha et al. (2002). In § 3, we discuss the kinematic profiles of this sample and distinguish between rotating and non-rotating dE’s. In §§ 3.2–3.4, respectively, we examine the position of the rotating and nonrotating subsamples in the fundamental plane, study galaxy morphologies, and probe stellar populations using absorption line strength indices. In § 4, we compare the local environments of rotating and nonrotating dE’s within the Virgo Cluster. Finally, in § 5, we argue that major-axis rotation velocity appears to be uncorrelated with other internal properties and local environment for the dE’s in our sample and discuss the broader implications of these results.

Throughout this paper, a Virgo Cluster true distance modulus of \( m-M = 30.92 \) is adopted, i.e., a distance of 15.3 Mpc, as determined by the Hubble Space Telescope\(^4\) (HST) Key Project on the extragalactic distance scale (Freedman et al. 2001). Line-of-sight extinction values are taken from Schlegel, Finkbeiner, & Davis (1998) assuming a standard Galactic reddening law with \( R_V = 3.1 \).

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\(^4\) Based on observations with the NASA/ESA Hubble Space Telescope, obtained at the Space Telescope Science Institute, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS 5-26555.
even after the slight smearing caused by interpolation during the rectification process.

A two-dimensional wavelength solution was determined for each rectified echelle order from a combined Cu/Ar/Hg/Ne arc lamp spectrum. The wavelength solution was applied to the data (to render vertical lines of constant wavelength) using either a logarithmic wavelength interpolation scheme (with 11.4 km s\(^{-1}\) pixels) or linear interpolation (with 0.2 Å pixels) for the kinematic and line-strength analyses, respectively. The sky spectrum was determined for each combined frame from a ~2\(\prime\) wide section near the end of the slit farthest from the galaxy center (\(r \sim 15\prime\)) and was subtracted from the rest of the two-dimensional spectrum. The galaxy data were extracted into one-dimensional spectra in spatial (radial) bins to achieve a signal-to-noise level of S/N > 10 per pixel in all radial bins, while ensuring that the spatial bin size is at least as large as the FWHM of seeing during the observations (~0.8\prime). The galaxy continuum flux in each order of one-dimensional spectrum was then individually normalized to unity. Finally, the strips from the different echelle orders were combined, weighted by the noise frame, to create a single two-dimensional long-slit spectrum. The reddest and two bluest echelle orders were not included in the analysis due to low signal-to-noise ratio; the final combined spectrum covers \(\lambda\lambda4800–9200\) Å.

The mean line-of-sight velocity and velocity dispersion as a function of radius were determined using a pixel-fitting method described in van der Marel (1994). As demonstrated in Geha et al. (2002), internal velocity dispersions from this observing setup can be measured down to the instrumental resolution of 23 km s\(^{-1}\) with an accuracy of \(\sim 1\%\). Velocity profiles were recovered using template stars ranging in spectral type from G8 III to M0 III. The best-fitting template stars, HD 48433 and HD 40460 (both K1 III stars with \([Fe/H] = -0.13\) and \(-0.42\) dex, respectively) were used to recover the velocity and velocity dispersion profiles presented in \(\S\) 3.1.
Imaging

Imaging for the above spectroscopic dE sample came from two sources: archival HST Wide Field Planetary Camera 2 (WFPC2) images were available for five of the dE’s, while the remaining six were imaged with ESI during our spectroscopic run. The WFPC2 data, first presented in Miller et al. (1998) and Stiavelli et al. (2001), consist of 2 × 230 s WFPC2 images in the F555W (V) bandpass, except in the case of VCC 1261 where only archival WFPC2 F702W (R-band) imaging was available (Rest et al. 2001); photometric parameters for this galaxy were transformed to V-band assuming V/R = 0.5 (Prugniel & Heraudeau 1998). The WFPC2 images were cleaned of cosmic rays and combined; instrumental magnitudes were calibrated to standard passbands using the transformations of Holtzman et al. (1995). The ground-based ESI images consist of 2 × 200 s V-band exposures, with the seeing FWHM ranging between 0″6 and 0″7. In imaging mode, ESI has 0″154 pixels and a 2′ × 8′ field of view. The ESI images were bias-subtracted and flat-fielded using twilight sky exposures. Photometric zero points were determined based on observations of standard-star fields taken on a different (but also photometric) night; our surface photometry and total magnitudes agree with previously published values.

Surface brightness profiles were determined for all galaxies using the IRAF ELLIPSE isophotal fitting routine (Jedrzejewski 1987). Half-light effective radii (r_eff) and effective surface brightnesses (μ_eff) were calculated by fitting a Sérsic profile of the form I(r) = I_0 exp [(r/r_0)^1/n] to the observed V-band data. A Sérsic index n = 1 represents an exponential profile, and n = 4 is a de Vaucouleurs’ law. The best-fit Sérsic profile is determined by nonlinear least-squares fitting to the region r = 1″–20″; in this region, contributions from the nucleus and effects of the different spatial resolution of ESI and WFPC2 should be negligible. Sérsic indices, half-light effective radii, and effective surface brightnesses are listed in Table 3. The average ellipticity and B_4 parameter (discussed in § 3.3) also listed in this table were determined over the same radial range.

3. RESULTS

3.1. Kinematic Profiles

Kinematic profiles for the 11 Virgo Cluster dE’s are presented in Figures 2 and 3. We have separately plotted dE’s...
### TABLE 3

**Photometric Properties**

| Galaxy                  | Imaging | $\epsilon$ | $n_{\text{Sersic}}$ | $r_{\text{eff}}$ [arcsec, (kpc)] | $\mu_{V,\text{eff}}$ (mag arcsec$^{-2}$) | $\kappa_1$ | $\kappa_2$ | $\kappa_3$ | $B_4 \times 100$ |
|-------------------------|---------|------------|---------------------|-----------------------------------|------------------------------------------|-------------|-------------|-------------|------------------|
| **Nonrotating dE Galaxies** |
| VCC 452                 | WFPC2   | 0.15       | 1.6                 | 9.6 (0.71)                        | 22.3                                     | 1.84        | 2.45        | 0.78        | 0.13 ± 0.28     |
| VCC 745/NGC 4366        | ESI     | 0.33       | 1.5                 | 10.0 (0.74)                       | 21.1                                     | 2.24        | 3.05        | 0.81        | 0.35 ± 0.03     |
| VCC 917/IC 3344         | WFPC2   | 0.42       | 2.9                 | 12.2 (0.90)                       | 21.4                                     | 2.07        | 2.80        | 0.65        | 0.34 ± 0.18     |
| VCC 940/IC 3349         | WFPC2   | 0.07       | 1.3                 | 13.9 (1.03)                       | 22.2                                     | 2.15        | 2.55        | 0.80        | 0.34 ± 0.22     |
| VCC 1073/IC 794         | WFPC2   | 0.20       | 1.9                 | 11.1 (0.82)                       | 21.1                                     | 2.29        | 3.05        | 0.79        | −0.03 ± 0.16    |
| VCC 1087/IC 3381        | ESI     | 0.26       | 1.4                 | 14.4 (1.07)                       | 21.1                                     | 2.26        | 2.95        | 0.64        | −0.41 ± 0.03    |
| VCC 1254                | WFPC2   | 0.07       | 2.9                 | 14.4 (1.07)                       | 22.4                                     | 2.13        | 2.45        | 0.83        | −0.60 ± 0.13    |
| VCC 1261/NGC 4482       | WFPC2   | 0.26       | 1.9                 | 7.3 (0.54)                        | 21.0                                     | 2.13        | 3.13        | 0.85        | 0.54 ± 0.11     |
| VCC 1308/IC 3437        | WFPC2   | 0.23       | 1.3                 | 9.5 (0.70)                        | 21.7                                     | 2.02        | 2.77        | 0.78        | 0.06 ± 0.20     |
| VCC 1386/IC 3457        | WFPC2   | 0.21       | 1.3                 | 17.1 (1.27)                       | 22.5                                     | 2.18        | 2.37        | 0.81        | −0.46 ± 0.25    |
| VCC 1488/IC 3487        | ESI     | 0.38       | 1.6                 | 10.0 (0.74)                       | 21.2                                     | 1.97        | 2.87        | 0.62        | 1.40 ± 0.05     |
| VCC 1577/IC 3519        | WFPC2   | 0.41       | 1.1                 | 10.5 (0.78)                       | 22.4                                     | 1.93        | 2.45        | 0.82        | 0.52 ± 0.49     |
| VCC 1876/IC 3658        | WFPC2   | 0.45       | 0.8                 | 10.5 (0.78)                       | 21.8                                     | 1.94        | 2.64        | 0.70        | 0.61 ± 0.30     |
| **Rotating dE Galaxies** |
| VCC 543/UGC 7436        | WFPC2   | 0.46       | 1.4                 | 11.9 (0.88)                       | 21.2                                     | 2.01        | 2.84        | 0.54        | −0.36 ± 0.26    |
| VCC 856/IC 3328         | ESI     | 0.09       | 1.6                 | 13.0 (0.96)                       | 21.4                                     | 2.14        | 2.81        | 0.67        | 0.04 ± 0.03     |
| VCC 1036/NGC 4436       | ESI     | 0.54       | 1.5                 | 13.8 (1.02)                       | 20.6                                     | 2.23        | 3.12        | 0.51        | 0.65 ± 0.03     |
| VCC 1947                | ESI     | 0.19       | 1.3                 | 8.3 (0.62)                        | 21.3                                     | 2.11        | 3.00        | 0.82        | −0.05 ± 0.02    |

**Notes.**—The second column refers to the source of our imaging (HST/WFPC2 or Keck/ESI). The ellipticity $\epsilon$ is the average measured between $1'' < r < 20''$. The Sérsic index $n_{\text{Sersic}}$, effective (half-light) radius $r_{\text{eff}}$, and effective surface brightness $\mu_{V,\text{eff}}$ are determined by fitting a Sérsic model to the galaxy surface brightness profile outside $r > 1000$, where the radius is measured along the major axis. The fundamental plane parameters $\kappa_1$, $\kappa_2$, and $\kappa_3$ were determined from quantities in this table and Table 1 according to the definitions of Bender et al. (1992). The $\kappa$-values are defined in the $B$ band, and we assume $B-V = 0.8$ in calculating these parameters. The last column lists the disky/boxy parameter $B_4$ (expressed as a percentage) discussed in §3.3 determined over the radial range $1'' < r < 20''$.

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**Fig. 2.**—Kinematic profiles for Virgo Cluster dE’s with significant major-axis rotation. The mean line-of-sight velocity offset relative to the galaxy’s systemic velocity (left) and velocity dispersion (right) are plotted as a function of radial distance along the major axis. At the distance of Virgo, $1''$ corresponds to $\sim 100$ pc. One $\sigma$ error bars are plotted in both panels, but they are often smaller than the plotted data points.
with significant rotation velocities and those that show no
evidence for substantial rotation along the major axis
\( (v_{\text{rot}} \leq 2.5 \text{ km s}^{-1}, \text{ or } v_{\text{rot}}/\sigma = 0.1 \text{ see below}) \). For the for-
mer kinematic profiles (Fig. 2), our observations do not
reach out to a large enough radius in three out of four dE’s
to observe a turnover in the rotation curve; in these galaxies,
we measure only a lower limit to the maximum rotational
velocity. We argue below that our observations are not far
from the turnover radius. The maximum rotation velocity
\( (v_{\text{rot}}) \) are quoted as lower limits in Table 1 and shown as
upward pointing arrows in Figure 4. For galaxies that show
no evidence for substantial rotation (Fig. 3), we estimate the
upper limit on the maximum rotation velocity by differenc-
ing the average velocities on either side of the major axis of
the galaxy and dividing by two. Error bars on rotational
motion were determined by adding in quadrature the error
of the mean velocity on either side of the major axis. These
quantities along with the heliocentric velocity and velocity
dispersion are listed in Table 1.

We note that five dE’s in our combined sample (VCC 543,
856, 1036, 1087, and 1261) have been previously observed
by Simien & Prugniel (2002) and/or Pedraz et al. (2002).
Our kinematic profiles are entirely consistent with these
measurements. Due to the higher spectral resolution and
signal-to-noise ratio of our observations, we are able to
place significantly tighter constraints on the rotational
velocity for two of these galaxies. In all cases, we obtain a
more accurate estimate of the velocity dispersions.

For the dE profiles in Figure 3, it is difficult to explain the
lack of observed major-axis rotation as being a result of
insufficient radial coverage. The majority of our kinematic
profiles are measured out to between 0.5 and 1.0 \( r_{\text{eff}} \).

Fig. 3.—Same as Fig. 2, but for those dE’s that show no evidence for substantial rotation along the major axis.
Two-integral dynamical models predict that if these galaxies were oblate, isotropic rotators we should have reached or measured beyond the maximum rotation velocity at these radii (see Figs. 8–9 in Dehnen & Gerhard 1994). Although these models are based on the specific case of density profiles with $\rho \propto r^{-4}$ at large radii and a varying inner cusp slope, the predictions for $v(r/r_{ed})$ are generic and should not be very different for a Sérsic profile (as is more appropriate for dE galaxies). As an example, we measure the velocity profile of the dE3 galaxy VCC 1261 out to its effective radius of $r_{eff} = 7.3$ (Fig. 3). As we discuss below, if the observed flattening in this galaxy was due to rotation, we would expect $v_{rot}/\sigma = 0.6$, implying a maximum rotation velocity of 30 km s$^{-1}$ given the average dispersion velocity of 45 km s$^{-1}$. This is in stark contrast to the measured upper limit on rotation in VCC 1261 of 0.5 km s$^{-1}$.

Conversely, for the four profiles with measurable rotation velocities (Fig. 2), it is not surprising that we observe a turnover in the rotation curve for only one out of four strongly rotating galaxies (VCC 856). For these dE’s, we only have kinematic data out to $\sim 0.5 r_{eff}$. The models of Dehnen & Gerhard suggest that we have barely reached the maximum rotation velocity in these systems and would need to observe a little further out in radius in order to see a turnover in these rotation curves. The rotation velocities for the these dE’s are listed as lower limits in Table 1.

To compare the degree of rotational support in our full sample of 17 dE’s, we plot the ratio of the maximum rotational velocity to the average velocity dispersion ($v_{rot}/\sigma$) versus ellipticity (Fig. 4, left). The solid line in this figure is the ratio expected from an oblate, isotropic, rotationally flattened body seen edge-on; systems that are not edge-on should have somewhat larger predicted $v_{rot}/\sigma$ values (Binney & Tremaine 1987). The lower limits on $v_{rot}/\sigma$ for the four galaxies with measured rotation are consistent with rotational flattening. The upper limits on $v_{rot}/\sigma$ determined for the majority of our dE’s are significantly smaller than expected if the observed flattenings were due to rotation and imply that these objects must be supported by anisotropic velocity dispersions. In our present sample, the degree of rotational support does not appear to be a continuous distribution: we observed either dE’s with no measurable major-axis rotation, or dE’s with rotation velocities approaching that expected for rotational support. There is a natural division in our sample between “rotating” and “nonrotating” dE’s; we arbitrarily place the dividing line in our sample as galaxies with rotational support greater or less than $v_{rot}/\sigma = 0.1$. Rotating and nonrotating dE’s cover a similar range of ellipticities and absolute magnitudes. Figure 4 suggests that rotational support is not correlated to either of these quantities. In the remaining sections, we explore whether or not any other global dE property is correlated to rotational properties.

The mean velocity dispersions for the dE’s in Figures 2 and 3, determined outside of $r=1''$ to exclude any nuclear contributions, range between 25 and 45 km s$^{-1}$. The velocity dispersion profiles are either constant as a function of radius or show a decrease in dispersion in the central region. As demonstrated in Geha et al. (2002), such profiles can in general be adequately modeled assuming that the stellar mass density profile is equal to the luminosity density profile times a constant mass-to-light ratio. Although spherical, isotropic models do not necessarily fit the observed velocity dispersion profiles in detail, such models do in general reproduce the overall shape of the observed dE velocity dispersion profiles.

### 3.2. Fundamental Plane

Dwarf elliptical galaxies lie in a region of fundamental plane space distinctly different from other stellar systems. This is best illustrated in the $\kappa$-projection of the multivariate space defined by central velocity dispersion, $\sigma_0$, effective surface brightness, $\mu_{eff}$, and effective radius, $r_{eff}$ (Bender et al. 1992). As shown in Figure 5, dE’s appear well separated from other stellar systems. Bender et al. (1992) argued that this separation represents a fundamental difference between the galaxy formation processes of dE’s and more luminous classical elliptical galaxies (see Guzmán et al. 2003, however, for an alternate viewpoint). Here, we are primarily
interested in the relative position of our rotating and nonrotating dE galaxies within fundamental plane space.

In both panels of Figure 5, the rotating and nonrotating dE’s occupy similar regions of the fundamental plane. As a statistical comparison, we use the one-dimensional Kolmogorov-Smirnov (K-S) test. This test gives the probability \( P_{KS} \) that the difference between two distributions would be as large as observed if they had been drawn from the same population. Two distributions are considered different if the probability that they are drawn from the same parent distribution is 0.3\% \( (P_{KS} = 0.003) \); thus this hypothesis can be ruled out at high confidence level. In comparing \( \kappa \)-values for rotating and nonrotating dE’s (listed in Table 3), the relatively high values of the K-S probability, \( P_{KS} = 0.6, 0.2, \) and 0.1 for \( \kappa_1, \kappa_2, \) and \( \kappa_3, \) respectively, indicate that we cannot demonstrate that these two samples are drawn from different populations. The rotating dE’s appear slightly offset in the direction of higher \( \kappa_1 \) and \( \kappa_2 \) values (corresponding to larger mass and surface brightness, respectively), but more data is required to establish such a correlation.

3.3. Morphology

Evidence for underlying disklike structure has been presented for a handful of cluster dE galaxies based on deep imaging. Five dE’s in the Virgo Cluster show evidence for a bar or weak spiral structure (Jerjen et al. 2000; Barazza et al. 2002) and two Fornax Cluster dE/dS0s show evidence for embedded disks (De Rijcke et al. 2003). This accounts for roughly 20\% of analyzed images. Two of these galaxies are in our sample: Jerjen et al. discovered faint spiral structure in VCC 856 (IC 3328) implying the presence of a nearly face-on disk, while Barazza et al. presented evidence for an elongated dumbbell-shaped structure along the major axis of VCC 940 (IC 3349). The former galaxy is a rotating dE in our sample, the latter is a nonrotating dE. In view of these results, we analyzed all our dE images to determine the level of substructure present and whether or not this is correlated with the amount of major-axis rotation.

Images of the dE galaxies in our sample appear to be smooth and without obvious signs of substructure, however, detailed analysis is required to detect possible low-level substructure. As discussed in § 2.3, we determine surface brightness profiles using the IRAF ELLIPSE isophotal fitting routine. Deviations from the best-fitting ellipse, often an indication of an underlying disk or other substructure, are quantified by expanding the intensity variations along the best-fitting ellipse in a Fourier series as follows:

\[
I(\phi) = I_0 + \sum_{n=1}^{N} \left[ A_n \sin(n\phi) + B_n \cos(n\phi) \right].
\]

The first- and second-order terms \( n = 1, 2 \) of equation (1) are zero by definition; nonzero values would indicate that the best-fitting ellipse has not been found. For \( n \geq 3 \), the quantities

\[
A_n = \frac{A_n}{(a(dI/da))},
\]

\[
B_n = \frac{B_n}{(a(dI/da))},
\]

measure deviations of the isophote from the best-fitting ellipse, where \( a \) is the semimajor axis length and \( (dI/da) \), the local intensity gradient. The quantity \( B_4 \) is similar to the quantity \( a_{\delta}/a \) used by, e.g., Bender, Doblereneir, & Moellenhoff (1988). Positive \( B_4 \) values indicate disky isophotes, whereas negative values indicate boxy isophotes (Jedrzejewski 1987). In Figure 6, we present surface brightness, ellipticity, position angle, and \( B_4 \) as a function of radius for those dE’s with ESI imaging. We note that in all cases the isophotal ellipticity varies with radius; two galaxies show significant departures from zero in their \( B_4 \) profiles. For the remaining dE’s in our sample for which we have only WFPC2 imaging, we present the averaged ellipticity and \( B_4 \) measurements in Table 3. We do not present the
WFPC2 radial profiles, since much of this data has been presented elsewhere (Geha et al. 2002; Stiavelli et al. 2001; Geha 2003), and because these images are too shallow to meaningfully constrain the amount of substructure present. As an illustration, the existing WFPC2 images do not show detectable substructure in VCC 940; however, as mentioned above, Barazza et al. (2002) present clear evidence for an elongated structure along its major axis from deep ground-based imaging.

In the first column of Figure 7, we present $V$-band ESI images for the profiles presented in Figure 6. In the second column of this figure, we plot the residual image resulting from subtraction of a two-dimensional model based on the ellipse fitting (excluding higher order components) from the original image. In the third column, we present unsharp-masked images created by subtracting a boxcar-smoothed image (with 4 arcsec smoothing length) from the original to highlight high-frequency spatial structure. The unsharp-masked images have the advantage of being independent of our ellipse fitting model, but can be difficult to interpret. For example, the “structure” apparent in the unsharp-masked images of VCC 1947 and 745 is due to ellipticity gradients evident in Figure 6; the model-subtracted images of these galaxies in the middle column of Figure 7 show no obvious structure. On the other hand, the model-subtracted images of two other dE’s in Figure 7, VCC 1036 and 1488, do show...
Fig. 7.—ESI imaging data for the same set of dE’s shown in Fig. 6: (left) original $V$-band image; (middle) residual image after subtracting a two-dimensional model based on ellipse fitting of the original image; and (right) residual image after subtracting a smoothed version of the original image from itself. Each panel covers a $1' \times 1'$ region centered on the galaxy.
clear signs of an underlying disk. This is seen in both the unsharp-masked images and the positive $B_4$ profiles in Figure 6. The rotating dE/dS0 VCC 1036 has a strong disk component, while the nonrotating dE VCC 1488 has a weaker underlying disk. Both these disks lie along the major axis defined by the outer isophotes. In addition, we confirm the faint spiral structure in VCC 856 first presented by Jerjen et al. (2000); this is strong evidence for a nearly face-on disk. The remaining three dE’s do not show any residuals. Most notably, the strongly rotating dE VCC 1947 shows no evidence for a disk component.

In summary, there is evidence for underlying disks and/or substructure in both rotating and nonrotating dE’s, but counterexamples also exist for both kinematic types that show no evidence of such structure. For the rotating dE’s, we present or confirm evidence for underlying disk structure in two dE’s but observe no evidence for any substructure in a third rotating dE. For the nonrotating dE’s, we present evidence for a weak disk in one galaxy, in addition to one nonrotating dE with substructure presented in the literature. Two nonrotating dE’s show no evidence for underlying structure. For the remaining dE’s in our sample, WFPC2 imaging is not deep enough to place limits on the presence of substructure. We conclude that there can be interesting substructure in dE’s, but its presence or absence does not appear to be a good indicator of the observed dynamics.

3.4. Line-Strength Indices

We compute line-strength indices according to the Lick/IDS system (Worthey et al. 1994) in the wavelength region 4800–6000 Å. This index system is calibrated to a fixed spectral resolution of ~8 Å. To match indices, we must degrade the spectral resolution of our spectra. Although this means sacrificing a wealth of fine structure almost certainly sensitive to stellar populations, higher spectral resolution stellar population models do not yet exist that cover a sufficient range of ages, metallicities, and wavelengths. The adopted approach also allows us to compare directly with the measured indices of more luminous elliptical galaxies.

Line-strength indices were computed by first shifting the spectra to rest-frame wavelengths and convolving with a wavelength-dependent Gaussian kernel to match the spectral resolution of the Lick/IDS system. Line strengths were then calculated according to the index definitions of Worthey et al. (1994). The size of the smoothing kernel was determined by matching the measured indices of 16 stars (spectral type F9 IV–M0 III) observed through the Keck/ESI setup to the values of Worthey et al. (1994). The size of the kernel ranged between 8 and 9 Å (40–45 ESI spectral pixels, Gaussian $\sigma$); the average residual between measured and published indices was 0.15 Å. The measured line strengths for these standard stars are plotted against the published values in Figure 8. Small zero-point corrections due to systematic effects such as sky-subtraction and flat-fielding errors both in our data and the published systems (Worthey & Ottaviani 1997) are applied to the measured indices of each galaxy. These corrections were determined from the best-fitting offset between our measured standard-star indices and the published values assuming a linear relation with unit slope. These corrections are listed in each panel of Figure 8 and range between 0.1 and 0.2 Å. We do not correct for line broadening due to the intrinsic velocity dispersion of each dE galaxy, since these are much smaller than the Lick/IDS broadening function.

Error bars on the indices were computed via Monte Carlo simulation. We added noise to a high signal-to-noise ratio template star based on the noise spectrum of each individual galaxy and compute indices with the same procedure described above. Error bars were determined for each index of each galaxy from the rms value after 1000 noise realizations. Error bars include contributions from photon noise, readout noise, and pixel-to-pixel correlations due to Gaussian smoothing.

We present line-strength indices for our Virgo Cluster dE galaxies measured from spectra extracted in a 0.7′×3′ aperture centered on each object. These spectra have signal-to-noise ratios ranging between 50 and 100 Å$^{-1}$. In Table 4, we list the central line-strength indices and error bars for $H\beta$, Mg $b$, Fe$5270$, and Fe$5335$ (see Worthey et al. for index definitions). In addition, we list the combined iron index (Fe) defined as $(Fe5270 + Fe5335)/2$. Our results for the central regions of VCC 1073 and VCC 543 agree, within the errors, with previously published values of $H\beta$ and (Fe) (Pedraz et al. 2002). We restrict our line-strength analysis to the central $r < 1.75$ to avoid galaxy light contamination in our sky spectrum. Based on the surface brightness profiles, we estimate the level of this contamination to be a few percent or less in the galaxy center, increasing to ~25% in the outer regions. A few percent contamination should not affect the central line-strength values or the kinematic profiles, but could lead to significant errors in the line strengths at large radii where the contamination level is larger.

In Figures 9 and 10, we present line-strength index diagrams comparing the $H\beta$, Mg $b$, and (Fe) indices for our dE sample. The majority of dE’s are confined to a small region in all three panels with some amount of intrinsic scatter between galaxies. The exception is VCC 1488, a nonrotating galaxy with noted nonaxisymmetric features (§ 3.3), which has a significantly higher $H\beta$ measurement. The line-strength indices of the rotating and nonrotating dE’s are similarly distributed in each index-index diagram. Based on the K-S test discussed in § 3.2, we compute the probability that, for each index, the line strengths of these two populations are drawn from different distributions. The K-S probability is greater than $P_{KS} = 0.5$ for all our measured indices, meaning the line strengths of these two samples are statistically consistent with being drawn from a single distribution. We conclude that rotating and nonrotating dE’s have similar stellar populations despite very different internal kinematics.

We next compare our dE line-strength indices to the single-burst stellar population models of Thomas, Maraston, & Bender (2003). These models predict line-strength indices for a wide range of metallicities ($-2.25 \leq [Fe/H] \leq -0.67$ dex) and include predictions for both solar and nonsolar element abundance ratios. In Figure 9, we investigate the $[\alpha/Fe]$ ratio of our dE sample by comparing the measured Mg $b$ and (Fe) indices to model predictions. In this diagram, effects due to age and metallicity are largely degenerate and sensitivity to abundance ratio is maximized. We assume that Mg traces the $\alpha$-elements. The majority of dE’s in Figure 9 are consistent with solar abundance ratios, with some scatter toward both the sub- and supersolar abundance ratios in the range $-0.3 \leq [\alpha/Fe] < +0.3$ dex that cannot be explained by differences in age and metallicity alone. We again note that the rotating and nonrotating dE’s have
similar inferred abundance ratios. Gorgas et al. (1997) first suggested that Virgo dE’s are consistent with solar abundance ratios based on a smaller dE sample. This is in marked contrast to the sample of classical elliptical galaxies, taken from Trager et al. (2000), also plotted in Figure 9 that have supersolar abundance ratios $[^{\alpha}/Fe] \sim +0.3$. This difference in abundance ratios can be interpreted as a difference in the timescale of star formation: $\alpha$-elements are created rapidly by Type II supernovae, while iron is produced by supernovae Type Ia on longer timescales. It can then be argued that the bulk of star formation in classical elliptical galaxies occurred on much shorter timescales as compared with dE galaxies. Our observations are further evidence that dwarf and classical elliptical galaxies have very different star formation histories.

To determine the luminosity-weighted stellar ages and metallicities for our dE sample, we plot the Mg $b$ and (Fe) indices against H$\beta$ in Figure 10. Note that while conclusions based on relative line-strength differences between dE galaxies are robust, the derived absolute ages and metallicities may be affected by unknown systematic errors. The best-fitting age and metallicity was determined for each galaxy by simultaneously minimizing the residuals between the observed line strengths and the predicted Mg $b$, (Fe), and H$\beta$ indices from the Thomas et al. (2003) solar abundance ratio models. The best-fitting age and metallicity for our sample of 17 dE are 5 Gyr and $[\text{Fe/H}] = -0.3$ dex, with rms spreads of 3 Gyr and 0.1 dex, respectively. This is consistent with the ages and metallicities implied by the dynamically determined $V$-band mass-to-light ratios, $3 \leq \Upsilon_V \leq 6$, calculated in Geha et al. (2002) for six dE’s in the present sample; the single-burst population models of Worthey (1994) predict $V$-band mass-to-light ratios in this range for the ages and metallicities stated above. Compared with the Trager et al. sample of classical elliptical galaxies plotted in Figure 10, the average dE in our sample has stronger H$\beta$ indices and weaker Mg $b$ and (Fe) indices, implying these dE’s are younger and more metal-poor than a typical classical elliptical galaxy.
Fig. 9.—Determination of [$\alpha$/Fe] ratios from a Mg b vs. (Fe) diagram. The dE's in our sample are plotted as 1 $\sigma$ error plus signs; dE's with significant rotation velocities are shown with solid squares. The classical elliptical galaxy sample of Trager et al. (2000) is plotted as open triangles. Model predictions by Thomas et al. (2003) are plotted for the abundance ratios [$\alpha$/Fe] = −0.3, 0.0, and +0.3 (light to dark gray lines), age = 1–15 Gyr in increments of 1 Gyr, and [Fe/H] = −2.25, −1.35, −0.33, 0.0, +0.35, and +0.67 dex. Rotating and nonrotating dE's cannot be distinguished in this plot. The majority of these dE's are consistent with solar abundance ratios, in contrast with the majority of classical elliptical galaxies, which have enhanced [$\alpha$/Fe] abundance ratios.

Fig. 10.—Line strengths of Mg b and (Fe) plotted vs. H$\beta$ (left and right, respectively). The dE's in our sample are plotted as 1 $\sigma$ error crosses. Dwarf elliptical galaxies with significant rotation velocities are indicated with solid squares; as in previous figures, these galaxies cannot be distinguished from the nonrotating dE's. The solar abundance ratio models of Thomas et al. (2003) are plotted for age between 1–15 Gyr in 1 Gyr intervals (solid gray lines) and [Fe/H] = −2.25, −1.35, −0.33, 0.0, +0.35, and +0.67 dex (dotted lines). In both panels, lines of constant age are steeper than those of constant metallicity. The average absolute age and metallicity for our dE's are 5 Gyr and −0.3 dex, respectively, determined as described in § 3.4. The galaxy with the largest H$\beta$ value is VCC 1488; excluding this dE in determining the mean age and metallicity does not significantly affect the values given above. The classical elliptical galaxy sample of Trager et al. (2000) is plotted as open triangles. The average dE has stronger H$\beta$ and weaker Mg b and (Fe) than the typical elliptical galaxy.
Despite the clear separation in the fundamental plane (see § 3.2) between dE’s and classical elliptical galaxies, Bender, Burstein, & Faber (1993) first noted that the magnesium line strengths of these two galaxy types follow a tight trend with velocity dispersion. Caldwell, Rose, & Concannon (2003) investigated this correlation for a sample of early-type galaxies that included a much larger number of galaxies with velocity dispersions less than $\sigma = 100$ km s$^{-1}$. They confirm this correlation for Mg$b$ and several other Lick/IDS indices. In addition, the scatter in the line strengths of H$\beta$, Mg$b$, and Fe5270 was found to be in excess of the measurement error for velocity dispersions less than $\sigma = 100$ km s$^{-1}$. In Figure 11, we plot line strengths as a function of velocity dispersion. We fitted a linear relation to the classical elliptical sample of Trager et al. (2000) and compare the result with the positions of the dE’s in our sample. The linear fit to classical elliptical galaxies, extrapolated to lower velocity dispersions, are consistent with our measured dE line strengths. Although the observed scatter for our dE sample is larger than that of the classical elliptical galaxies, our sample size is too small to make a quantitative statement regarding the intrinsic scatter.

4. LOCAL ENVIRONMENT OF ROTATING VERSUS NONROTATING dE’s

In the above sections, we have demonstrated that dE’s with and without significant rotation velocities cannot be distinguished based on their internal properties. We next examine whether or not internal rotation is correlated with a dE’s local environment within the Virgo Cluster. As shown in Figure 1 (left), rotating and nonrotating dE’s are found at varying radii from the center of Virgo. In velocity space (Fig. 1, right), the nonrotating dE’s span the full range of radial velocities found in the Virgo, whereas the rotating dE’s appear clustered near the average Virgo radial velocity of $\sim 1000$ km s$^{-1}$. This is more clearly evident in the first panel of Figure 12. Based on the K-S test discussed in § 3.2, the radial velocity distributions of the rotating versus nonrotating dE’s are not significantly different ($P_{KS} = 0.3$), although including two additional dE’s from the literature (Simien & Prugniel 2002) makes this difference marginally significant ($P_{KS} = 0.06$) in the sense that rotating dE’s have a narrower range in radial velocities. Conselice et al. (2001) have argued that Virgo Cluster dE’s as a population span a much larger range of radial velocities as compared with more luminous classical elliptical galaxies. They interpret this as evidence that dE’s are a more recently accreted population. If larger dE samples confirm that rotating dE’s span a narrower range of radial velocities compared with nonrotating dE’s, this would suggest that their history in the Virgo Cluster is more closely associated with classical elliptical galaxies.

In the remaining panels of Figure 12, we further quantify the local environment of our dE sample by examining neighboring galaxies within 2" (0.5 Mpc) and 300 km s$^{-1}$ of each dE. These scales were chosen to probe local enhancements within the Virgo Cluster on the scale of small galaxy groups. As a population, Virgo dE’s are not preferentially found around larger parent galaxies (Ferguson & Sandage 1991) in contrast to dE’s in the field; local overdensities or proximity to large galaxies would be evidence of recent accretion into the Virgo Cluster from the surrounding field/groups. We compare for the rotating and nonrotating dE’s: the number of luminous companions ($M_r < -20$) in this same region, and the physical distance to the nearest of these companions.

### Table 4

**Line-Strength Indices**

| Galaxy   | $\text{H}\beta$ (\AA) | Mg$b$ (\AA) | Fe5270 (\AA) | Fe5335 (\AA) | (Fe) (\AA) |
|----------|-------------------------|-------------|--------------|--------------|--|---|
| VCC 452  | 2.89 ± 0.34             | 1.92 ± 0.24 | 2.65 ± 0.27  | 2.26 ± 0.29  | 2.46 ± 0.20 |
| VCC 745  | 2.01 ± 0.22             | 2.46 ± 0.15 | 2.76 ± 0.19  | 2.30 ± 0.20  | 2.53 ± 0.14 |
| VCC 917  | 2.73 ± 0.09             | 2.02 ± 0.07 | 2.38 ± 0.09  | 1.76 ± 0.09  | 2.07 ± 0.06 |
| VCC 940  | 2.07 ± 0.23             | 2.53 ± 0.16 | 2.46 ± 0.21  | 2.06 ± 0.22  | 2.26 ± 0.15 |
| VCC 1073 | 2.11 ± 0.10             | 3.17 ± 0.07 | 2.80 ± 0.09  | 2.36 ± 0.08  | 2.58 ± 0.06 |
| VCC 1087 | 2.02 ± 0.28             | 3.25 ± 0.19 | 2.62 ± 0.23  | 2.18 ± 0.26  | 2.40 ± 0.17 |
| VCC 1254 | 2.18 ± 0.08             | 2.42 ± 0.06 | 2.09 ± 0.07  | 1.55 ± 0.08  | 1.82 ± 0.05 |
| VCC 1261 | 2.50 ± 0.09             | 2.22 ± 0.06 | 2.33 ± 0.09  | 2.12 ± 0.09  | 2.23 ± 0.06 |
| VCC 1308 | 2.34 ± 0.13             | 2.51 ± 0.10 | 2.41 ± 0.12  | 1.86 ± 0.13  | 2.13 ± 0.09 |
| VCC 1386 | 2.21 ± 0.24             | 1.69 ± 0.18 | 2.35 ± 0.23  | 1.95 ± 0.23  | 2.15 ± 0.16 |
| VCC 1488 | 4.17 ± 0.20             | 1.35 ± 0.15 | 1.78 ± 0.19  | 1.80 ± 0.22  | 1.79 ± 0.14 |
| VCC 1577 | 2.05 ± 0.34             | 1.97 ± 0.24 | 2.58 ± 0.26  | 1.69 ± 0.29  | 2.13 ± 0.20 |
| VCC 1876 | 2.20 ± 0.27             | 2.32 ± 0.19 | 2.06 ± 0.23  | 1.38 ± 0.26  | 1.72 ± 0.17 |

**Notes.** Line-strength indices are determined according to the definitions of Worthey et al. (1994). Error bars are computed via Monte Carlo simulations as described in § 3.4. The combined iron index is defined as $(\text{Fe}) \equiv (\text{Fe5270} + \text{Fe5335})/2$.  

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**Nonrotating dE Galaxies**

**Rotating dE Galaxies**

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**TABLE 4**

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bright galaxies. In all cases, the rotating and nonrotating dE’s are similarly distributed based on both inspection of Figure 12 and results of the K-S test. In all three cases, the K-S probability is greater than $P_{KS} = 0.25$, meaning that the distribution of the two kinematic types in these panels cannot be distinguished. We conclude that internal dE rotation properties are not correlated with proximity to bright galaxies or the local environment within the galaxy cluster.

5. DISCUSSION AND CONCLUSIONS

We have established that the internal dynamics of dE galaxies span a wide range in rotational support as determined from major-axis spectroscopy of 17 dE’s in the Virgo Cluster. In our present dE sample, the degree of rotational support does not appear to span a continuous distribution: we observe either dE’s with no measurable major-axis rotation, or dE’s with rotation velocities approaching that expected for a rotationally flattened object. We therefore have separated our sample into rotating and nonrotating dE’s (nominally defined as galaxies with $v_{rot}/\sigma > 0.1$ and $v_{rot}/\sigma \leq 0.1$, respectively) and investigated whether or not other dE properties are correlated with rotation velocity. We show that rotation velocity is not correlated with a dE’s position in the fundamental plane, the presence or absence of underlying disks or substructure, absorption line strength indices, or local environment.

Currently favored formation models do not naturally predict a dichotomy in the internal dynamics of dE galaxies. One possible explanation for the varying amount of rotational support is different mechanisms for the formation of rotating and nonrotating dE’s. Although our observations do not rule out multiple formation mechanisms, they do place very tight constraints on variations in observable properties between the resulting dE populations. In particular, significantly different origins for rotating and non-rotating dE’s would need to result in stellar populations that are indistinguishable between the two dE types yet very
different from those of more luminous classical elliptical galaxies. It is equally challenging, however, to produce the range in rotational properties via a single physical process.

Our conclusion that the internal properties and local environments of rotating versus nonrotating cannot be distinguished is limited by the size of our dE sample; increasing the number of dE’s, particularly rotating dE’s, with spatially resolved measurements of internal kinematics is an important step toward further understanding the formation of these galaxies. It is equally important to refine the predictions and better understand the limitations of currently proposed dE formation models. For example, does the harassment scenario in which dE’s are formed from larger disk galaxies via gravitational interactions produce the observed range of rotational support, and, in particular, can it account for the large fraction of dE’s without significant rotation? To what extent do these interactions disrupt the disk of a progenitor galaxy and at what level is substructure predicted in dE’s? Similar questions should be asked of any proposed dE formation model. Because dE’s are so numerous in nearby galaxy clusters, constraining the formation and evolution of these objects is an important step toward assembling a global picture of galaxy evolution in these regions.

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Fig. 12.—Local environment of Virgo dE’s. In each panel, the black shaded portion of the histogram represents dE’s with significant rotation velocity, the gray shaded region includes rotating dE’s from the literature, and the clear region includes all dE’s with measured internal kinematics in the Virgo Cluster. (Top left) Distribution of radial velocities, (top right) number of neighboring galaxies inside a radius of 2′ (0.5 Mpc) and within 300 km s$^{-1}$, (bottom left) number of galaxies brighter than $M_V = -20$ in the same region, and (bottom right) radius in kiloparsecs to the nearest of these bright galaxies.
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