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KINEMATIC PROPERTIES AS PROBES OF THE EVOLUTION OF DWARF GALAXIES IN THE VIRGO CLUSTER

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ABSTRACT

We present new observational results on the kinematical, morphological, and stellar population properties of a sample of 21 dEs located both in the Virgo Cluster and in the field, which show that 52% of the dEs (1) are rotationally supported, (2) exhibit structural signs of typical rotating systems such as disks, bars, or spiral arms, (3) are younger (∼3 Gyr) than non-rotating dEs, and (4) are preferentially located either in the outskirts of Virgo or in the field. This evidence is consistent with the idea that rotationally supported dwarfs are late-type spirals or irregulars that recently entered the cluster and lost their gas through a ram pressure stripping event, quenching their star formation and becoming dEs through passive evolution. We also find that all, but one, galaxies without photometric hints for hosting disks are pressure supported and are all situated in the inner regions of the cluster. This suggests a different evolution from the rotationally supported systems. Three different scenarios for these non-rotating galaxies are discussed (in situ formation, harassment, and ram pressure stripping).

Key words: galaxies: clusters: individual (Virgo) – galaxies: dwarf – galaxies: evolution – galaxies: formation – galaxies: kinematics and dynamics

1. INTRODUCTION

Dwarf galaxies ($M_B > -18$) are the most numerous objects in the nearby universe. They have gained importance since hierarchical models proposed dwarfs as the building blocks of massive galaxies (e.g., White & Rees 1978; White & Frenk 1991). These systems can be divided in star-forming (Im, BCD, Sd, etc.) and quiescent (dE, dS0) dwarfs, the latter being the dominant population in clusters, the former the most common in the field (Sandage et al. 1985; Ferguson & Binggeli 1994; Blanton et al. 2005; Croton et al. 2005). The study of the population of low-mass galaxies and of the mechanisms leading to the strong morphology segregation between the different types of dwarfs is fundamental to understand the assembly and evolution of the overall population of galaxies.

In the case of dEs, various scenarios have been suggested to explain their formation. Whether they are the low-luminosity extension of the giant ellipticals (Es) or they are the result of different formation and evolution processes is still an open question (Ferguson & Binggeli 1994). It has been proposed that dEs were late-type systems where the interstellar medium (ISM) was swept away by the kinetic pressure due to supernova explosions (Yoshii & Arimoto 1987; see, however, Silich & Tenorio-Tagle 2001). Other theories suggested that late-type spirals stopped their star formation once their ISM was removed during their interaction with the environment and evolved into quiescent dwarfs. The existence of a morphological segregation effect on the dwarf galaxy population (Ferguson & Binggeli 1994) favors this second scenario. Different processes could be at the origin of gas removal in clusters: interaction with the intergalactic medium (IGM; e.g., van Zee et al. 2004), as ram pressure stripping, galaxy–galaxy interactions (e.g., Byrd & Valtonen 1990) and harassment (e.g., Moore et al. 1998; Mastropietro et al. 2005). These mechanisms are able to reproduce some of the observed properties of local dEs in clusters. Structural parameters, such as surface brightness, and spectrophotometric properties, such as stellar populations, are easily reproduced after a ram pressure event (Boselli et al. 2008a, 2008b). The detailed study of Lisker et al. (2006a, 2006b, 2007) shows that there exists a population of galaxies that have properties in between those of dEs and star-forming dwarfs. In these objects, which are classified as dEs, some remains of spiral disks, such as spiral arms or irregular features, are still visible. If dEs are formed from star-forming galaxies through ram pressure stripping, we expect that the angular momentum of the parent galaxies should be conserved, while in the case of multiple dynamical perturbations the system is rapidly heated and the rotation is lost. Measuring the kinematics of dEs is therefore an important test to understand their origin.

In the last decade, considerable efforts have been made to measure the kinematic properties of dE in Virgo, the closest rich cluster (e.g., Pedraz et al. 2002; Geha et al. 2002, 2003; van Zee et al. 2004). These works have shown the existence of both rotating and pressure-supported systems. This fact, together with the varieties of morphologies found by Lisker et al. (2006a) makes it clear that the formation of dEs might rather be complex. Would every different population of dEs have a separate formation process? To answer this question, we started a kinematical survey of dE in the Virgo Cluster. This is the first of a series of papers devoted to the study of the kinematics and stellar populations of dEs in the Virgo Cluster.

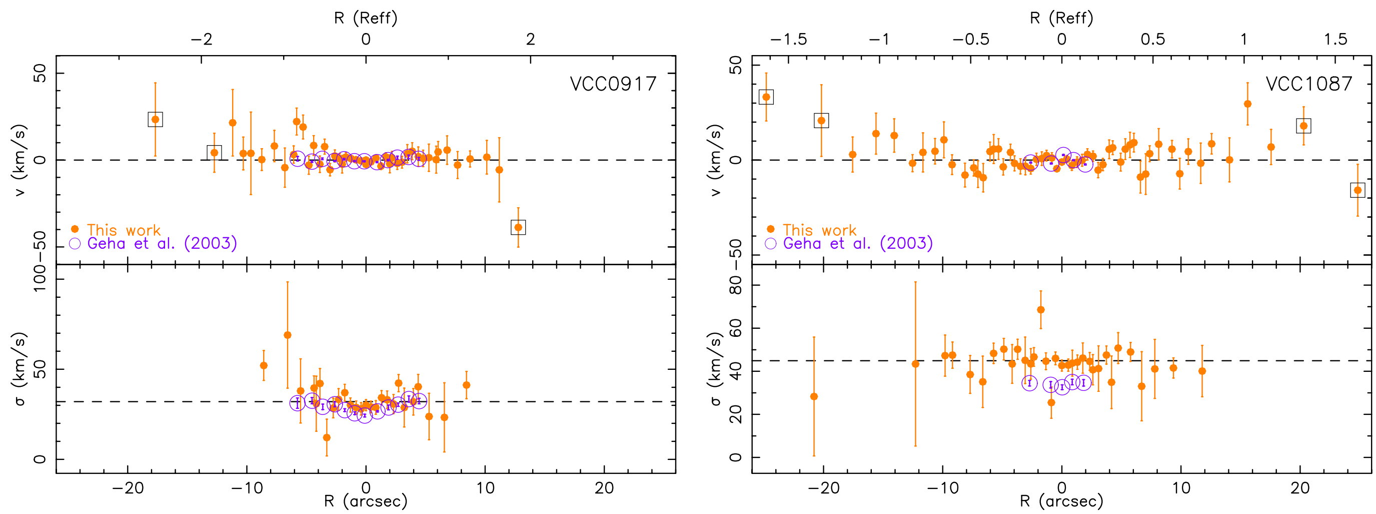

Figure 1. Example of the kinematical profiles obtained. The open squares show the values used to calculate v_{max} and the dashed line the lower panel, the central σ.

2. THE DATA

2.1. Observations and Data Reduction

The data were obtained as part of the MAGPOP-ITP collaboration (Multiwavelength Analysis of Galaxy Populations-International Time Program), a Marie Curie Research Training Network. The observed sample, selected from the Sloan Digital Sky Survey (SDSS) as described in Michielsen et al. (2008), contains 18 Virgo and 3 field dEs. The Virgo galaxies were chosen to have $m_B > 15$ and dE or dS0 classification in the Virgo Cluster Catalog (VCC) Binggeli et al. (1985), with available *Galaxy Evolution Explorer* (*GALEX*) data (Boselli et al. 2005). The field sample was required to be in the SDSS velocity range 375 km s^{-1} < v_{hel} <1875 km s^{-1} and $-18.5 < M'_r < -15$ mag. Quiescent galaxies were selected to have FUV–NUV >0.9 or $u - g$ >1.2 when there were no UV detections.

We obtained medium resolution ($R \simeq 3800$) long-slit spectroscopy along the major axis of 21 dEs during three different runs at Roque de los Muchachos Observatory, Canary Islands: two at the William Herschel Telescope (WHT) (4.2 m), using the spectrograph ISIS (3445–8950 Å), and one at the Isaac Newton Telescope (INT) (2.5 m) with the IDS (4600–5960 Å). With a slit width of 2″ and exposure times of 1 hr/configuration, the gratings used in each campaign were R1200B for IDS and R1200B and R600R for ISIS. ISIS has the possibility to observe with a dichroic and split the light into two beams to cover a larger wavelength range. Only in the first run we also used the mirror to cover the range 4800–5600 Å. The spectral resolution obtained was 1.6 Å (FWHM) (49 km s^{-1}) and 3.2 Å (FWHM) (58 km s^{-1}) in the blue and red arms of ISIS, respectively, and 1.8 Å (FWHM) (45 km s^{-1}) with IDS.

The reduction was done using standard procedures for long-slit spectra in the optical range, using REDucmE (Cardiel 1999), a package specially focused on the parallel treatment of errors. The flux calibration was done using the stars observed from the MILES and CaT libraries (Sánchez-Blázquez et al. 2006; Cenarro et al. 2001, respectively). More details of the observations will be presented in E. Toloba et al. (2010, in preparation) (Paper I).

2.2. Kinematic and Photometric Parameters

To calculate the stellar kinematics, we used MOVEL, available in REDucmE. MOVEL is an algorithm based on the Fourier quotient method described by Sargent & Turner (1977) and improved with OPTEMA (González 1993) that allows us to overcome the typical template mismatch problem. MOVEL uses an iterative procedure to determine the radial velocity and the stellar broadening of the galaxy, by fitting a galaxy model, created as a linear combination of the stars introduced as templates, to the data.

To make sure that the stars used as templates have the same instrumental profile as the target galaxies, they were defocused to fill the slit in the same way as the galaxies. In Paper I, more details are given about how this was exactly done.

The maximum rotational velocity (v_{max}) was calculated as the weighted average of the two highest velocities along the major axis on both sides of the galaxy at the same radius (for non-symmetric profiles at least three values are required), typically located at around 10″ from the center (Figure 1). After de-redshifting the spectra using the rotation curves, the central velocity dispersion (σ) has been computed co-adding all the individual spectra up to one effective radius. The typical signal-to-noise ratio (S/N) for the central σ is ~60 Å^{-1}, while S/N ⩾10 for v_{max} at 10″.

The photometric parameters, the effective radius (R_{eff}), the ellipticity (ϵ) at R_{eff}, and the boxyness/diskyness parameter (A_4/A), measured in a radius range from 5″ to 4R_{eff}, were calculated using the IRAF[9] task ELLIPSE over the *H*- and *K*-band photometry observed within the MAGPOP collaboration (R. F. Peletier et al. 2010, in preparation).

3. RESULTS

Given the radial decrease of the galaxy surface brightness, the S/N in the outer parts of some of the galaxies was not enough to reach a plateau of the rotation curves. To be cautious, for those galaxies where the v_{max} is measured at a radius <6″, the value is considered as a lower limit.

Figure 2 shows the anisotropy diagram. v_{max}/σ is the ratio between the maximum rotational velocity and the central velocity dispersion of the galaxies. The color code corresponds to the classification of Lisker et al. (2006a). In blue are all the dEs that have signs indicating a possible spiral origin, those classified as

[9] IRAF is distributed by the National Optical Astronomy Observatory, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.

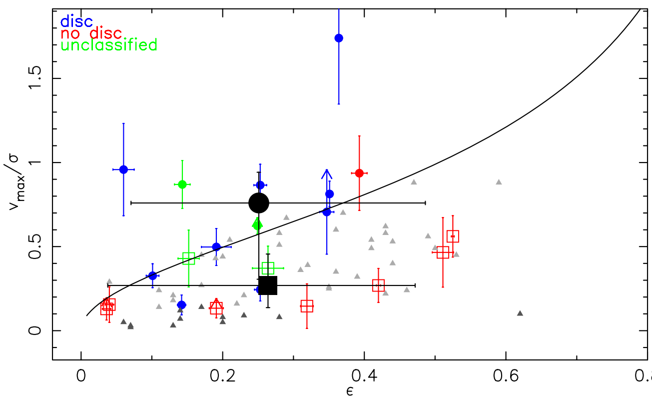

Figure 2. Anisotropy diagram. The solid line is the model for an isotropic oblate system flattened by rotation (Binney 1978). Triangles are giant ellipticals (from Emsellem et al. 2007), with slow rotators ($v_{max}/\sigma < 0.1$) in dark gray, and fast rotators ($v_{max}/\sigma > 0.1$) in light gray. Blue, red, and green symbols show our sample of dEs as classified by Lisker et al. (2006a). The filled dots and the open squares indicate galaxies with and without disks on the basis of A_4/A. Lower limits on v_{max} are indicated with arrows. The black symbols represent the median for dEs with (black dot)/without disk (black square) based on A_4/A classification, their error bars contain 34.1% ($\sim 1\sigma$) of the values at both sides of the median.

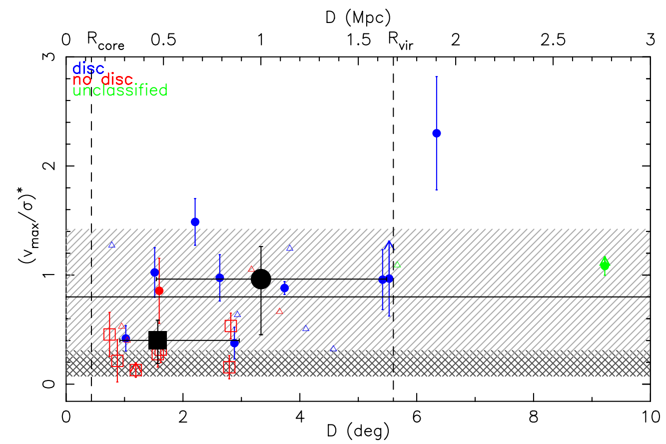

Figure 3. Anisotropy parameter vs. the angular distance to M87 (center of Virgo). The symbols are as in Figure 2. The light dark gray rectangles limit the $(v_{max}/\sigma)^*$ regions for fast and slow rotating Es as defined by Emsellem et al. (2007). The open triangles are van Zee et al. (2004), included in the median values. The dashed lines show the Virgo core radius (130 kpc) and virial radius (1.68 Mpc) (Boselli & Gavazzi 2006). The solid line divides the diagram into rotationally ($(v_{max}/\sigma)^* > 0.8$) and pressure-supported galaxies ($(v_{max}/\sigma)^* < 0.8$).

Table 1
A_4/A Alternative Classification

Galaxy	v_{max}/σ	ϵ	$100\times A_4/A$	A_4/A Classification
PGC1007217	0.87 ± 0.14	0.14 ± 0.01	0.48 ± 0.11	Disk
PGC1154903[a]	0.37 ± 0.13	0.26 ± 0.02	0.02 ± 0.35	No disk
NGC3073	0.43 ± 0.17	0.15 ± 0.02	−0.35 ± 0.03	No disk
VCC0308	0.96 ± 0.27	0.06 ± 0.02	−0.09 ± 0.07	No disk
VCC0917	0.94 ± 0.22	0.39 ± 0.01	6.32 ± 1.63	disk
VCC1947	0.62 ± 0.05	0.25 ± 0.01	0.35 ± 0.05	disk

Notes. Galaxies without morphological classification in Lisker et al. (2006a) and VCC0308 and VCC0917 whose classification by A_4/A disagrees with Lisker et al. (2006a).
[a] In NED: 2MASXJ02420036+0000531.

certain, probable and possible disks (spiral arms, edge-on disks, or bars) and also those classified as "other" (mainly irregular central features). In red are indicated those that do not show any underlying structure and in green the galaxies that were not in the sample of Lisker et al. (2006a); those are the three field dEs and VCC1947. We do not distinguish between galaxies with and without blue centers (Lisker et al. 2006b) and between nucleated and non-nucleated dwarfs (Binggeli et al. 1985) due to the lack of statistics, with only three galaxies with a blue nucleus and three non-nucleated objects.

The average A_4/A parameter, which measures how different the isophotes are from a perfect ellipse ($A_4/A > 0$ means disky isophotes, $A_4/A < 0$ boxy isophotes; Kormendy & Bender 1996), shows that all disky galaxies (except two) have been classified by Lisker et al. (2006a) as disks. The two exceptions are (see Table 1): VCC0917 where Lisker et al. (2006a) did not see the disk revealed by the disky isophotes and VCC0308 where the low ellipticity suggests that the galaxy is face-on, so A_4/A cannot accurately determine the underlying features (the unsharp masking technique of Lisker et al. (2006a) is here more useful). Regarding the four galaxies not included in the sample of Lisker et al. (2006a) (Table 1) A_4/A suggests that the two with higher v_{max}/σ contain disks (PGC1007217 and VCC1947), while the two with lower v_{max}/σ do not (NGC3073 and PGC1154903).

The anisotropy diagram (Figure 2) separates rotationally supported galaxies (above the solid line) from pressure dominated (below the solid line). Figure 2 shows that (1) as ellipticals, dEs can be separated into slow (v_{max}/σ <0.1) and fast (v_{max}/σ >0.1) rotators (Emsellem et al. 2007), (2) a large fraction (52%) of the dEs are rotationally supported, and (3) all of the rotationally supported galaxies have morphological and/or photometric signs of a spiral origin.

The apparent discordance with Geha et al. (2003), who found that the majority of the dEs were not rotating, is due to the fact that their data are limited to the core of the galaxies, never reaching radii larger than 6″ (Figure 1), where the increase of the rotational velocity is generally observed (Paper I). A maximum offset of 10 km s^{-1} in σ with respect to Geha et al. (2003) is found; however, it does not affect this result, since it makes v_{max}/σ larger. This discrepancy could be due to the use of a K-type star template in the case of Geha et al. (2003), whereas a linear combination of different spectral types (from B to M in our case) is more appropriate for dEs. Also a wider slit (2″ compared to 0″.5 in Geha et al. 2003) could increase the σ measured if there were some ordered motion along the minor axis.

Figure 3 shows $(v_{max}/\sigma)^* = \frac{v_{max}/\sigma}{\sqrt{\epsilon/(1-\epsilon)}}$ as a function of the projected angular distance from the cluster center (we assume Virgo to be at 17 Mpc; Gavazzi et al. 1999). $(v_{max}/\sigma)^*$ is v_{max}/σ divided by the isotropic oblate model, which means that for values of $(v_{max}/\sigma)^* > 0.8$ the galaxies are rotationally supported. To improve statistics, we have included the dEs of van Zee et al. (2004) (open triangles), whose data are consistent with ours (see Paper I).

Rotationally supported systems are generally located in the cluster outskirts or in the field, while the σ-dominated dwarfs are found only in the central regions of the cluster. This idea had been suggested before (Geha et al. 2003; van Zee et al. 2004), but no clear confirmation was found. van Zee et al. (2004) studied the inner 6° (radius) of Virgo, and found a hint that very slow rotators or non-rotating dEs were located in the core or in the highest density clumps. Our observations reach distances further away from M87, and the evidence of a trend is clearer. The non-parametric Spearman statistical test finds a correlation (r = 0.54) with a confidence of 98.9%. Indeed a significant difference

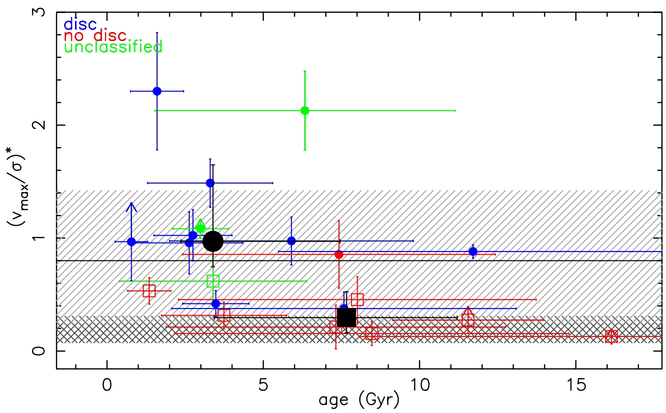

Figure 4. Anisotropy parameter vs. the luminosity-weighted age from Michielsen et al. (2008). Symbols and shaded areas are as in Figures 2 and 3.

in the two dwarf galaxy populations can be seen also in their median values, with dE with signs of a spiral origin having systematically higher velocity rotations and being situated at the periphery of the cluster ($(v_{max}/\sigma)^* = 0.96^{+0.30}_{-0.51}$, $D = 0.99^{+0.64}_{-0.53}$ Mpc) with respect to non-disk dE ($(v_{max}/\sigma)^* = 0.40^{+0.19}_{-0.21}$, $D = 0.47^{+0.41}_{-0.19}$ Mpc). We emphasize that any relation with the cluster-centric distance is smeared out by projection effects.

Figure 4 shows the anisotropy parameter as a function of the age of the galaxies from Michielsen et al. (2008). The Spearman non-parametric test finds a correlation ($r = -0.64$) with a 99.9% of confidence. Indeed the median values for the two populations are significantly different; the dEs with disks are ∼3 Gyr younger than the others. Figure 4 also shows that while dEs with no signs of a spiral origin might be of all ages but on average old (5/8 of the squares are older than 7 Gyr), disk galaxies are preferentially young (9/12 of the dots are younger than 7 Gyr), suggesting that the two populations might have a different origin.

To conclude, our results suggest that the rotationally supported dEs are preferentially located in the field or in the outskirts of the cluster and are on average younger than those that are pressure supported, with no signs of spiral features, generally situated in the core of the cluster.

4. DISCUSSION

It is believed that the difference between fast and slow rotators in Es is due to a different formation origin, with slow rotators, the most massive objects, principally located in dense environments and resulting from major mergers, while fast rotators, being less massive and more gas rich (Emsellem et al. 2007), have a star formation history that is more extended in time. For dwarf galaxies, this segregation in mass is difficult to be appreciated because of their small dynamical range ($8.8 < L_H/L_{H\odot} < 9.7$ in our sample). Moreover, models indicate that the probability that dEs have undergone a major merging event is almost null (De Lucia et al. 2006). This is consistent with the fact that dEs are on average much younger than Es (Michielsen et al. 2008), whose formation happened probably at $z > 2$ (Renzini 2006). If their star formation activity was quenched in recent epochs, this would hardly be due to major merging events since the high σ of clusters already formed prevented strong dynamical interactions (Boselli & Gavazzi 2006).

Dwarf elliptical systems might have a different origin according to their structural, spectrophotometric, and kinematical properties. Although harassment would be able to explain the origin of the pressure-supported dwarfs, it is not likely to explain all the properties of rotationally supported systems ($(v_{max}/\sigma)^* > 0.8$). Harassment has long timescales since it needs multiple encounters to be efficient in removing gas and stars and quenching the star formation (Boselli & Gavazzi 2006), a scenario inconsistent with the observations which indicate that the star formation was active down to recent epochs, as the luminosity-weighted ages derived by Michielsen et al. (2008) suggest (see Figure 4). Furthermore, dynamical interactions heat the system removing rotation and enhancing velocity dispersion. In the simulations of Mastropietro et al. (2005), those galaxies that keep rotation after the harassment still retain an important spiral structure, yet they can not be classified as ellipticals. Moreover harassment is more efficient in the core of the clusters (in the inner 100 kpc), while our result indicates that these rotationally supported systems are located mostly in the outskirts. All these evidences are, however, consistent with a recent ram pressure stripping event as proposed by Boselli et al. (2008a, 2008b). Indeed, ram pressure would easily remove the total gas content of the infalling low-luminosity, late-type galaxies, quenching their star formation, but conserving, at least on short timescales, their angular momentum and therefore their rotation. The spectrophotometric and structural properties of dE in Virgo are consistent with a recent (⩽2 Gyr) interaction with the cluster hot IGM (Boselli et al. 2008a, 2008b). Consistent with observations (Crowl & Kenney 2008), hydrodynamical simulations indicate that ram pressure stripping can be efficient up to the virial radius, or even more outside in dwarf systems with shallow potential wells as those analyzed here (Roediger & Brüggen 2008).

Pressure-supported galaxies ($(v_{max}/\sigma)^* < 0.8$) might have a different origin: (1) they might be galaxies formed in situ through the isotropic collapse of the gas at early epochs, thus not transformed by the environment, and be the extension of Es, with the exception that they probably did not undergo major merging events (De Lucia et al. 2006). Indeed they have old stellar populations, they do not present spiral structures (Lisker et al. 2006a), and they are virialized within the cluster, thus are members since early epochs (Conselice et al. 2001). (2) They can be star-forming systems that entered into the cluster in the early epochs, maybe through the accretion of groups where preprocessing was active, and later modified by galaxy harassment or (3) they are star-forming systems that entered into the cluster several Gyr ago, where ram pressure, although less efficient than today, because of the lower density of the IGM and of the smaller velocity dispersion of the cluster still in formation, had the time through multiple cluster crossing to remove the gas and stop the star formation activity. The lack of supply of new generations of stars on the plane of the disk increases σ on long timescales, while a decrease of the rotation would in any case require dynamical interactions. The two σ-dominated disk dwarfs (VCC1183 and VCC1910) could be galaxies in the last stages of their transformation into dEs.

The analysis done so far, although crucial for understanding the origin of the rotationally supported systems, is still insufficient to explain the origin of the σ-supported galaxies. It is probable that harassment and ram pressure were acting together with a relative weight that might have changed with time. Observations of high-redshift clusters, mainly populated by massive, red sequence galaxies at late epochs (De Lucia et al. 2006) consistently suggest that harassment and ram pressure are the most probable effects. It is, however, clear that a complete study of the kinematical, structural, and spectrophotometric properties of early- and late-type galaxies in clusters combined with model predictions, is a powerful way to study the role of the environment on their evolution, a work we plan to do in the near future.

In summary, we report the first clear evidence of a correlation between the presence of rotationally supported dEs and the distance to the center of the Virgo Cluster. We have seen that the further away a dwarf galaxy is from M87, the larger its rotation is and the younger it appears. In the outer parts, many of them show spiral features beside their elliptical appearance. These kinematical data are consistent with the idea of ram pressure stripping transforming dwarf star-forming galaxies into dEs. Dwarf ellipticals that are pressure supported and show no sign of spiral features are likely to be late-type systems that entered in the cluster at early epochs and were later transformed by a combined effect of multiple encounters with nearby companions and the interaction with the hot and dense IGM. They might also be originally formed in clusters from an isotropic collapse of the primordial gas cloud.

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REFERENCES

Binggeli, B., Sandage, A., & Tammann, G. A. 1985, AJ, 90, 1681
Binney, J. 1978, MNRAS, 183, 501
Blanton, M. R., et al. 2005, ApJ, 631, 208
Boselli, A., Boissier, S., Cortese, L., & Gavazzi, G. 2008a, ApJ, 674, 742
Boselli, A., Boissier, S., Cortese, L., & Gavazzi, G. 2008b, A&A, 489, 1015
Boselli, A., & Gavazzi, G. 2006, PASP, 118, 517
Boselli, A., et al. 2005, ApJ, 629, L29
Byrd, G., & Valtonen, M. 1990, ApJ, 350, 89
Cardiel, N. 1999, PhD thesis, Univ. Complutense de Madrid, Spain
Cenarro, A. J., et al. 2001, MNRAS, 326, 959
Conselice, C. J., Gallagher, J. S., III, & Wyse, R. F. G. 2001, ApJ, 559, 791
Croton, D. J., et al. 2005, MNRAS, 356, 1155
Crowl, H. H., & Kenney, J. D. P. 2008, AJ, 136, 1623
De Lucia, G., Springel, V., White, S. D. M., Croton, D., & Kauffmann, G. 2006, MNRAS, 366, 499
Emsellem, E., et al. 2007, MNRAS, 379, 401
Ferguson, H. C., & Binggeli, B. 1994, AA&R, 6, 67
Gavazzi, G., Boselli, A., Donati, A., Franzetti, P., & Scodeggio, M. 2003, A&A, 400, 451
Gavazzi, G., Boselli, A., Scodeggio, M., Pierini, D., & Belsole, E. 1999, MNRAS, 304, 595
Geha, M., Guhathakurta, P., & van der Marel, R. P. 2002, AJ, 124, 3073
Geha, M., Guhathakurta, P., & van der Marel, R. P. 2003, AJ, 126, 1794
González, J. J. 1993, PhD thesis, Univ. California, Santa Cruz
Kormendy, J., & Bender, R. 1996, ApJ, 464, L119
Lisker, T., Glatt, K., Westera, P., & Grebel, E. K. 2006a, AJ, 132, 2432
Lisker, T., Grebel, E. K., & Binggeli, B. 2006b, AJ, 132, 497
Lisker, T., Grebel, E. K., Binggeli, B., & Glatt, K. 2007, ApJ, 660, 1186
Mastropietro, C., et al. 2005, MNRAS, 364, 607
Michielsen, D., et al. 2008, MNRAS, 385, 1374
Moore, B., Lake, G., & Katz, N. 1998, ApJ, 495, 139
Paturel, G., Petit, C., Prugniel, P., Theureau, G., Rousseau, J., Brouty, M., Dubois, P., & Cambresy, L. 2003, A&A, 412, 45
Pedraz, S., Gorgas, J., Cardiel, N., Sánchez-Blázquez, P., & Guzmán, R. 2002, MNRAS, 332, L59
Renzini, A. 2006, ARA&A, 44, 141
Roediger, E., & Brüggen, M. 2008, MNRAS, 388, 465
Sánchez-Blázquez, P., et al. 2006, MNRAS, 371, 703
Sandage, A., Binggeli, B., & Tammann, G. A. 1985, AJ, 90, 1759
Sargent, W. L. W., & Turner, E. L. 1977, ApJ, 212, L3
Silich, S., & Tenorio-Tagle, G. 2001, ApJ, 552, 91
van Zee, L., Skillman, E. D., & Haynes, M. P. 2004, AJ, 128, 121
White, S. D. M., & Frenk, C. S. 1991, ApJ, 379, 52
White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341
Yoshii, Y., & Arimoto, N. 1987, A&A, 188, 13