Formation and evolution of dwarf early-type galaxies in the Virgo cluster

I. Internal kinematics

E. Toloba¹, A. Boselli², A. J. Cenarro³, R. F. Peletier⁴, J. Gorgas¹, A. Gil de Paz¹, and J. C. Muñoz-Mateos¹⁵

¹ Departamento de Astrofísica y CC. de la Atmósfera, Universidad Complutense de Madrid, 28040, Madrid, Spain
² Laboratoire d’Astrophysique de Marseille, UMR 6110 CNRS, 38 rue F. Joliot-Curie, F-13388 Marseille, France
³ Centro de Estudios de Física del Cosmos de Aragón, E-44001, Teruel, Spain
⁴ Kapteyn Astronomical Institute, Rijksuniversiteit Groningen, Postbus 800, 9700 AV Groningen, the Netherlands
⁵ National Radio Astronomy Observatory, 520 Edgemont Road, Charlottesville, VA 22903-2475

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ABSTRACT

We present new medium resolution kinematic data for a sample of 21 dwarf early-type galaxies (dEs) mainly in the Virgo cluster, obtained with the WHT and INT telescopes at the Roque de los Muchachos Observatory (La Palma, Spain). These data are used to study the origin of the dwarf elliptical galaxy population inhabiting clusters. We confirm that dEs are not dark matter dominated galaxies, at least up to the half-light radius. We also find that the observed galaxies in the outer parts of the cluster are mostly rotationally supported systems with disky morphological shapes. Rotationally supported dEs have rotation curves similar to those of star forming galaxies of similar luminosity and follow the Tully-Fisher relation. This is expected if dE galaxies are the descendant of low luminosity star forming systems which recently entered the cluster environment and lost their gas due to a ram pressure stripping event, quenching their star formation activity and transforming into quiescent systems, but conserving their angular momentum.

Key words. Galaxies: clusters: individual: Virgo Galaxies: dwarf Galaxies: elliptical and lenticular, cD Galaxies: kinematics and dynamics Galaxies: evolution Galaxies: dark matter

1. Introduction

The processes involved in galaxy formation and evolution through cosmic time are still poorly understood. It is indeed still unclear how matter assembled to form the present day galaxy population, whether it followed a passive evolution after the collapse of the primordial density fluctuations (secular evolution), through a subsequent merging of growing structures (hierarchical formation) or a combination of the two. A way of quantifying the relative role of these different mechanisms is to study dwarf galaxies, the most numerous objects in the universe (Ferguson & Binggeli [1994]). Their importance resides in the fact that these low-luminosity systems are expected to be the building blocks of massive galaxies in lambda cold dark matter (ΛCDM) hierarchical merging scenarios (e.g., White & Rees [1978], White & Frenk [1991]).

Among dwarf galaxies, quiescent dwarfs (which we here define to be all quiescent galaxies with $M_B > -18$, including both dwarf ellipticals and spheroidals, hereafter indicated as dEs) are of particular interest since they are the most numerous population in clusters (Ferguson & Binggeli [1994]). These objects were originally thought to be the low luminosity extension of giant ellipticals (Es). Since the 1990s it is known that dEs are composed of several families of objects (e.g. compact and low surface brightness dwarfs) (Bender et al. [1992]; Kormendy et al. [2009]). Later on, it was shown that dEs were no longer small Es with simple, old and metal-poor stellar populations, but much more complex objects exhibiting a wide range of stellar contents. For example, in the Virgo cluster, they have stellar populations ranging from very young (around 1 Gyr old) luminosity-weighted ages to as old as the oldest Es galaxies (14 Gyr) (Michielsen et al. 2008). Their proximity allowed detailed studies of their structural properties which indicated that, behind their elliptical appearance, dEs show a great variety of underlying structures, like discs, spiral arms, irregular features, etc., making them a very heterogeneous class of galaxies (Lisker et al. [2006a, 2007]).

These evidences indicate a complex formation process shaping the evolution of dEs in clusters. Two main different processes have been proposed in the literature: the first mechanism is based on the idea that dEs are formed through internal processes, like supernova feedback, where the interstellar medium (ISM) of the progenitor star forming galaxy is swept away by the kinetic pressure generated by supernovae (Yoshii & Arimoto [1987]), although it seems highly unlikely in dark-matter dominated systems (Silich & Tenorio-Tagle [2001]); the second mechanism rests upon external processes induced by the interaction with the hostile environment in which dEs reside.
In a dense environment several mechanisms are affecting galaxies. This might happen through interactions with the intergalactic medium (IGM), as ram-pressure stripping (Boselli et al. 2004b), galaxy-galaxy interactions (e.g., Byrd & Valtonen 1990) and galaxy harassment (e.g., Moore et al. 1998; Mastropietro et al. 2004). It has been shown that these interactions are able to reproduce some of the observational properties of local dEs in clusters, like their structural parameters (Lisker et al. 2006a, 2007) or their stellar populations. (Geha et al. 2002, 2003; Van Zee et al. 2004) and Paudel et al. 2010). These models have been shown to be consistent with recent observational data.

3. Observations

The observing time that we obtained for this work was part of the International Time Program (ITP 2005-2007) at El Roque de los Muchachos Observatory. We focus on the medium resolution (R ≈ 3800), long-slit spectroscopy carried out during three observing runs. In runs 1 and 3 (December 2005, February 2007) we used the ISIS double-arm spectrograph at the 4.2m WHT, and in run 2 (January 2007) we used the IDS spectrograph at the INT (2.5m telescope).

The advantage of ISIS over optical systems is that it allows us to use a dichroic (5300 Å dichroic in our case) to split the light into two beams to observe simultaneously two wavelength ranges, one in the blue optical part of the spectra and another in the red. This technique allowed us to cover, in 3 settings in the first run, the full wavelength range from 3500 Å to 8950 Å, using a mirror to cover 5000-5600 Å, the only range that we could not cover with this dichroic. In the third run we used 2 settings to cover the same wavelength range except for the dichroic gap.

The wavelength range covered by the IDS was smaller (4600-5960 Å), since detector and grating are the same as on the blue arm of ISIS, the data obtained had similar resolution. The spectral resolution (R = 3800) is high enough to obtain reliable kinematics for dwarf galaxies.

All the details of the configurations used in each run are specified in Table 1.

In Table 2 we list the observed sample. Column 5 presents the morphological type classification according to Lisker et al. (2006a) and Lisker et al. (2006b): dE(di) indicates dwarf ellipticals with a certain, probable or possible underlying disk (i.e. showing spiral arms, edge-on disks and/or a bar) or other structures (such as irregular central features (VCC21)); dE(bc) refers to galaxies with a blue center; dE to galaxies with no evident underlying structure. Four out of our 21 dwarf galaxies were not in the Lisker et al. sample (NGC3073, PGC1007217, PGC1154903 and VCC1947), therefore we classified them as described in Section 6 attending only to their boxyness/diskyness. Column 6 gives the Virgo substructure to which the galaxy belongs, taken from GOLDMine Database (Gavazzi et al. 2003) and defined as in Gavazzi et al. (1999). Columns 7 and 8 refer to the observational campaign (see Table 1) and the exposure time for each setting, which allowed us to get a typical signal-to-noise ratio for the central spectra of ∼ 60 Å⁻¹, enough to obtain reliable central kinematics. The galaxies were observed along their major axis. Their position angles (PA) from the HyperLEDA Database (Paturel et al. 2003) are given in column 9. Column 10 gives the Galactic colour excess from Schlegel et al. (1998).

A total of 37 B to M stars in common with the MILES library (Sánchez-Blázquez et al. 2006) and the CaT library (Cenarro et al. 2001) were observed to flux-calibrate our data and to use them as templates for velocity dispersion measurements.

1. The S/N per Å⁻¹ is obtained dividing the S/N per pixel by the square root of the spatial scale along the slit. This measurement is therefore independent of the instrument used.
Table 1. Observational configurations

| Date          | Run 1              | Run 2              | Run 3               |
|---------------|--------------------|--------------------|--------------------|
| Telescope     | Dec.24-27 2005     | Jan.21-23 2007     | Feb.10-12 2007     |
| Spectrograph  | WHT 4.2m           | INT 2.5m           | WHT 4.2            |
| Detector      | EEV12 (blue)       | EEV10              | RedPlus (red)      |
| Grating       | R1200B (blue)      | R1200B             | R1200B             |
| Wavelength range 1 (Å) | 3500-4300         | 3700-4790          | 3500-4300          |
| Wavelength range 2 (Å) | 4100-4900         | 4600-5600          | 4100-4900          |
| Wavelength range 3 (Å) | 4800-5600         |                    | 7750-8950          |
| Dispersion (Å/pixel) | 0.44              | 0.48               | 0.44               |
| Spectral Resolution (FWHM, Å) | 1.56              | 1.80               | 3.23               |
| Instrumental Resolution (km s⁻¹) | 40                | 46                 | 58                 |
| Spatial scale ("/pix) | 0.40              | 0.40               | 0.44               |
| Slit width (") | 1.95              | 1.95               | 1.91               |

Table 2. The observed galaxies.

| Galaxy | Other name | RA(J2000) (h:m:s) | Dec.(J2000) (°:′:") | Type | Env. | Run | t_exp (sec) | PA (°) | E(B-V) (mag) |
|--------|------------|-------------------|----------------------|------|-----|-----|------------|-------|-------------|
| M 32   | NGC 221    | 10:42:41.84       | +40:51:37.4          | cE2  | M31 | 1   | 1350      | 170   | 0.062       |
| NGC 3073 | UGC 05374 | 10:00:52.10       | +55:37:08.0          | dE(di) | Field | 1   | 3200     | 120    | 0.010       |
| PGC 1007217 | 2MASX J02413514-0810243 | 02:41:35.8          | -08:10:24.8          | dE(di) | Field | 1   | 3600     | 126    | 0.024       |
| PGC 1154903 | 2MASX J02420436+0000531 | 02:42:00.03        | +00:00:52.3          | dE   | Field | 1   | 3600     | 126    | 0.031       |
| VCC 21 | IC 3025    | 12:10:23.14       | +10:11:18.9          | dE(di,bc) | Virgo N Cloud | 2   | 3600     | 99     | 0.021       |
| VCC 308 | IC 3131    | 12:18:50.77       | +07:51:41.3          | dE(di,bc) | Virgo B Cluster | 3   | 2400     | 109    | 0.021       |
| VCC 397 | CGCG 042-031 | 12:20:12.25      | +06:37:23.6          | dE(di,bc) | Virgo B Cluster | 3   | 3600     | 133    | 0.020       |
| VCC 523 | NGC 4306   | 12:22:04.13       | +12:47:15.1          | dE(di,bc) | Virgo A Cluster | 1   | 3400     | 144    | 0.044       |
| VCC 856 | IC 3328    | 12:25:57.93       | +10:33:13.8          | dE(di,bc) | Virgo B Cluster | 2   | 2740     | 72     | 0.024       |
| VCC 917 | IC 3344    | 12:26:32.40       | +13:34:43.8          | dE(di,bc) | Virgo A Cluster | 3   | 3600     | 57     | 0.032       |
| VCC 990 | IC 3369    | 12:27:16.91       | +16:01:28.4          | dE(di,bc) | Virgo A Cluster | 2   | 3000     | 135    | 0.028       |
| VCC 1087 | IC 3381   | 12:28:17.88       | +11:47:23.7          | dE   | Virgo A Cluster | 3   | 3600     | 106    | 0.026       |
| VCC 1122 | IC 3393    | 12:28:41.74       | +12:54:57.3          | dE   | Virgo A Cluster | 3   | 3600     | 132    | 0.021       |
| VCC 1183 | IC 3413    | 12:29:22.49       | +11:26:01.8          | dE(di,bc) | Virgo A Cluster | 2   | 3600     | 144    | 0.031       |
| VCC 1261 | NGC 4482   | 12:30:10.35       | +10:46:46.3          | dE   | Virgo A Cluster | 2   | 6930     | 133    | 0.028       |
| VCC 1431 | IC 3470    | 12:32:23.39       | +11:15:47.4          | dE   | Virgo A Cluster | 2   | 3000     | 135    | 0.054       |
| VCC 1549 | IC 3510    | 12:34:14.85       | +11:04:18.1          | dE   | Virgo A Cluster | 2   | 3300     | 13     | 0.030       |
| VCC 1695 | IC 3586    | 12:36:54.79       | +12:31:12.3          | dE(di,bc) | Virgo A Cluster | 3   | 3600     | 39     | 0.045       |
| VCC 1861 | IC 3652    | 12:40:58.60       | +11:10:04.1          | dE   | Virgo E Cloud | 3   | 3600     | 109    | 0.030       |
| VCC 1910 | IC 809     | 12:42:08.68       | +11:45:15.9          | dE(di,bc) | Virgo E Cloud | 2   | 3800     | 135    | 0.030       |
| VCC 1912 | IC 810     | 12:42:09.12       | +12:35:48.8          | dE(di,bc) | Virgo E Cloud | 2   | 3600     | 166    | 0.032       |
| VCC 1947 | CGCG 043-003 | 12:42:56.36     | +03:40:35.6          | dE(di,bc) | Virgo E Cloud | 2   | 3060     | 126    | 0.027       |

4. Data reduction

The data reduction was performed with RED ucm E (Cardiel 1999), a package specially designed to reduce long-slit spectroscopy with particular attention to the treatment of errors. This package is ideal for treating in parallel the data and error frames, producing an error spectrum associated with each individual data spectrum, which means that the errors are controlled at all times.

Due to the similar instrumental configurations used on all observing runs, the reduction process for both telescopes was the same. The standard procedure for long-slit spectroscopy data reduction consists of bias and dark current subtraction, flat-fielding (using observations of tungsten lamps and twilight sky to correct for high and low frequency variations respectively), cosmic ray cleaning, C-distortion correction, wavelength calibration, S-distortion correction, sky subtraction, atmospheric and interstellar extinction correction and flux calibration. We give below some comments on steps of particular importance:

**Flat-fielding.** The flat-fielding correction is a delicate step at near infrared wavelengths due to the fringe effects. In the first run, the Marconi CCD suffered from significant fringing that varied with the telescope position. Since complete removal of the fringe in run 1 was not possible, we did not use the red Marconi-CCD data to determine the galaxy kinematics. The fringing produced by RedPlus, the new CCD optimised to avoid these patterns, was much lower, with an amplitude of only ~1% independent of position.

**Wavelength calibration.** The wavelength calibration was performed using between 65-100 arc lines depending on the instrumental configuration. They were fitted with a 5th order polynomial that lead to a typical RMS dispersion of 0.1-0.25 Å.

**S-distortion, alignment of the spectra.** During the spectroscopic observations, the galaxies were not perfectly aligned with the rows of the detector. This effect is crucial when measuring gradients of any type (rotation curves, velocity dispersion profiles or line-strength indices). The correction of this effect was
performed using a routine that found the position of the galaxy center as a function of wavelength, fitted all these positions with a low order polynomial and straightened the spectra using that polynomial. This alignment was done with a technique that minimised the errors due to the discretization of the signal. This technique consists of adopting a more realistic distribution of the light in each pixel than just assuming it to be constant. To achieve this the signal in each pixel is fitted with a second order polynomial using the available information in the adjacent pixels.

Sky subtraction. The sky subtraction is critical for studies where the spectra are analysed at light levels corresponding to only a few per cent of the sky signal, as in our case. For each galaxy observation a sky image was generated fitting the data at each wavelength with a first order polynomial in regions at both sides of the galaxy close to the ends of the slit (which has a length of 3.7 arcmin on the WHT and 3.3 arcmin on the INT). This was possible since for all targets except M32 the galaxy filled only a small region of the slit, so this synthetic sky image was free from contamination from the galaxy. For M32, we observed a separate sky frame moving the telescope from the coordinates of the galaxy to a position $\Delta \alpha = -416''$ (West), $\Delta \delta = 459''$ (South) far enough from M32 to avoid its light but with the same level of contamination from M31.

Extinction correction. Atmospheric extinction was calculated using the extinction curve for El Roque de los Muchachos Observatory (www.ing.iac.es/Astronomy/observing/manuals/ps/tech_notes/tnt031.pdf). The Galactic extinction was corrected using the curve of Fitzpatrick (1999) and the reddening from Schlegel et al. (1998) listed in Table 2. Flux calibration. The relative flux calibration of the spectra was performed using the observed stars in common with the MILES library (Sánchez-Blázquez et al. 2006) for the optical spectra, and with the CaT library (Cenarro et al. 2001) for the near infrared. For each observed star we obtained a flux calibration curve. All of them were averaged to obtain one unique flux curve for each run and instrumental configuration. The deviations of each flux calibration curve from the averaged one were introduced as uncertainties in the error spectra. The typical deviation was of 2% reaching $\sim$7% in the first and last $\sim$150 Å of each setup spectra where the noise is the highest.

5. Measurement of the kinematic parameters

The stellar kinematics of galaxies (radial velocities and velocity dispersions) were calculated using the routine MOVEL included in REDUCE package (Cardiel 1999). This routine is based on the Fourier quotient method described by Sargent & Turner (1977) and refined with the OPTEMA algorithm (González 1993) that allows us to overcome the typical template mismatch problem. In order to do this, a number of stars of different spectral types and luminosity classes were introduced in the program to create a model galaxy. These stars were of spectral type B9, A0, A3V, G0, G2III, G5III, G8III, G9III, K0III, K01, K2II, K3III, M0III and M2III. The model galaxy was created and processed in parallel to the galaxy spectrum. To build the model galaxy all the template spectra were scaled, shifted and broadened according to a first guess of $\gamma$ (mean line-strength), $v$ (radial velocity) and $\sigma$ (velocity dispersion). Then the algorithm looked for the linear combination of these template stars that best matched the observed galaxy spectrum. The best linear combination of observed stars was chosen as the one that minimises the residuals between the galaxy spectrum and the broadened optimal template. This provided a first model galaxy with a first kinematic output ($\gamma$, $v$ and $\sigma$). This model galaxy was then improved using this new guess of kinematic parameters. The process was iterated until it converged. The emission lines, found only for the field dwarf galaxies, and some large sky line residuals, only present in some cases, were masked, so that the program did not use them for the minimisation of the residuals.

To minimize template mismatch effects, it is essential to use as templates a variety of spectral types and luminosity classes which are representative of the stellar population of the observed galaxy; as we will discuss in Section 5.3, small differences in ages and metallicities could lead to a partial fit of the strongest lines and therefore affect the derived velocity dispersion of the galaxy.

It is also important to check whether the observed stars were filling the slit during the observation. If they were not, the instrumental profile would not affect them in the same way as in the galaxies, and as a consequence, the $\sigma$ that one would measure from contamination from the slit would be $\sqrt{\sigma_{inst}^2 + \sigma_{gal}^2}$, where $\sigma_{gal}$ is the intrinsic velocity dispersion of the galaxy and $\sigma_{inst}$, in this case, is the quadratic instrumental difference between the galaxies and the stars.

To correct for this effect the physical slit width is required. We calculated it from the spatial scale and the FWHM (in pixels) of the arc lines, which illuminate homogeneously the slit. To see whether the stars were filling the slit completely we checked that the FWHM of their spatial profile was larger than the physical slit width. If this was not the case, the spatial profile of the star was broadened accordingly. Although this introduced some uncertainties, the data quality improved by making this correction. The value of $\sigma$ measured and adopted in this work is thus the intrinsic velocity dispersion of the galaxy corrected for possible instrumental effects.

Figure 1 shows a typical fit of the observed central spectral of a galaxy and the corresponding optimal template broadened with a gaussian with the derived dynamical parameters. The errors in velocity and $\sigma$ were computed through Monte-Carlo simulations, repeating the whole process (including the derivation of the optimal template) for 100 simulated galaxy spectra created using the error spectra obtained during the reduction process. The observed and simulated spectra perfectly match.

5.1. Kinematic parameter profiles

To measure kinematic gradients it is important to determine the minimum S/N needed to measure reliable radial velocities and velocity dispersions. To do that we have designed and carried out a test exercise based on Monte-Carlo simulations that constraints the errors and systematic effects in the measurement of radial velocities and velocity dispersions on fake galaxy spectra with known input kinematic parameters and different ages, metallicities and S/N ratios. This can be outlined in the following steps: i) from the simple stellar population models from PEGASE.HR (FWHM $\sim$ 0.55 Å, Le Borgne et al. 2003) we selected a subset of 9 model spectra (3 ages and 3 metallicities) representative of quiescent dwarf galaxies: ages 1 Gyr, 4 Gyr, 10 Gyr; metallicities of $Z = 0.0$, $Z = -0.4$, $Z = -0.7$. The spectral resolution of these models are needed since in our bluer configuration the resolution is $\sim$ 1.6 Å; ii) Taking into account our instrumental

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2 During the observation an indicative width of the slit is selected by the user through a web interface.
resolution, each model was broadened and redshifted to match a set of input velocity dispersions, $\sigma_i$, (9 values between 20 km s$^{-1}$ and 60 km s$^{-1}$ in steps of 5 km s$^{-1}$) and radial velocities, $v_i$, (800 km s$^{-1}$ and 1500 km s$^{-1}$, typical values of Virgo cluster members). This amounts a total of 162 model spectra. i) For each one of the above spectra we added different levels of random noise to match S/N ratios of 10, 15, 20, 25, 30 and 50, hence ending up with 972 model galaxy spectra. ii) For each simulated galaxy spectrum we run exactly the same MOVEL procedure as we did for our dE galaxy sample, using the same template stars and MOVEL parameters. 100 Monte-Carlo simulations for each model galaxy were carried out to get reliable errors of the derived kinematic parameters, $\sigma_i$ and $v_i$ obtained as the mean value of the 100 Monte-Carlo simulations in each case. Since the input kinematics $\sigma_i$ and $v_i$ are set by construction, comparison and reliability analysis are immediate to perform.

The above procedure was carried out for each instrumental configuration in each of the 5 different spectral regions. The results obtained are shown in Figures 2, 3 and 4.

After correcting for any systematic offsets in radial velocity and velocity dispersion due to small intrinsic differences between PEGASE.HR models and our observed stars, we have analysed the simulations looking at the relative differences between the measured values and the parameters introduced in the simulated galaxies ($\Delta v/v = (v - v_i)/v_i$ and $\Delta \sigma/\sigma = (\sigma - \sigma_i)/\sigma_i$). Figures 2, 3 and 4 show these differences as a function of S/N in the wavelength range 4100-4900 Å, a range in common between the WHT and INT observations and where lines as important as the G-band are located. The error bars in these 3 Figures show the relative uncertainties obtained by MOVEL as the RMS scatter resulting from the 100 Monte-Carlo simulations for each model galaxy.

In Figure 2 we study the influence of the S/N ratio and the instrumental resolution on the measurement of the velocity dispersion of a galaxy. Each point represents a galaxy of similar stellar populations (age 4 Gyr and metallicity $-0.4$) but different velocity dispersion (from 20 to 60 km s$^{-1}$). As expected, the errors increase dramatically at the lowest S/N ratios. For low S/N ratios (S/N=10) offsets are found even for galaxies with high $\sigma$, so the velocity dispersions derived at this S/N cannot be trusted. On the contrary, for S/N ratios higher than or equal to 15 we do not find statistically significant offsets, with the exception of measurements below half the instrumental resolution ($\sigma = 20$ km s$^{-1}$) where special care must be taken. Only for S/N larger than 20 the measured $\sigma$ can be fully trusted for velocity dispersions as low as half the instrumental resolution.

Figure 3 presents the influence of the stellar populations on the measurement of the velocity dispersion of a galaxy. In the upper panel we show the effect of the age on a dwarf galaxy of $\sigma = 40$ km s$^{-1}$ and $Z = -0.4$, while in the lower panel we show the effect of the metallicity for a galaxy with $\sigma = 40$ km s$^{-1}$ and 4 Gyr old. In this case, although the errors barely depend on metallicity, the age-dependence is crucial, and for populations as young as 1 Gyr the $\sigma$ measurements are underestimated for a S/N ratio below 15.

In Figure 4 we analyse the effect of the stellar populations on the computation of the radial velocity. Neither a change in the velocity dispersion nor in the metallicity have appreciable effects on this variable. Only the age of the stellar population have appreciable influence on the determination of the radial velocity whenever the age is young, around 1 Gyr. The uncertainty induced by age variations, however, is small, $\leq$1%, thus rotation velocities can be accurately measured down to S/N=10.

In Figure 5 we plot the expected RMS error (i.e. RMS of the average of all the simulations) as a function of S/N ratio in order to have a statistical estimate of the uncertainty. The average of all the simulations (corresponding to different velocity dispersions, ages and metallicities) for each S/N, takes into account that for a target galaxy we do not have a priori information about either its velocity dispersion or the parameters of the stellar population.

Figures 2, 3 and 4 clearly show that data with S/N ratios below 15 might induce errors as large as 22% in the determination of $\sigma$, in particular for small velocity dispersions ($\sigma \sim 20$ km s$^{-1}$), while only 0.4% for radial velocities. All these tests have been computed for the different wavelength ranges covered by our survey and the results obtained are...
Fig. 3. Simulations to study the dependence of the stellar population of the galaxy on the measurement of its velocity dispersion. We plot the relative offsets found between the measured $\sigma$ and the velocity dispersion introduced in the simulated galaxy as a function of the S/N ratio. In both panels a typical $\sigma$ of 40 km s$^{-1}$ has been considered. In the upper panel we fix the metallicity of the galaxy to $-0.4$ and study the influence of the age of the stellar population. In the lower panel the parameter fixed is the age to 4 Gyr, and we analyse the influence of the metallicity on $\sigma$.

Fig. 4. Simulations to study the influence of the stellar populations and the S/N ratio on the measurement of the radial velocities. We plot the relative uncertainty when measuring the radial velocities ($\Delta v/v$, defined as $(v_o - v_i)/v_i$) as a function of the S/N ratio. Only the results for the radial velocity $v = 1500$ km s$^{-1}$ are shown because the offsets and errors found are independent of the radial velocity of the galaxy. The results plotted are for a typical dwarf galaxy with velocity dispersion of 40 km s$^{-1}$ and metallicity $-0.4$. The velocity dispersion does not have any effect on the measurement of radial velocities nor the metallicities. Note the different scale in the y-axis compared to Figures 2 and 3.

Fig. 5. Total scatter in the differences found for the 972 simulations computed as a function of the S/N ratio. In this Figure all models for all stellar populations and velocity dispersion parameters have been used.

rather similar. For the red arm of ISIS, where the instrumental resolution is larger, we obtain similar results as those shown in the blue arm (Figures 5) but with slightly larger uncertainties. These simulations show that radial velocities can be computed with spectra of S/N as low as 10 given that the uncertainty is always below 1%. However, in the study of velocity dispersions, we must discard any measurement with S/N below 15 because $\sigma$ is, in this case, highly dependent on age and not reliable for $\sigma$ as low as half the instrumental resolution.

When running the MOVEL algorithm as a function of galaxy radius, we fitted the optimal template at every radius, rather than using the central optimal template, in order to improve the fit. As a result, the optimal templates turn out to be radial dependent. The differences, however, are not very large, because in the linear combination of templates, G-stars always contribute with the highest weight.

Due to the different instrumental configurations used in the observation campaigns (see Table 1), more than one kinematic profile per galaxy was obtained. These profiles, consistent within the errors, were averaged to produce a single, high S/N profile per galaxy (see Figure 6).

The recessional velocity of each single galaxy, removed for the determination of the rotation curve (Figure 6), has been determined by averaging, with a weighted mean, the recessional velocity measured in each single position along the radius. This improved technique for measuring recessional velocities (listed on Table 4) can be applied since the rotation curves are symmetrical.

Table 3 gives an example of the tables electronically available with the values of the kinematic profiles.

5.2. Central velocity dispersion and maximum rotational velocity

To compute the central velocity dispersion ($\sigma$) we shifted all the spectra to the same wavelength scale using the rotation curves displayed in Figure 6, and we coadded all the individual spectra.

3 Note that galaxies as VCC856, those with the poorest quality, have a non-zero central velocity.
Fig. 6. Kinematic profiles of the galaxy sample. Each diagram shows in the left upper panel the folded rotation curve of the galaxy and in the left bottom panel the folded velocity dispersion profile. The different sides of the galaxy are indicated with red squares and black dots. On the upper x-axis the radius is given as a fraction of the effective radius ($R_{\text{eff}}$) of each galaxy in the I band (see Section 6). The purple open squares show the points used to calculate the maximum rotation for each galaxy and the purple line indicates this $v_{\text{max}}$. The dashed line in the velocity dispersion profiles indicate the central $\sigma$ computed up to the $R_{\text{eff}}$ (see Table 4). In the right panels the not-folded kinematical profiles are plotted.
up to one effective radius. The typical S/N ratio for the spectrum where the central \( \sigma \) is computed is \( \sim 60 \) Å\(^{-1}\). These results are shown in Table 3.

The maximum rotational velocity (\( v_{\text{max}} \)) 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 were required). As a consequence values with larger errors weight less than those with smaller errors. For each galaxy these values are presented in Figure 6 as purple squares. We show in Appendix A that, given the uncertainty, all galaxies with \( v_{\text{max}} < 9 \) km s\(^{-1}\) can be considered non-rotators.

The ratio between these two kinematic measurements, the maximum rotation velocity \( v_{\text{max}} \) and the velocity dispersion \( \sigma \), is called anisotropy parameter, \( \sigma_{\text{ans}} / \sigma \), and it is used to study the rotational/support of the galaxies. In Table 3 we show \( (v_{\text{max}}/\sigma)^\epsilon \), the anisotropy parameter corrected from the inclination. This correction is done following the expression \( (v_{\text{max}}/\sigma)^\epsilon = \frac{v_{\text{max}}}{\sigma_{\text{inst}}} \), where \( \epsilon \) is the ellipticity. Note that for those galaxies with ellipticity close to zero, no correction can be done because they are nearly face on. We choose a conservative value of \( (v_{\text{max}}/\sigma)^\epsilon = 0.8 \) as the limit between pressure and rotationally supported systems in order to include those objects that, within the errors, are consistent with being flattened by rotation. This assumption is justified by the fact that the measured \( v_{\text{max}} \) is a lower limit since the rotation curves are still rising.

### 5.3. Comparison to the literature

Displaying simultaneously the kinematic profiles measured in this work with those of other authors (Figure 7), one sees that the radial extent of the kinematic curves varies from one work to another. In addition, the offsets found in the velocity dispersions are not always consistent within the errors (Figure 8). These two differences are important, because different radial extents lead to different maximum rotation velocities and offsets in the velocity dispersion profiles lead to different central \( \sigma \) values.

### Notes

#### Table 3. Kinematic profiles for VCC990.

| \( R_i (\prime) \) | \( v (\text{km s}^{-1}) \) | \( R_o (\prime) \) | \( \sigma (\text{km s}^{-1}) \) |
|------------------|----------------|----------------|----------------|
| -3.56 | 16.8±6.4 | -3.26 | 47.2±6.0 |
| -2.58 | 9.8±6.3 | -1.38 | 39.2±5.4 |
| -2.00 | 10.5±6.4 | -0.80 | 35.8±4.6 |
| -1.60 | 1.7±6.2 | -0.40 | 32.5±3.5 |
| -1.20 | -6.3±4.4 | 0.00 | 42.2±3.1 |
| -0.80 | 3.9±2.7 | 0.40 | 41.3±2.8 |
| -0.40 | 0.1±2.3 | 0.80 | 39.7±3.6 |
| 0.00 | 6.8±2.0 | 1.38 | 37.7±3.9 |
| 0.40 | 2.2±2.4 | 2.36 | 36.1±8.5 |
| 0.80 | 10.3±1.1 | 4.97 | 37.4±5.6 |
| 1.20 | -5.2±5.2 | | |
| 1.60 | -11.8±5.6 | | |
| 2.00 | -25.3±6.4 | | |
| 2.58 | -17.1±7.2 | | |
| 3.56 | -29.6±5.7 | | |
| 5.42 | -25.3±6.2 | | |

NOTES: Column 1: radius for the rotation speed profile. Column 2: rotation velocities. Column 3: radius for the velocity dispersion profile. Column 4: velocity dispersions. All the kinematicic profiles are electronically available.

### Notes

#### Table 4. Kinematic parameters.

| Galaxy | \( \sigma (\text{km s}^{-1}) \) | \( v_{\text{max}} (\text{km s}^{-1}) \) | \( (v_{\text{max}}/\sigma)^\epsilon \) | \( v_{\text{ans}} (\text{km s}^{-1}) \) |
|--------|----------------|----------------|----------------|----------------|
| PGC1007217 | 35.2±0.9 | 30.6±5.0 | 2.3±0.4 | 1592.3±3.3 |
| PGC1154903 | 23.1±4.1 | 8.6±2.6 | 0.5±0.2 | 1156.3±6.4 |
| NGC3073 | 39.8±0.3 | 17.1±6.7 | 1.1±0.4 | 1168.9±2.5 |
| VCC21 | 26.1±4.0 | 18.4±5.9 | 0.9±0.3 | 463.6±9.2 |
| VCC308 | 31.7±1.2 | 30.4±8.6 | 1.0±0.3 | 1515.3±3.2 |
| VCC397 | 29.9±1.1 | 52.0±11.6 | 2.5±0.6 | 2434.9±2.4 |
| VCC523 | 45.8±0.7 | 39.6±5.7 | 1.5±0.2 | 1515.7±2.6 |
| VCC856 | 29.6±2.5 | 9.7±1.9 | 1.0±0.2 | 980.2±1.9 |
| VCC917 | 31.4±1.4 | 21.6±7.5 | 0.8±0.3 | 1236.2±2.4 |
| VCC990 | 40.6±1.0 | 26.3±1.6 | 0.9±0.1 | 1691.5±2.1 |
| VCC1087 | 48.3±0.7 | 7.1±6.4 | 0.2±0.2 | 644.6±3.2 |
| VCC1122 | 37.2±0.8 | 17.3±7.7 | 0.5±0.2 | 447.8±2.7 |
| VCC1183 | 41.3±1.2 | 10.1±2.8 | 0.5±0.1 | 1290.7±2.3 |
| VCC1261 | 51.8±0.9 | 13.9±5.2 | 0.4±0.1 | 1806.4±2.1 |
| VCC1431 | 54.1±1.2 | 7.0±3.6 | 0.1±0.1 | 1472.8±3.1 |
| VCC1549 | 39.8±1.9 | 5.2±2.3 | 0.3±0.1 | 1377.3±2.0 |
| VCC1695 | 28.7±1.1 | 14.3±3.1 | 0.9±0.2 | 1706.0±3.0 |
| VCC1861 | 40.4±0.9 | 6.3±4.3 | 0.2±0.1 | 617.2±2.6 |
| VCC1910 | 39.0±1.1 | 6.0±2.3 | 0.4±0.2 | 178.6±2.2 |
| VCC1912 | 37.1±1.0 | 20.8±4.5 | 0.5±0.1 | 110.5±2.0 |
| VCC1947 | 45.3±1.1 | 28.3±2.1 | 1.1±0.1 | 956.3±1.8 |

NOTES: Column 1: galaxy name. Column 2: central velocity dispersions computed within the \( R_{eff} \). Column 3: maximum rotation velocities. The \( v_{\text{max}} \) adopted for VCC0856, VCC0990 and VCC1183 have been measured in the rotation curves of Chilingarian (2009) due to their larger extent (see Section 5.3). Column 4: anisotropy parameter corrected from inclination. Column 5: mean radial velocity observed. Values in agreement with those of NED database.

### 5.3.1. Velocity dispersions

There are two factors that critically affect the measurements of the velocity dispersion of the galaxies: the not identical instrumental \( \sigma \) for the stars and the galaxies and the spectral types of the stars used to fit the width of the galaxy lines.\(^[4]\) Caldwell et al. (2003) made their observations with a \( \sigma_{\text{inst}} = 100 \) km s\(^{-1}\), too high to accurately measure velocity dispersions of typical dwarf galaxies, below 50 km s\(^{-1}\).

Concerning the equality of the instrumental resolution in the templates and in the galaxies Chilingarian (2009) used simple stellar population (SSP) models of PEGASE.HR (Le Borgne et al. 2003), based on ELODIE (Prugniel et al. 2007) (\( R = 10000 \)). In this case, the broadening of the SSP models to \( \sigma_{\text{inst}} \) of the galaxies must be cautiously done because \( \sigma_{\text{inst}} \) of the models is based on the mean value of the spectral resolution of the library they are based on, therefore small differences after the broadening between the SSP models and the galaxies can arise.

Continuing with the same effect, in the works of Pedraz et al. (2002) and van Zee et al. (2004) the stars observed were not filling the slit because they were not defocused and the seeing was smaller than their slit width. But in the case of Geha et al. (2003) and Beasley et al. (2009), where their slit widths were 0.75” and 1.0” respectively, it is possible that some stars were filling the slit thanks to the seeing. However, in none of these works a correction was made to assure that the instrumental profile in the stars was the same as in the galaxies.

In reference to the templates used to perform \( \sigma \), some of the authors mentioned above used only one star to fit the galaxy spectrum, and in such a case the fact that the template is not representative of the stellar population of the galaxy might lead...
to large errors. We have computed Monte-Carlo simulations to see the differences between fitting the galaxy spectrum with only one star and a linear combination of stars of spectral types from B to M, with different luminosity classes. The simulations consisted of a selection of PEGASE.HR models of 3 different ages (1 Gyr, 4 Gyr and 10 Gyr) and 3 different metallicities (Z = 0.0, Z = −0.4, Z = −0.7) with Salpeter IMF (Le Borgne et al. 2003); a total of 9 models. The stars used as templates were from MILES library (Sánchez-Blázquez et al. 2006). First of all we checked that after broadening the models (originally FWHM=0.55 Å) to the MILES resolution (FWHM=2.3 Å) we obtained σ = 0 km s$^{-1}$ when running MOVEL, thereby showing that there was no zero point offset. Secondly, we broadened the models to 40 km s$^{-1}$ to simulate dwarf galaxies of different stellar populations. And finally, we ran MOVEL using 3 different kinds of templates: only one K1III star (as in Geha et al. 2003), only one G8III star (as in van Zee et al. 2004b), and a linear combination of B to M stars with different luminosity classes (as in this work). To measure σ we have masked the Balmer lines, especially those bluer than H$\alpha$ to avoid possible problems due to emission lines. Our simulations show that a linear combination of different stars is the most accurate method to obtain the velocity dispersion of the galaxies, never finding an error above 25%, independent of the stellar population considered. Note that if a young population dominates the light of the galaxy (for ages of 1 Gyr and below), and a single G or K star is used as a template, an error up to 70% can be done. When a single star is used as template, a dependence on metallicity for young populations (1 or 4 Gyr) is also found, in the sense that decreasing the metallicity increases the uncertainty. This dependence is likely due to offsets introduced by the method employed to compute σ. The results obtained have been summarised in Table 5.

### Table 5. Uncertainties introduced when different templates are used to calculate the velocity dispersion of a dwarf galaxy with different stellar populations. ∆σ/σ, defined in Figure 8, uses as σ, 40 km s$^{-1}$.

| Age (Gyr) | Linear combination of B to M stars | G8III | K1III |
|----------|-----------------------------------|-------|-------|
| Z=+0.0  | 15% 19% 1%                         | 32% 54% 71% | 29% 47% 59% |
| Z=−0.4  | 8% 18% 19%                         | 15% 18% 20% | 19% 18% 20% |
| Z=−0.7  | 7% 14% 23%                         | 17% 13% 11% | 17% 13% 11% |

5.3.2. Rotation curves

Different criteria have been used in the literature to measure the maximum rotation velocity. The main difficulty here is to have an extended rotation curve that reaches a clear plateau where the maximum rotation can be measured. As this is not so easy for dEs, an objective criteria, independent of the shape of the rotation curve in each case, must be adopted. The different criteria used by the various authors have led to maximum rotational velocities that are nevertheless in the majority of the cases nearly consistent within the errors (Figure 9). The criterion used by Pedraz et al. (2002) is the same as the one adopted here. Although we achieved a radial extent of 23′′ for VCC1122 and Pedraz et al. (2002) only 8′′, the latter value was enough to reach the flat part of the rotation curve, and, as a consequence, both measurements of the maximum rotation are identical. The explanation for the differences found with Simien & Prugniel (2002) are mainly based on the fact that only two points were considered to obtain the maximum rotation in that paper. The differences with Geha et al. (2003) are due to the limitation of their data to the core of the galaxies, never reaching radii larger than 6′′ (see Figure 7). The differences with van Zee et al. (2004b) and Chilingarian et al. (2009) are related to a different radial extent of the rotation curves. Note that Chilingarian (2009) does not calculate the maximum rotation, but we have applied our criterion to his rotation curves. Finally, the differences found with Beasley et al. (2009) are due to the fact that $v_{\text{max}}$ is obtained from the analysis of Globular Clusters located up to $\sim 7R_{\text{eff}}$. When their kinematic data were compared to the stellar component using long slit spectroscopy along the major axis of the galaxy, never reaching radii larger than 6′′ (see Figure 7). The maximum rotation values adopted for the analysis (see Table 4) are our own values, except for VCC856, VCC990 and VCC1183, where the data come from Chilingarian (2009), since he obtained larger radii than us. Note that the values from Beasley et al. (2009) can not be adopted here because our work is dedicated to the analysis of the stellar component of dEs.

The comparison with Beasley et al. (2009), who finds rotation speeds much larger at $7R_{\text{eff}}$ (100 and 50 km s$^{-1}$ higher for VCC1087 and VCC1261, respectively) than our data at the $R_{\text{eff}}$, indicate that the rotation curves of these galaxies are still rising.

6. Photometric parameters

In order to make a complete analysis of the kinematics, comparison with some photometric parameters is needed. For our study, we require I-band (Johnson-Cousins) total magnitudes and optical radii ($R_{\text{opt}}$, radius containing 83% of the total I-band luminosity (Catinella et al. 2006)) to study the shape of the rotation...
curves. Effective radii (R_{eff}, radius containing 50% of the total light) is needed to measure the extent of the radial profiles in physical units of the galaxy. Ellipticities (\epsilon) are needed to make the appropriate corrections due to inclination. A parameter to measure the boxyness/diskyness of the isophotes (C_4) is also required to study the possible late-type origin of these dwarf early-type galaxies.

All these parameters have been obtained from i-band Sloan Digital Sky Survey (SDSS, York et al. (2000)) data release 6 (DR6, Adelman-McCarthy et al. (2008)) photometry. They have been calculated using the IRAF4 task ellipse as described in Appendix B. The transformation from i-band (SDSS) to I-band (Johnson-Cousins) has been done assuming m_i = m_I - 0.52 \pm 0.01 mag (Fukugita et al. 1995).

6.1. C_4: boxyness/diskyness parameter

The boxyness/diskyness (C_4) parameter measures the deviations of the isophotes from a perfect ellipse. If C_4 > 0 the isophotes are disky, indicating that some disk substructure is present in the galaxy, and when C_4 \leq 0 the isophotes are boxy (Carter 1978, Kormendy & Bender 1996). This parameter is independent from the surface brightness profile of the galaxy. The C_4 parameter, determined for our galaxies as described in Appendix D, is provided in Table 4.

Our C_4 classification for disky isophotes agrees in general with the morphological classification of Lisker et al. (2006a) as can be seen in Figure 10. Note that Lisker et al. (2006a) classified a galaxy as disky when disk features (spiral arms, edge-on disks, or bars) were detected after subtracting an axisymmetric light distribution from the original image or after unsharp masking. In this Figure we can see that the red dots, those galaxies classified as being without underlying structures in Lisker et al. (2006a), are grouped around C_4 \leq 0 (boxy or elliptical isophotes), while the blue dots (galaxies with some disky structure in Lisker et al. (2006a)) are all consistent with C_4 > 0 (disky isophotes). This justifies the use of the C_4 parameter to detect the presence of an underlying disk. Three exceptions are found and discussed in Appendix D.

In this respect, it is important to underline the correlation between C_4 and the anisotropic parameter evident in Figure 10, first found by Bender et al. (1988) for more massive elliptical galaxies.

7. Analysis

The analysis presented in this work is primarily focused on the rotationally supported systems. Although the majority of the dwarf galaxies (15 out of 21) show some rotation (v_{max} > 9 km s^{-1}, Table 4), only 11 are rotationally supported ((v_{max}/\sigma)^* > 0.8) (Toloba et al. 2009). Here we try to understand whether the observed kinematic properties of the rotationally supported systems are consistent with those of star forming galaxies of similar luminosity.

7.1. Shape of the rotation curves

Catinella et al. (2006) made a systematic study of the shape of the rotation curves of late-type spiral galaxies as a function of luminosity based on the method described in Persic et al. (1996). They fitted the rotation curves following the Polyex model (Giovanelli & Haynes 2002) which has the form:

\[ V_{PE}(r) = V_0 \left(1 - e^{-r/r_{PE}}\right) \left(1 + \frac{\alpha r}{r_{PE}}\right) \]  

(1)

This analytical function depends on 3 parameters: V_0, r_{PE} and \alpha, which represent the amplitude, the exponential scale of the inner region and the slope of the outer part of the rotation curve, respectively. The mean fitted rotation curves from Catinella et al.
Table 6. Derived parameters.

| Galaxy     | d (Mpc)  | $M_I$ (mag) | $\epsilon$ | $R_{1/2}$ ('') | $C_{e} \times 100$ | Disk classification (L60b) |
|------------|----------|-------------|-------------|----------------|---------------------|-----------------------------|
| PGC1007217 | 20.23 ± 1.40 | -17.39 ± 0.15 | 0.13 ± 0.05 | 11.11 ± 0.02 | 4.8(0.7) ± 0.6 | — |
| PGC1154903 | 15.00 ± 1.10 | -15.91 ± 0.16 | 0.34 ± 0.02 | 8.36 ± 0.04 | 0.3 ± 0.44 | — |
| NGC3073    | 33.73 ± 14.44 | -20.43 ± 0.93 | 0.14 ± 0.02 | 14.78 ± 0.03 | 3.2(0.7) ± 0.2 | — |
| VCC21      | 16.74 ± 0.15 | -17.78 ± 0.03 | 0.36 ± 0.03 | 15.48 ± 0.11 | 3.7(0.7) ± 0.6 | Disk |
| VCC308     | 16.41 ± 0.32 | -18.78 ± 0.05 | 0.04 ± 0.03 | 19.22 ± 0.04 | 0.2(0.7) ± 0.0 | Disk |
| VCC397     | 16.41 ± 0.32 | -17.62 ± 0.05 | 0.33 ± 0.03 | 13.75 ± 0.02 | 5.1(0.7) ± 0.3 | Disk |
| VCC523     | 16.74 ± 0.15 | -19.16 ± 0.03 | 0.25 ± 0.01 | 20.90 ± 0.03 | 2.6(0.7) ± 0.3 | Disk |
| VCC856     | 16.83 ± 0.46 | -18.49 ± 0.06 | 0.09 ± 0.03 | 15.82 ± 0.06 | -0.2 ± 1.7 | Disk |
| VCC917     | 16.74 ± 0.15 | -17.39 ± 0.03 | 0.41 ± 0.02 | 9.68 ± 0.04 | 4.3(0.7) ± 0.2 | No Disk |
| VCC990     | 16.74 ± 0.15 | -18.27 ± 0.03 | 0.34 ± 0.02 | 9.73 ± 0.02 | 4.1(0.7) ± 0.3 | Disk |
| VCC1087    | 16.67 ± 0.46 | -19.94 ± 0.06 | 0.28 ± 0.03 | 22.74 ± 0.05 | -0.9 ± 1.1 | No Disk |
| VCC1122    | 16.74 ± 0.15 | -17.94 ± 0.03 | 0.50 ± 0.04 | 14.06 ± 0.05 | 3.8(0.7) ± 0.2 | No Disk |
| VCC1183    | 16.74 ± 0.15 | -18.59 ± 0.03 | 0.22 ± 0.12 | 18.23 ± 0.01 | 1.7(0.7) ± 0.0 | Disk |
| VCC1261    | 18.11 ± 0.50 | -19.39 ± 0.06 | 0.37 ± 0.05 | 22.07 ± 0.03 | 1.5(0.7) ± 0.6 | No Disk |
| VCC1431    | 16.14 ± 0.45 | -18.47 ± 0.06 | 0.03 ± 0.01 | 10.32 ± 0.01 | 0.2 ± 0.1 | No Disk |
| VCC1549    | 16.74 ± 0.15 | -18.18 ± 0.03 | 0.16 ± 0.01 | 13.56 ± 0.05 | -1 ± 3.5 | No Disk |
| VCC1695    | 16.52 ± 0.61 | -18.13 ± 0.08 | 0.22 ± 0.05 | 19.98 ± 0.10 | -0.9 ± 3.7 | Disk |
| VCC1881    | 16.14 ± 0.45 | -18.57 ± 0.06 | 0.04 ± 0.02 | 18.52 ± 0.04 | 0.8 ± 2.5 | No Disk |
| VCC1910    | 16.07 ± 0.44 | -18.63 ± 0.06 | 0.14 ± 0.04 | 13.70 ± 0.02 | -0.4 ± 1.0 | Disk |
| VCC1912    | 16.74 ± 0.15 | -18.62 ± 0.03 | 0.54 ± 0.06 | 23.34 ± 0.02 | 3.6(0.7) ± 0.2 | No Disk |
| VCC1947    | 16.74 ± 0.15 | -18.46 ± 0.03 | 0.23 ± 0.01 | 10.70 ± 0.02 | 4.2(0.7) ± 0.5 | — |

NOTES: Column 1: galaxy name. Column 2: distances in Mpc from Surface Brightness Fluctuations (SBF) for individual Virgo galaxies from Mei et al. (2003) when available, or the mean A/B Cluster distance from Mei et al. (2003) for the rest of them (note that E, N and S Clouds are East, North and South areas of Cluster A). The distance for NGC3073 from SBF by Tonry et al. (2001) and PGC1007217 and PGC1154903 distances are from NED/IPAC Database derived from redshift with $H_0 = 73 ± 5$ km s$^{-1}$ Mpc$^{-1}$ (these two distances must be used cautiously). Column 3: Absolute magnitudes in I-band (Johnson-Cousins in AB system) converted from i-band measured in SDSS images using $m_i = m_r - 0.52$ mag. Column 4: ellipticities from i-band (SDSS) images. The quoted errors indicate the RMS scatter in the ellipticity between $3\sigma$ and the $R_{1/2}$. Column 5: Effective radius from i-band (SDSS) images. Column 6: Diskyness/Boxyness parameter from i-band (SDSS) images. The asterisks indicate $C_1$ measured as the maximum in the region $3\sigma$. $R_{1/2}$ if prominent disky features are found; in the rest of the cases the quoted values are the average in this same radial range and the errors the RMS scatter (see Appendix D). Column 7: Disk/No Disk classification by Lisker et al. (2006b) and (L60b) (no values indicate that these galaxies are not included in their analysis).

The comparison between the mean rotation curves of Catinella et al. (2006) and those of our rotationally supported objects must be done in the same luminosity regime since the derived parameters of the Polyex model are luminosity dependent. As the dwarf galaxies analysed in this work have magnitudes below the minimum magnitude in Catinella et al. (2006) ($M_I = −19.4$), the reference Polyex model of low luminosity star forming systems has been determined extrapolating linearly the three faintest values of the Polyex parameters to $M_I = −18.49$, the mean I-band magnitude of the galaxies here analysed. The parameters used to construct this curve are $V_0 = 74.58$ km s$^{-1}$, $r_{PE} = 0.35''$ and $\alpha = 0.03$. For early-type spirals $q_0 = 0.2$ (Giovanelli et al. 1997a). The most recent measurements of the thickness of dwarf galaxies gives $q_0 = 0.3 − 0.35$ (Sanchez-Janssen et al. 2011). The difference in $V_{max}$ after the correction for inclination between using $q_0 = 0.2$ and $q_0 = 0.35$ is of 4.4%, insignificant.

In Figure 11 we compare the mean fitted rotation curves of Catinella et al. (2006) for late-type spirals (obtained from emission lines, black solid curves) with the rotation curves of our rotationally supported dEs determined from absorption lines (grey symbols). Of the 11 rotationally supported dEs, only 7 have been considered for this analysis because 3 of them, VCC21, VCC917 and NGC3073, have poor quality rotation curves (P$\sigma_{\max}$ larger than 25%), and VCC308 has $\epsilon$ lower than 0.1, implying that the galaxy is nearly face on. The blue dots in Figure 11 show the median rotation curve of our dEs in bins of $r_{PE} = 0.1$. The grey area contains the 1$\sigma$ deviation from this median value (68% of the values are inside this area). The blue dashed line is the extrapolated Polyex model for $M_I = −18.49$.

It is evident from Figure 11 that our rotationally supported galaxies are characterised by rotation curves that are similar to those of late-type spiral galaxies of equal luminosity. Or, in other words, galaxies with similar rotation curves have similar absolute magnitudes despite their morphological type. We see that rotationally supported dEs dynamically behave like small late-type spiral galaxies.

It is interesting to see that, despite their similar exponential radial light distribution, dEs have two different kinematic behaviour, they can be either pressure or rotationally supported. Furthermore, rotationally supported dEs have rotation curves similar to those late-type spirals despite the fact that these latter objects are gas dominated systems.
Fig. 11. The observed rotation curves of rotationally supported dEs (grey symbols) are compared to the mean rotation curves of late-type spiral galaxies (black solid and blue dashed lines) from Catinella et al. (2006). Blue filled dots represent the median observed rotation curve of rotationally supported dEs in bins of $r/R_{\text{opt}} = 0.1$. The last bin contains all data for $r/R_{\text{opt}} \geq 0.5$. The grey area indicates rotation velocities within 1σ from the median.

7.2. Tully-Fisher relation

Given the similarity in the kinematic properties of rotation supported dEs with those of late-type spirals we expect that these systems follow the Tully-Fisher relation, as firstly proposed by van Zee et al. (1997a,b) (grey symbols) and de Rijcke et al. (2007) (red dashed area), respectively. Figure 12 clearly shows that these rotationally supported dEs follow the Tully-Fisher relation with a similar scatter as the normal spirals of De Rijcke et al. (2007) (red limited area). Absolute magnitudes of dEs have been obtained using distances from Mei et al. (2007) (Table 6). For Giovanelli et al. data we use $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$ (Mei et al. 2007)). The arrows indicate lower limits of $v_{\text{max}}$ (those obtained in the inner 6"). Fits of the Tully-Fisher relation are indicated in black for the normal spirals of Giovannelli et al. (1997a,b) and in red for de Rijcke et al. (2007, DR07). DR07 fit has been transformed to I band using the colour-morphology relation from Fukugita et al. (1995) and using $H_0 = 73$ km s$^{-1}$ Mpc$^{-1}$ and $M_B = 4.08$ and $M_B = 5.48$ from Binney & Merrifield (1998).

where $M_{\text{press}}$ is the mass inferred from the velocity dispersion after the contribution from rotation has been removed and $M_{\text{rot}}$ is the mass deduced by the intrinsic rotation velocity of the galaxies. $M_{\text{press}}$ inside the half-light radius is defined as in Cappellari et al. (2006):

$$M_{\text{press}} = 2.5G^{-1} \sigma^2 R_{\text{eff}}$$

$$\approx 580 \left( \frac{\sigma^2}{\text{km}^2\text{s}^{-2}} \right) \left( \frac{R_{\text{eff}}}{\text{pc}} \right) M_\odot \tag{4}$$

The rotation curves of rotationally supported systems are characterised by an approximately constant gradient suggesting solid body rotation up to the $R_{\text{eff}}$. In this case $M_{\text{rot}}$ is given by the relation:

$$M_{\text{rot}} = \frac{R_{\text{eff}} v_{\text{max}}^2}{G}$$

$$\approx \left( \frac{R_{\text{eff}}}{\text{pc}} \right) \left( \frac{v_{\text{max}}}{\text{km}^2\text{s}^{-2}} \right) \left( \frac{1}{4.3 \times 10^{-3}} \right) M_\odot \tag{5}$$

Dynamical mass-to-light ratios ($\Upsilon_G$, Table 7) are then measured using the I-band luminosities and equation (4) for pressure-supported systems and the sum of equations (1) and (5) for rotationally supported objects. Stellar mass-to-light ratios ($\Upsilon_G$, Table 7) are computed using the models of single stellar populations

7.3. Dark matter content

The shape of the rotation curves gives information about the dark matter content and distribution of late-type galaxies (e.g., Catinella et al. 2006). Similarly, $\sigma$ can be used to measure the dark matter content of pressure supported systems. Following Beasley et al. (2009) we estimate the total dynamical mass of our sample galaxies using the relation:

$$M_{\text{tot}} = M_{\text{press}} + M_{\text{rot}} \tag{3}$$

No asymmetric drift is applied neither to our dEs nor to those of van Zee et al. (2004b). This correction would increase $v_{\text{max}}$ by $2.5 \pm 0.9$ in those rotationally supported systems plotted in Figure 12.
### Table 7. Dynamical and stellar mass-to-light ratios in I-band in solar units.

| Galaxy      | $\Upsilon_e$ (as calculated by van Zee et al. 2004a) | $\Upsilon_I$ |
|-------------|----------------------------------------------------|--------------|
| PGC1007217  | 4.0 ± 0.8                                          | 1.9          |
| PGC1154903  | 1.8 ± 3.1                                          | 1.2          |
| NGC3073     | 0.6 ± 0.4                                          | 0.2          |
| VCC21       | 1.5 ± 0.4                                          | 0.5          |
| VCC308      | 1.5 ± 0.3                                          | 1.1          |
| VCC397      | 4.8 ± 1.2                                          | 0.9          |
| VCC523      | 2.2 ± 0.2                                          | 1.3          |
| VCC856      | 1.1 ± 0.2                                          | 2.0          |
| VCC917      | 2.5 ± 0.4                                          | 2.4          |
| VCC990      | 1.9 ± 0.1                                          | 2.8          |
| VCC1087     | 2.3 ± 0.1                                          | 2.4          |
| VCC1122     | 2.4 ± 0.1                                          | 2.2          |
| VCC1183     | 1.9 ± 0.1                                          | 1.4          |
| VCC1261     | 2.3 ± 0.1                                          | 1.4          |
| VCC1431     | 2.3 ± 0.1                                          | 3.4          |
| VCC1549     | 2.1 ± 0.2                                          | 3.1          |
| VCC1695     | 1.7 ± 0.3                                          | 1.2          |
| VCC1861     | 1.6 ± 0.1                                          | 2.8          |
| VCC1910     | 1.6 ± 0.1                                          | 3.2          |
| VCC1912     | 2.1 ± 0.1                                          | 1.0          |
| VCC1947     | 1.8 ± 0.1                                          | 1.7          |

NOTES: ($\Upsilon_e$) is only indicative, the large errors in the stellar populations (Michielsen et al. 2008) make the uncertainties of ($\Upsilon_I$) of the same order as the values.

Figure 13 presents the relation between the dynamical mass-to-light ratio and the absolute I-band magnitude for our galaxies (red and blue dots), the sample of classical elliptical galaxies from Cappellari et al. (2006), the dEs from Geha et al. (2002) and the Milky Way dwarf spheroidals (dSphs) from Wolf et al. (2010). Consistently with Zaritsky et al. (2006) and Wolf et al. (2010), we observe that the total mass-to-light ratio within the $R_e$ of dEs is the lower limit of the decreasing and increasing $\Upsilon_I$ vs. luminosity relations observed in giant ellipticals (Cappellari et al. 2006) and dSphs (Wolf et al. 2010), respectively.

Dwarf early-type galaxies have on average $\Upsilon_I = 2.00 \pm 0.04 \ U_{I,0}$, with a slightly higher dispersion in rotating systems ($RMS = 0.06 \ U_{I,0}$) than in pressure supported systems ($RMS = 0.04 \ U_{I,0}$).

8 The $\Upsilon_I$ values of Wolf et al. (2010) have been converted to equation 4 for consistency.

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### 8. Discussion

How does this observational evidence compare with the different scenarios of galaxy formation? In a more general context we recall that in the most recent hierarchical models of galaxy formation only the most massive ellipticals have been formed through major merging events (De Lucia et al. 2008). The strong morphological segregation in high density environments (Sandage et al. 1985; Ferguson & Binggeli 1994; Blanton et al. 2005) indicates that the cluster environment plays a major role in the formation of dEs.

In Toloba et al. (2009) we have shown that rotationally supported dEs, characterised by a disky structure, are preferentially located in the field and in the periphery of the cluster, while pressure supported systems are closer to the center. We also found that rotationally supported dEs have, on average, younger stellar populations than pressure supported systems. This evidence suggests that rotationally supported dEs are low luminosity late-type galaxies which recently entered the cluster and lost their gas because of the interaction with the hostile environment, being transformed, on short time scales, into dEs. It seems thus clear that not all dwarf early-type galaxies are the low luminosity extension of massive ellipticals.

The new kinematic data in our hand support this scenario: rotationally supported systems have rotation curves similar to those of late-type galaxies of similar luminosity and follow the Tully-Fisher relation, the most representative scaling relation for late-type systems. Since the angular momentum of these objects is conserved, the most plausible scenario for gas stripping is the ram pressure exerted by the dense and hot IGM on the fragile late-type systems. Since the angular momentum of these objects is conserved, the most plausible scenario for gas stripping is the ram pressure exerted by the dense and hot IGM on the fragile ISM of the low luminosity star forming galaxies freshly entering the cluster environment (see Boselli et al. 2008, ab for an extensive discussion).

For these rotationally supported objects gravitational interaction with the cluster potential or with other cluster members (galaxy harassment) can be excluded since they would, on relatively short time scales, reduce the angular momentum of the perturbed galaxies, leading to the formation of pressure supported systems. This process, however, could still be invoked to explain the kinematic and structural properties of the remaining pressure supported dEs populating the core of the cluster (half of our sample), whose statistical analysis of their scaling relations...
9. Conclusions

We present medium resolution ($R\sim3800$) spectroscopy for 21 dwarf early-type galaxies, 18 located in the Virgo cluster and 3 in the field. This spectroscopic campaign (Fundamental Plane) will be the subject of a future communication. We have found that rotationally supported dEs have rotation curves similar to those of star forming systems of similar luminosity and follow the same Tully-Fisher relation. Combined with the evidence that these systems are young objects with disk-like structures generally located in the outskirts of the cluster (Toloba et al. 2009), these observations are consistent with a picture where these rotationally supported dEs result from the transformation of star forming systems that recently entered the cluster and lost their gas through their interaction with the environment. The observed conservation of the angular momentum in the rotationally supported dEs suggests that a milder ram pressure stripping event as the responsible of the gas removal has to be preferred to more violent gravitational interactions (harassment) which would rapidly heat up the perturbed systems. Therefore, all these evidences suggest that dEs are not the low luminosity end of massive early-types because if that was the case all dEs would be rotating with $v_{\text{max}}/\sigma$ higher than those of Es, but a population of non-rotators has also been found and, in addition, the evidences of being stripped late-type spirals are strong enough as to consider it as a possible origin of dEs in clusters.

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Fig. A.1. Simulations performed to quantify the bias that can be introduced in the measurement of $v_{\text{max}}$. Plotted are the 100 folded rotation curves computed with random numbers distributed as a Gaussian with width the typical errors of the target galaxies for that radius. Red squares and black dots are the left and right arms of the unfolded rotation curves respectively. The thick black line is the mean $v_{\text{max}}$ for all the simulations. The grey shaded area is the scatter for this mean.

Appendix A: Quantification of the bias introduced in $v_{\text{max}}$

Using the technique described in Section 5.2 to measure the maximal rotation speed, it seems that none of the galaxies have zero rotation (look at the $v_{\text{max}}$ presented in Table 3). However, rotation curves like PGC1154903 or VCC1087 (Figure 6) appear to be statistically consistent with no rotation. The fact that we always find positive maximum velocities is a consequence of the method used to measure it. To quantify the bias introduced by using this technique we have run some simulations. We have taken a zero-rotation object with errors typical of those galaxies that statistically are non-rotators. We have taken a typical rotation curve with 11 bins, at 0, 2″, 4″, 7″, 12″ and 16″, with symmetrical errors of 2, 5, 7, 10, 12 and 15 km s$^{-1}$ respectively. From these errors we have generated 100 simulated rotation curves assigning to each radius a random number with a Gaussian distribution, of which the width is the error associated to that radius. After folding these simulated rotation curves, shown in Figure A.1 we calculated $v_{\text{max}}$ following exactly the same technique as the one we used for the target galaxies. We then obtained a mean value for the 100 values of $v_{\text{max}}$ and its scatter, 9 ± 6 km s$^{-1}$, shown as a thick black line and a grey shaded area in Figure A.1. As a result, we consider that those galaxies with $v_{\text{max}} < 9$ km s$^{-1}$ are not rotating, based on our data. For the other galaxies the rotation is significant (three times above the standard deviation, except for VCC1122 and VCC1261, see Table 3 3rd column), so that the systematic bias described here is much less relevant. For VCC1122 (17.3 ± 7.7 km s$^{-1}$) and VCC1261 (13.9 ± 5.2 km s$^{-1}$) the rotation is marginal, as also shown by their low $v_{\text{max}}/\sigma$.

Appendix B: Absolute I band magnitudes, optical and half-light radii and ellipticity

The I-band images for our sample of 21 dwarf galaxies were drawn from Sloan Digital Sky Survey (SDSS, York et al. (2000)) data release 6 (DR6, Adelman-McCarthy et al. (2008)) and converted to Johnson-Cousins systems following Appendix C. The photometric parameters were calculated using the IRAF task ELLIPSE.

To remove the stars from the images we used the IRAF taskrifpix. This task allows us to remove the stars interpolating the surrounding galaxy area. To improve the final outcome, we averaged the results of interpolating along the horizontal and vertical directions for each star. For those galaxies that were on the edge of the FITS images or had a very bright nearby star, a more careful procedure was implemented. Taking advantage of the fact that the galaxies are ellipticals, so that they have smooth and axisymmetric surface brightness profiles, the $\omega$ task of IRAF can be used to replace the affected areas of the galaxy by the azimuthal average of the unaffected ones. The output from $\omega$ was used only to replace a small fraction of pixels, so this procedure was not affected by the possible presence of more subtle features, such as bars or spiral arms, which could not be reproduced by the model provided by the $\omega$ task. Once extremely bright nearby stars had been removed the same procedure as above was followed with ELLIPSE and rifpix.

The procedure followed to run ELLIPSE is dependent on the parameters we want to measure. First of all we run ELLIPSE fixing only the center of the galaxy assuming a step between isophotes of 1 pixel, the rest of the parameters were left free. We also made the masks for the stars to be removed as described above. With the aim of measuring the absolute magnitude, $R_{\text{opt}}$ and $R_{\text{eff}}$ we run ELLIPSE again fixing, the center of the galaxy, the ellipticity and the position angle (PA) to avoid overlap between consecutive isophotes. The adopted $\epsilon$ and PA in this case are the typical values in the outer parts of the galaxy (beyond 1.5-2$R_{\text{eff}}$, region where these two parameters stabilise). To measure $\epsilon$ and $C_4$ we run again ELLIPSE after removing the stars leaving fixed only the center of the galaxy.

Asymptotic magnitudes and the radii were derived as in Gil de Paz et al. (2007). We first computed the accumulated flux and the gradient in the accumulated flux (i.e., the slope of the growth curve) at each radius, considering as radius the major-axis value provided by ELLIPSE. After choosing an appropriate radial range, we performed a linear fit to the accumulated flux as a function of the slope of the growth curve. The asymptotic magnitude of the galaxy was the Y-intercept, or, equivalently, the extrapolation of the growth curve to infinity. Once the asymptotic magnitude was known, the optical and effective radii of each galaxy were obtained as the major-axis of an elliptical isophote containing 83% and 50% of the total flux respectively. For the asymptotic magnitudes different sources of error have been considered (see Appendix C). The resulting uncertainty is ~0.02 mag.

The ellipticities ($\epsilon$) were measured as the mean value between 3° and the $R_{\text{eff}}$, the galaxy region covered by our spectroscopic observations.

Appendix C: Errors in magnitudes

The zero points (ZP) and the errors in the $i$-band magnitudes have been computed as described in SDSS documentation. The ZP have been obtained from $F_0$, the flux a source produces in
counts per second in the image, calculated as a function of three parameters (\(aa, kk\) and \(airmass\)) defined as:

\[
F_0 = \frac{t_{exp}}{10^{(aa+kk+airmass)}} 
\]

where the exposure time \(t_{exp}\) is the same for all the SDSS images (53.91 seconds). The uncertainties in the \(i\)-band magnitudes are affected by different sources of error: firstly, the errors in the flux, that can be calculated following the equation:

\[
\Delta F = \sqrt{ \frac{F + sky\ gain}{gain} + N_{pix}(dark\ variance + \Delta sky) } 
\]

where \(F\) is the total flux in counts, the \(sky\) and \(\Delta sky\) are the background sky and its error (in counts), the \(gain\) and the \(dark\ variance\) are given in the header and \(N_{pix}\) is the number of pixels in the largest aperture where the flux is measured. This error was typically \(10^{-3}\) mag. Other error sources are the error introduced in the fit to the growth curve (between \(10^{-3}\)mag and \(6 \times 10^{-3}\)mag), and the error due to photometric zero point differences between the different scans of SDSS, which might lead to an error of 0.01 mag. SDSS \(i\)-band magnitudes are not exactly in the AB system, so an error of 0.01 mag might also be introduced (see SDSS documentation about the photometric flux calibration). And finally, we have transformed our data from the SDSS \(i\)-band to the Johnson-Cousins \(I\)-band assuming \(m_i = m_R - 0.52 \pm 0.01\) mag given that their \(r - i\) colour ranges from 0.23 mag to 0.57 mag.

Adding quadratically all these sources of error, the final estimated error is 0.02 mag for the apparent \(I\)-band magnitudes.

**Appendix D: The \(C_4\) Boxyness/Diskyness parameter**

The boxyness/diskyness parameter is defined as the fourth moment in the Fourier series as follows:

\[
I(\Phi) = I_0 + \sum_k [S_k sin(k\Phi) + C_k cos(k\Phi)] 
\]

\(I(\Phi)\) is the intensity measured in each isophote. The first two moments in this series describe completely an ellipse. Higher order moments \((k \geq 3)\) define deviations of the isophotes from ellipses. The third order moments \((S_3\) and \(C_3)\) represent isophotes with three fold deviations from ellipses (e.g. egg-shaped or heart-shaped), while the fourth order moments \((S_4\) and \(C_4)\) represent four fold deviations. Rhomboidal or diamond shaped isophotes have nonzero \(S_4\). For galaxies that are not distorted by interactions, \(C_4\) is the most meaningful moment indicating the disky/boxy shapes of the isophotes (see Figure 1 from Peletier et al. (1990) for an example of these different shapes).

\(C_4\) is measured in \(i\)-band SDSS images using \texttt{ellipse} that performs equation \texttt{[D.1]} along the radius of the galaxy fixing only the center of the galaxy and leaving the rest of \texttt{ellipse} parameters free, as described in Section \texttt{[C]} Figure \texttt{[D.1]} shows \(C_4\) as a function of radius for 3 dEs. Due to the large changes of \(C_4\) with radii taking an averaged value is therefore not the best way to detect disks in these galaxies, especially if they cover only a limited range in radius. We have thus adopted the following procedure:

If at least one prominent bump is detected, which has a width larger than \(\sim 6\)" inside three effective radii (above this radius the scatter of \(C_4\) and its error becomes too large to be reliable), we consider the galaxy to be disky, and assign the maximum \(C_4\) between \(3\"\) and \(3R_{eff}\) to the global \(C_4\). The error in this measurement has been estimated by dividing the photometric error of the maximum of \(C_4\) by the square root of the number of points that describe the disky structure in order to quantify the reliability of the bump considered. If the bump is described by a large number of points it is highly likely that the bump is truly there and as a consequence the error will be small, but if the number of points is small but the photometry is of high quality then the error will be small again. In any other case the error will be large and the result must be used cautiously.

Otherwise, if the values oscillate around \(C_4 \sim 0\) (lower panel of Figure \texttt{[D.1]}), are always negative or if there is a bump with a small radial coverage (see middle panel Figure \texttt{[D.1]}), we assign a mean value and its scatter between \(3\"\) and \(3R_{eff}\) to the global \(C_4\). In this case, the RMS quantifies simultaneously the quality.
of the photometry and the possible presence of small bumps (as it is the case of VCC308, middle panel of Figure D.1).

The results obtained for this parameter are listed in Table 6 and plotted vs. the anisotropic parameter, \((v_{\text{max}}/\sigma)^*\), in Figure 10. The agreement between the \(C_4\) classification in disky/boxy galaxies and the morphological classification from Lisker et al. (2006b) is evident but apart from three red dots. These filled circles correspond to VCC917, a rotationally supported galaxy (above the horizontal dashed line) with strong disky isophotes but no structure found by Lisker et al. (2006a); VCC1122, a not rotationally supported dE but with an appreciable rotation in Figure 6 and very important disky structures in the inner \(R_{\text{eff}}\) not detected by Lisker et al. (2006a); and VCC1912, inside half the effective radius a moderate rotation is found in this system with a clear disky feature that peaks at 1.5\(R_{\text{eff}}\). For this galaxy however, no underlying structure was found by Lisker et al. (2006a).

More importantly VCC308 and VCC856, two rotationally supported galaxies with boxy \(C_4\), present prominent spiral arms in Lisker et al. (2006a). In Ferrarese et al. (2006b), based on ACS-HST images, VCC856 also shows spiral arms but their analysis of the isophotes’ shapes shows that they are boxy too. Looking at Table 6 we see that both galaxies are nearly face-on, which means that the isophotes are boxy since face-on disks are round and not disky. As a consequence we emphasise the fact that boxy isophotes could miss disk features (mainly if the galaxies are face-on), but not the other way round (see VCC917).
Fig. 6. Continued
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Fig. 7. Comparison of our kinematic profiles with other works. In each diagram it is shown the rotation curve (upper panel) and the velocity dispersion profile (lower panel). The bottom X-axis is measured in arcseconds and the upper X-axis is measured as a fraction of the effective radius ($R_{\text{eff}}$) of each galaxy in i band (see Section 6). For Van Zee et al. (2004) we only present their velocity profiles for Mg b I, more similar in wavelength to our data.
Fig. 7. Continued