Early-type dwarf galaxies in clusters: a mixed bag with various origins?

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The formation of early-type dwarf (dE) galaxies, the most numerous objects in clusters, is believed to be closely connected to the physical processes that drive galaxy cluster evolution, like galaxy harassment and ram-pressure stripping. However, the actual significance of each mechanism for building the observed cluster dE population is yet unknown. Several distinct dE subclasses were identified, which show significant differences in their shape, stellar content, and distribution within the cluster. Does this diversity imply that dEs originate from various formation channels? Does “cosmological” formation play a role as well? I try to touch on these questions in this brief overview of dEs in galaxy clusters.

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1 Introduction

Early-type dwarf (dE) galaxies play a key role in understanding galaxy cluster evolution. Their low mass and low density make them more susceptible to physical effects than giant galaxies, and they are a large population, outnumbering all other galaxy types in dense environments by far. They are thus ideal probes of the mechanisms that govern galaxy formation and evolution in a cluster environment. Nevertheless, dEs are also interesting in their own right. Despite their rather unspectacular appearance, a surprising complexity in their characteristics has become evident, in terms of kinematics (rotating vs. pressure supported), structure (flat vs. round), and spatial distribution (cluster center vs. outskirts). This zoo of dEs and their possible origin(s) is an ongoing challenge for observers and theorists.

2 Morphology and classification

2.1 What is an early-type dwarf?

Morphological classification of early-type galaxies can be subjective to a certain extent, and the division between dwarf and normal/giant galaxies is often rather arbitrary. It thus appears reasonable to consider these two terms separately.

Early-type: Elliptical (E) and lenticular (S0) galaxies are commonly subsumed under the term early-type galaxies. Their main characteristic is the absence of substructure like spiral arms or strong asymmetries: their overall appearance is smooth and regular (Fig. 1). A complication is added by the fact that weak spiral structure has been identified in a number of early-type dwarfs by image processing techniques. In some cases, the spiral features extend across the whole galaxy (Fig. 2). Should such an object be re-classified as spiral galaxy, once the spiral arms are discovered? What if the spiral arms are strong enough in one galaxy to be seen

Fig. 1 Two Virgo cluster dEs (VCC 856 & 839) in a deep exposure with ESO 2.2m/WFI. The image shows an area of 6′ × 5′.

Fig. 2 The galaxy VCC 0308, classified as dwarf S0 by Binggeli et al. (1985), in a deep exposure with ESO 2.2m/WFI (left). A residual image of the weak spiral arm structure was created by subtracting a model of the smooth light distribution. This residual image was then multiplied by a factor of 2 and 3, and added again to the smooth model, yielding the middle and right images.
in the initial image, but not in another galaxy, for which special techniques are necessary? B. Binggeli identified a handful of “dwarfish looking S0/ Sa” galaxies in the Virgo cluster (unpublished, see Lisker et al., 2006a), whose appearance is similar to the illustration in Fig. 2. Here, classification (and the subsequent selection of a working sample!) becomes arbitrary to some extent, and it would be more important to locate those galaxies in their physical parameter space.

Dwarf: While the term dwarf would imply that an object is small and faint, Figure 1 illustrates that a brighter dwarf might appear as an object of rather high surface brightness when compared to fainter, “low surface brightness” dwarfs (cf. Adami et al., 2006; Sabatini et al., 2003), since size and surface brightness are correlated with total magnitude (Binggeli & Cameron, 1991). Dwarf elliptical is a widely used term, indicating that the overall appearance is similar to that of an E galaxy, yet reduced to dwarf scale. However, another class of elliptical galaxies also has dwarf sizes and magnitudes, but a surface brightness similar to the giants: the compact ellipticals or low-luminosity ellipticals (de Vaucouleurs, 1961), with M32 typically considered as prototype (but see Graham, 2002).

Some authors (Kormendy et al., 2009; Moore et al., 1998) instead refer to early-type dwarfs as spheroidals (Sph). This avoids implying a priori a physical relation between Es and early-type dwarfs, since the latter could also be more closely related to late-type galaxies. However, spheroidal is a three-dimensional description, which can be somewhat impractical for astronomical classification, since we only see the projected twodimensional appearance. Many “spheroidals” are (now) known to be of relatively flat, disk-like shape (Lisker et al., 2007). In contrast, the term elliptical applies, to first approximation, even to the disky early-type dwarfs, since they still have a nearly elliptical projected shape.

Using surface brightness as the main criterion to separate dEs from Es (Sandage & Binggeli, 1984), and thereby creating a significant overlap of their total magnitudes (Jerjen & Tammann, 1997), might indeed be a more “physical” way to go: early-type galaxies seem to arrange themselves in two main sequences (Fig. 3). One sequence follows the more diffuse objects, from dEs to the fainter dwarf spheroidals (dSphs), the other sequence contains the more compact or centrally concentrated objects, ranging from massive Es to spiral bulges (Graham & Worley, 2008) and compact ellipticals (Kormendy et al., 2009), probably continuing to ultra-compact dwarf galaxies and the brightest globular clusters (Dabringhausen et al., 2008). Given these relations, it might be the clearest (although not the most common) expression to call the dEs diffuse ellipticals (Prugniel & Simien, 1996), or more general diffuse early-type galaxies.

2.2 Structural characteristics

Early-type dwarfs have surface brightness (SB) profiles less steep than massive ellipticals – yet the frequently quoted “exponential vs. de Vaucouleurs” scenario is too simplistic. In fact, SB profiles of both dwarf and giant early types can be well described by continuous Sérsic profiles (Sérsic, 1963), with the logarithm of the Sérsic index $n$ linearly increasing with central surface brightness and magnitude (Gavazzi et al., 2005; Graham & Guzmán, 2003; Young & Currie, 1994). This is illustrated for Virgo dEs in Fig. 4 where an exponential profile would be a straight line, which clearly does not fit the brighter dEs.

While a clear correlation exists between (effective or central) surface brightness and magnitude (Binggeli & Cameron, 1991), albeit with significant scatter (Binggeli & Jerjen, 1998), the size-magnitude correlation is somewhat less well defined (also see Janz & Lisker, this issue), and the half-light radius decreases only slightly towards fainter galaxies (Misgeld et al., 2009), with typical values around 1 kpc (Smith Castelli et al., 2008). Whether dEs and Es form a continuous family in all basic scaling relations is still debated (compare, e.g.,
Graham & Guzmán (2003) and Kormendy et al. (2009). While the correlation between Sérsic index \( n \) and magnitude is not put into question, Janz & Lisker (2008) showed that, at those magnitudes where dEs and Es approach each other and eventually overlap, most dEs are larger and most Es are smaller than the expected one-family relation for varying \( n \) (also compare Misgeld et al. 2009). However, no significant systematic departure from this relation was found by Graham & Worley (2008). Kormendy et al. (2009) interpret the different behaviour of Es and dEs with fundamentally different formation mechanisms.

Analogous to the bright S0s, Sandage & Binggeli (1984) introduced the class of dwarf S0 (dS0), defined by having the overall appearance of a dE, but exhibiting features that probably indicate the presence of a disk. These criteria were, a bulge-disk-like structure, high flattening, a lens-like surface brightness distribution, a global asymmetry like boxiness or a bar, or a central irregularity (Binggeli & Cameron, 1991). Later, weak spiral structure was identified in a dE for the first time (Jerjen et al., 2000), with similar discoveries following (e.g. Barazza et al., 2002; Graham et al., 2003). A systematic search for weak disk signatures was carried out by Lisker et al. (2006a) for Virgo cluster dEs, revealing such features (Fig. 2) in one quarter of the brighter dEs (Fig. 5), with the “disky fraction” even reaching 50% at the bright end. While these identifications do have a large overlap with the dS0 classification in the Virgo cluster catalogue (VCC, Binggeli et al., 1985), a significant number of dS0s remained where no disk features were found. These were mainly those with blue central colours from young stars (Lisker et al., 2006b), where central irregularities and dust structures are seen. Therefore, Lisker et al. (2007) suggested a new subclassification, starting with \( dE \) (for dwarf or diffuse early-type galaxy) and adding in brackets (\( d \)) for disk, (\( bc \)) for blue center, (\( N \)) for nucleated (which had been \( dE,N \) in the VCC), and (\( nN \)) for non-nucleated. The latter was to avoid the ambiguity that \( dE \) could either refer to dEs in general, or explicitly to non-nucleated dEs. Nevertheless, Lisker et al. (2007) were somewhat inconsequent, in that they did not use this subclassification in a cumulative way, e.g. \( dE(N,di) \) for a nucleated dE with disk substructure, or \( dE(nN,di,bc) \) for a non-nucleated dE with disk substructure and blue central colors. Furthermore, having a blue center is of course no morphological feature.

A different approach to identify dS0 galaxies, based on the two-component criterion of Binggeli & Cameron (1991), was applied to Coma cluster dEs by Aguerri et al. (2005): those objects whose SB profile was not well fitted by a single Sérsic profile, but required a Sérsic-exponential fit, were classified as dS0s. Like Binggeli & Popescu (1995) for the Virgo cluster, Aguerri et al. (2005) found the dS0s to be flatter than the ordinary dEs. Furthermore, Ferguson & Sandage (1989) and Ryden & Terndrup (1994) showed that the non-nucleated dEs are flatter than the nucleated ones. From the distributions of projected axial ratios, Lisker et al. (2007) estimated intrinsic axial ratio distributions for the different subclasses, which are illustrated in Fig. 5 indeed, \( dE(nN) \)s are flatter than \( dE(N) \)s (the difference disappears towards fainter magnitudes), \( dE(bc) \)s have similarly flat shapes as the \( dE(nN) \)s, and \( dE(di) \)s are the flattest population.

The classification of a dE as nucleated and non-nucleated is not unambiguous. Many Virgo dEs that were classified as non-nucleated in the VCC actually host a faint nucleus that was hardly detectable with the VCC data (Côtes et al. 2006; Grant et al. 2005). A more appropriate term might be \( dE \) without a nucleus of significant relative brightness as compared to the central galaxy light. Grant et al. (2005) pointed out that dEs classified as nucleated and non-nucleated might actually form a continuum with respect to relative nucleus brightness. This makes the identification of systematic differences between them even more interesting. For the sake of simplicity, I continue to use non-nucleated for those without a “significant” nucleus. Due to the limited space, I do not further discuss the central structural properties of dEs (e.g. Côtes et al. 2007), their nuclei (e.g. Lotz et al. 2004), and their globular cluster systems (e.g. Peng et al. 2006, 2008).

3 Colours and stellar populations

3.1 Age and metallicity

Studies of Lick absorption line indices in galaxy spectra revealed intermediate to old ages (~5 Gyr, with rather large scatter), subsolar metallicities (~1 ≤ [Fe/H] ≤ 0), and more or less solar α-element abundances (e.g. Chilingarian, 2009; Geha et al., 2003; Koleva et al., 2009; Michielsen et al., 2008; Paudel et al., 2009; Van Zee et al., 2004b). From narrowband photometry, Rakos & Schombert (2004) inferred an age bimodality: they found that nucleated dEs are several Gyr older than non-nucleated dEs, and have old ages comparable to globular clusters.

Stellar population gradients were studied for the brighter dEs by Chilingarian (2009) and Koleva et al. (2009), who found a range of metallicity gradients between steeply radially decreasing and constant metallicity, but no positive gradients. The stellar population age remains constant or
shows a slight increase with radius. These findings would seem consistent with the simple picture that all dEs had their last star formation activity in their centers, as seen in those dEs with blue cores: if gas could be retained in the central region, while being stripped much earlier in the outskirts, the metal enrichment would be higher in the center, and the average age would be younger due to the longer duration of star formation there. Note also that the nuclei or nuclear regions were found to have younger ages than their host galaxies (Paudel & Lisker, this issue; Chilingarian, 2009).

While detailed studies of resolved stellar populations of cluster dEs are hardly possible at distances of Virgo and beyond, the first steps were already done: Caldwell (2006) and Durrell et al. (2007) presented analyses of resolved red giant branch populations for dEs and a dSph in the Virgo cluster.

### 3.2 Relations with luminosity

A fundamental characteristic of early-type galaxies is the well-defined relation between colour and magnitude, with more luminous objects having redder colours (e.g. Caldwell, 1983; Sandage & Visvanathan, 1978). While this trend includes the dEs, there has been disagreement about whether or not they follow the same CMR as the giant ellipticals, and whether this CMR is linear. Although Caldwell (1983) reported a linear CMR over a range of $-15 \leq M_V \leq -23$ mag, his Figure 3 actually seems to indicate that the CMR might slightly bend towards the dEs, such that with decreasing magnitude, dwarfs become bluer more rapidly than giants do. This is similar to the non-linear CMR of Virgo cluster dwarf and giant early types that was reported by Ferrarese et al. (2006), who found that a parabolic curve provided a good fit to the data. However, Andreon et al. (2006) remarked that, when taking into account an intrinsic scatter in the statistical analysis, the data of Ferrarese et al. do not support this parabolic model, and are consistent with a linear relation. Andreon et al. (2006) themselves report a linear CMR in the cluster Abell 1185.

Interestingly, the conclusion of de Vaucouleurs (1961), that the dwarfs are “systematically bluer” than the giants, was confirmed by Janz & Lisker (2009), who used SDSS ugri photometry for several hundred Virgo cluster early-type galaxies, and found a CMR with an S-like shape (see Janz & Lisker, this issue). This is caused by an apparent transition region at intermediate magnitudes, where the CMR slope is different than brightward and faintward of it. While the CMRs presented by Misgeld et al. (2008) for the Hydra I and Centaurus clusters appear still consistent with the Virgo results, they are well fitted with a linear CMR. A linear relation from dwarf to giant early types was also found in the Antlia cluster by Smith Castelli et al. (2008).

Two results are common to all of those studies: i) there is no gap between dwarfs and giants, and ii) the CMR is still well defined even at faint ($M_B \approx -14$ mag) magnitudes, pointed out by Lisker et al. (2008) and Smith Castelli et al. (2008). The CMR of dEs in the Perseus cluster presented by Conselice et al. (2003) showed a considerable increase in scatter at magnitudes $M_B \geq -15$ mag, apparently caused by a colour bimodality of faint dwarfs. However, this result was partly revised by Penny & Conselice (2008), who showed with new spectroscopic measurements that most of the redder objects are not members of the cluster. Still, a significant increase in the scatter remains, caused by objects bluer than the CMR extrapolation.

A further investigation of the CMR is possible by dividing the dEs into different subsamples. Lisker et al. (2008) found that Virgo dEs sitting in projected cluster regions of different local galaxy density exhibit a slightly different CMR slope: those in higher-density regions are redder at brighter magnitudes as compared to dEs in lower-density regions, while their colours are similar at fainter magnitudes. The same is true when comparing nucleated with non-nucleated dEs: the nucleated ones are redder at brighter magnitudes (Lisker et al. 2008), consistent with the conclusion that they have older ages (Rakos & Schombert, 2004).

Faber (1973) showed that the strength of absorption features in the spectra of galaxies is related to their luminosity. This can be seen as the spectroscopic analogue to the CMR. Faber interpreted the CMR as a trend of increasing metallicity with luminosity, which today is still considered to be the primary determinant of the CMR. Andreon et al. (2006) pointed out by Lisker et al. 2008 and Smith Castelli et al. (2008) that Virgo dEs sitting in projected cluster regions of different local galaxy density exhibit a slightly different CMR slope: those in higher-density regions are redder at brighter magnitudes as compared to dEs in lower-density regions, while their colours are similar at fainter magnitudes. The same is true when comparing nucleated with non-nucleated dEs: the nucleated ones are redder at brighter magnitudes (Lisker et al., 2008), consistent with the conclusion that they have older ages (Rakos & Schombert, 2004).

Nevertheless, there is also evidence that the average stellar population age decreases with decreasing luminosity from early-type giants to dwarfs. In a multiwavelength spectrophotometric study, extending from the ultraviolet (UV) to the near-infrared (NIR), Gavazzi et al. (2002) found that the timescale for the duration of star formation increases with decreasing galaxy luminosity, when fitting galaxy SEDs to population synthesis models with fixed formation epoch. Similarly, the $H\beta$ absorption index, which serves as indicator for recent star formation and stellar age, was found to increase with decreasing luminosity (Poggianti et al., 2001) and velocity dispersion (Geha et al., 2003) from giants to dwarfs. Thus the CMR could, at least partly, also be governed by the stellar population age. Note, however, that the above-mentioned correlations were mainly defined by comparing giant early types and brighter dwarfs. While indeed the former have higher stellar population ages than the latter (Michielsen et al., 2008), it is not yet clear whether and how age and luminosity are correlated within the dwarf regime. A large range of dE ages was found by Michielsen et al.
and there are even indications for an anticorrelation of age and luminosity (Paudel et al. 2009).

The UV photometry of GALEX (Martin et al. 2005) recently brought new insight into these issues. Boselli et al. (2005) presented the near-UV (NUV) and far-UV (FUV) colours of Virgo early-type galaxies. The CMR is again continuous from dwarfs to giants in UV − optical and UV − NIR colours. However, while its shape appears rather linear in NUV − V and NUV − H, except for the region of constant colour at the highest luminosities (cf. Janz & Lisker 2009), a clear bend is present when NUV is replaced by FUV, or even stronger when FUV − NUV is considered. In the latter case, while dwarfs become bluer with decreasing luminosity, giants do so with increasing luminosity, probably explained by the UV-upturn phenomenon (Gil de Paz et al. 2007). There might even be a break between the dwarf and giant parts of the CMR, but a definite conclusion is hampered by sparse sampling at intermediate luminosities. Since this wavelength region is governed not only by the intermediate-age stars responsible for the UV-upturn, but of course also by very young stars, the interpretation of Boselli et al. (2005) was that residual star formation activity is present in the dEs. However, based on the above-mentioned idea of continuously decreasing stellar age with decreasing galaxy luminosity, Lisker & Hart (2003) remarked that the observed colour behaviour would be consistent with the expectations from population synthesis models if a continuous increase in the duration of star formation from giants to dwarfs was assumed. The real situation might be more complex: as shown by Kim et al. (this issue), significant differences become apparent when analysing the UV − optical colours separately for dEs with and without disks, with the former being systematically bluer, and for dEs in the center and outskirts of the cluster, with the latter clearly having bluer colours.

4 Kinematics

After it has become clear that at least some early-type dwarfs do show significant rotation (Bender & Nieto 1990), the questions were (and still are), how many of them rotate, and how strong is the rotation? This was addressed by several studies through medium-resolution spectroscopy in one or two dimensions (Chilingarian 2009; De Rijcke et al. 2005; Geha et al. 2002; Pedraz et al. 2002; Simien & Prugniel 2003; van Zee et al. 2004a), finding significant rotation in some, but not all dEs. In many cases, the rotation curve is still rising at the end of the radial extent of the data.

The Faber-Jackson relation (Faber & Jackson 1976) of galaxy luminosity and velocity dispersion clearly flattens when going from luminous Es to dEs (De Rijcke et al. 2005; Matković & Guzmán 2005). The Tully-Fisher relation (Tully & Fisher 1977) of spiral and irregular galaxies was shown by van Zee et al. (2004a) to be followed by dEs with significant rotation. Note, however, that if these systems were pure disks, their relatively high velocity dispersions would cause a large asymmetric drift effect on the measured velocity (De Rijcke et al. 2007; Lisker & Fuchs 2009). Dynamical models are thus used by De Rijcke et al. (2007) to infer the circular velocities, finding that dEs fall slightly below the baryonic Tully-Fisher relation followed by early-type and late-type galaxies. Furthermore, at least for a single Virgo dE with weak spiral structure (VCC 856) (Lisker & Fuchs 2009) concluded that the galaxy most likely has a significantly dynamical hot component, in which a disk with much lower velocity dispersion is embedded, thus having only a small asymmetric drift effect.

Common practice is to compare the measurements of rotational velocity v and velocity dispersion σ with the theoretical curve for an isotropic oblate spheroid flattened by rotation and viewed edge-on (Binney 1978), as exemplified in Simien & Prugniel (2002). This curve can be approximated analytically, following Kormendy (1982), so that the ratio v/σ can be normalized with respect to the curve:

\[
\frac{v}{\sigma} = \frac{v/\sigma}{\sqrt{\epsilon/(1-\epsilon)}},
\]

with \(\epsilon\) being the measured (projected) ellipticity. \(\langle v/\sigma \rangle^*\) is frequently called the anisotropy parameter, since in case of \(\langle v/\sigma \rangle^* \ll 1\) and a non-spherical shape of the galaxy, it indicates that the flattened shape must be caused by anisotropic velocity dispersion.

The terms used to interpret the values of \(\langle v/\sigma \rangle^*\), like rotationally supported or pressure-supported, are not always applied in the same way or with the same criteria. In particular, it is not always clear whether rotational support is meant as support against gravity, or just as support of the galaxy’s shape, i.e. being rotationally flattened. For example, a close-to-spherical galaxy with just a small ellipticity needs only a little amount of rotation to make it above the theoretical line. Clearly, this galaxy would not be rotationally supported against gravity, but would still be pressure supported, albeit with some rotational flattening. On the other hand, we know for those galaxies where weak spiral arms or bars were identified, that they are not seen edge-on, and that they are relatively flat intrinsically — it is thus not straightforward to speak of pressure or rotational support just on the basis of \(\langle v/\sigma \rangle^*\).

The current inventory of rotation curves for dEs is, unfortunately, not very impressive — owing to the fact that these faint galaxies require much longer exposure times than their giant counterparts. For the Virgo cluster, I collected published tabulated values of v and σ (mostly \(\sigma_0\)) from the studies named above, judged the radial extent of the rotation curve visually from the published rotation curve figures (using the second to last data point), compared it to the half-light semimajor axis (\(a_{hl}\)) in SDSS-R from Lisker et al. (2007), and excluded those not reaching 1/3\(a_{hl}\). For galaxies appearing in more than one publication, I took those values that correspond to the largest radial extent, even if the quoted errors were larger in this reference as compared to others. This results in only 27 dEs with useful values, 11 of them (41%) having \(\langle v/\sigma \rangle^* \gtrsim 1\), i.e. being flattened...
by rotation. As discussed above, a value for being rotationally supported might be rather arbitrary; when choosing \((v/\sigma)^* \gtrsim 1.3\), 5 objects (19%) remain. Interestingly, the correlation with those dEs with identified disk features (Lisker et al. 2006a) is not (yet) significant: of the 12 dEs with disks among the 27 galaxies (44%), only 6 (55%) belong to the group with \((v/\sigma)^* \gtrsim 1\).

Of those 27 galaxies, only 16 reach beyond 0.8\(a_{\text{hl}}\) in their rotation curve extent, and only 11 actually reach the point of half light. Compared with the number of Virgo dEs in the same magnitude range \((M_r < -16.3\), using \(m - M = 31\)), 101 galaxies, this is a rather small fraction of only 11%. Nevertheless, it is sufficient for taking a look at possible relations with environmental density and galaxy magnitude. Penny et al. conclude that only the fainter dEs require dark matter to remain stable within the cluster potential.

5 Environmental relations

Among dwarf galaxies, the fraction of those with early-type morphology is significantly larger in dynamically more evolved environments (Trentham & Tully, 2002). Apart from this global trend, early-type dwarfs also show a pronounced relation with local galaxy density within a given cluster or group: Binggeli et al. (1987) found that their number strongly increases with local density, analogous to the correlation for giants (Dressler, 1980), and Tully & Trentham (2008) observed in (rich) galaxy groups that early-type dwarfs strongly cluster around major E/S0 galaxies.

In addition, there is also a morphology-density relation within the dE class. As illustrated in Fig. 7, dEs with a blue center and no nucleus, which have relatively flat shapes (Fig. 5), are preferentially found in the low-density cluster regions. Those with disks, which are the flattest subpopulation, are located more towards intermediate-density regions, and nucleated dEs (without disks or blue centers), which are the roundest dEs, dominate the high-density regions. The different clustering properties of nucleated and non-nucleated dEs (e.g. Ferguson & Sandage, 1989; van den Bergh, 1986) were challenged by Côté et al. (2004), who conjectured that this might only be due to a selection bias, but Lisker et al. (2007) showed that no bias is present.

The stellar population properties also correlate with location in the cluster. Smith et al. (2008) reported significantly younger ages of dEs in the Coma cluster outskirts,
and also higher metallicities. Similar correlations are seen in Virgo, yet they appear not as strong if dEs with disks are excluded (Paudel et al., 2009). These findings agree with the UV/optical photometric study of Virgo dEs by Kim et al. (this issue), who find blue UV – optical colours for dEs in the outskirts as compared to the center, and a different, bluer CMR for dEs with disks than for those without disks. This gives a consistent picture with the results of Toloba et al. (2009), that rotationally flattened dEs are preferentially found in the cluster outskirts, and are also younger than the non-rotating ones.

It is important to note that the scaling relations and the CMR of dEs were found to be very similar in environments of different density, from groups to clusters (De Rijcke et al., 2009). In this respect, it is also noteworthy that Tully & Trentham (2008) found a high fraction of dEs with blue central star-forming regions in an intermediate-mass group – as compared to the rather small fraction in the Virgo cluster – and Gu et al. (2006) even presented an isolated dE with such a blue core (also see Peeples et al., 2008).

6 Formation scenarios

It has become popular belief that dEs were formed at relatively late epochs by environmental effects that structurally transformed spiral and irregular galaxies (e.g. Moore et al., 1998). At the same time, however, dEs are predicted to form in models of a ΛCDM universe, as the descendants of building blocks in hierarchical structure formation (e.g. Moore et al., 1999). Before discussing these scenarios in more detail, it might be useful to summarize what a dE formation mechanism, or a combined effect of several mechanisms, needs to produce: a galaxy with (i) smoothly distributed starlight (Fig. 1), (ii) a SB profile whose slope is determined by the galaxy luminosity and is not necessarily exponential (Fig. 2), (iii) a nearly ellipsoidal shape, although allowing a rather large range of axial ratios (Fig. 5), (iv) little or no remaining gas (di Serego Alighieri et al., 2007), (v) a relatively old stellar population with at most only a small contribution of young stars (in terms of mass, Lisker et al., 2006b), nevertheless allowing a large range in ages (Paudel et al., 2009). This list could of course be continued with metallicity, kinematics, or further characteristics.

The simplest route to dEs would be if no modification of the shape were necessary. This would merely require to remove the gas from the galaxy (stripping, e.g. through the ram-pressure of the hot intracluster medium, Gunn & Gott, 1972, as well as the cold gas reservoir around the galaxy (starvation, Larson et al., 1980). Both are typical processes of a cluster environment and are not restricted to the central region (Tonnesen et al., 2007). At least for the non-nucleated dEs (dE(nN)s), star-forming galaxies with similar shapes are the (dwarf) irregulars (Irrs; Binggeli & Popescu, 1995). The median observed axial ratios of bright and faint Virgo dE(nN)s (Lisker et al., 2007) are 0.51 and 0.71, respectively, calculated from VCC values. When subdividing the Irrs at their median B magnitude, their corresponding median axial ratios are 0.54 and 0.63. With a more extreme definition of bright and faint, by excluding ±0.5 mag around the median magnitude, the values are 0.54 and 0.68. These values, and the presence of a correlation with galaxy luminosity, are very similar between Irrs and dE(nN)s, and might seem to imply that dE(nN)s could indeed be stripped Irrs.

However, the direct evolution from Irrs to dEs faces some problems: the Irrs have a too low metallicity (Thuan, 1985) and would end up with a too low surface brightness after cessation of star formation (Boselli et al., 2008, Bothun et al., 1986). These problems can be overcome by a scenario in which the initially lower metallicity and surface brightness of an Irr are increased by several bursts of star formation (Davies & Phillipps, 1988), during which the galaxy appears as blue compact dwarf (BCD). After the last BCD phase it fades to become a dE (cf. Dellenbusch et al., 2008). It can be regarded as support for this scenario that Vaduvescu et al. (2006) and Vaduvescu & McCall (2008) found dEs and BCDs to fall on the “fundamental plane of dwarf irregulars”, a relatively tight relation between near-infrared absolute K magnitude, central surface brightness, and H I line width, substituted by stellar velocity dispersion for the dEs. The required bursts of star formation could be triggered by tidal interactions (Lavery & Henry, 1988, Moss et al., 1998), leading to a rapid conversion of gas into stars.

This indirect way of making a dE out of an Irr, by enhanced consumption of gas, might seem more appealing than simple gas removal (Sabatini et al., 2005); if those evolutionary paths leading to today’s Irrs would have been altered by ram-pressure stripping events that removed the gas at some time in the past, the resulting dEs would be even fainter (in total magnitude and surface brightness) than today’s Irrs (Boselli et al., 2008). Stripped Irrs – or more precisely: stripped galaxies that would otherwise have become today’s Irrs – could thus be the progenitors of fainter dEs or dSphs, but not of the brighter ones. If the latter were to be explained by ram-pressure stripping, the corresponding progenitors need to be spiral (Sc/Sd) galaxies (Boselli et al., 2008). However, these galaxies, or at least their disks, are much flatter than even the dEs with disks, so pure stripping seems not sufficient. A plausible solution could be that tidal interactions lead to significant disk thickening (Gnedin, 2003). If they even lead to the disruption of the disk, the bulge – if present – would remain, and its properties might fall in the parameter space of dEs (Ferruson & Binggeli, 1994, Graham & Worley, 2008, Whitmore et al., 1993).

A similarly violent scenario is possible also with a bulgeless disk entering a cluster: repeated close encounters with massive galaxies can lead to substantial mass loss and a complete structural transformation, resulting in a dE (Moore et al., 1996). The simulations of Mastroietti et al. (2005) showed that only those galaxies that end up on orbits within the central cluster region experience such a strong transformation. Those with more eccentric and/or outer orbits retain more
of their original disk structure, as well as a larger \( v/\sigma \). A further investigation of such fast galaxy–galaxy interactions was performed by [Aguerri & González-García (2009)], who confirmed that these processes are efficient mechanisms to transform late-type disks galaxies into dEs, and whose simulated remnants are at least able to populate part of the fundamental plane locus of dEs. Since neither tidal interactions nor ram-pressure stripping are avoidable for galaxies within a cluster, the real situation is probably best described with an interplay of the different mechanisms.

At the same time, however, dEs are predicted to form in models of a ΛCDM universe, as descendants of building blocks in hierarchical structure formation. Cosmological simulations of galaxy clusters do predict a large number of dark matter subhaloes that are appropriate to host dEs (e.g. [Moore et al., 1999]) — there is no “missing satellites problem” for clusters. In that sense, dEs could be close relatives to their giant counterparts, sharing a cosmological origin. Indeed, semi-analytical models of galaxy formation, which are tied to cosmological N-body simulations, are able to reproduce the location of dEs on the fundamental plane when taking into account the dynamical response after supernova-driven gas-loss ([De Rijcke et al., 2005; Janz & Lisker, 2008]). Since this effect is mostly negligible at higher masses, it explains naturally the apparently different behaviour of Es and dEs (see Janz & Lisker, this issue).

Further possibilities for dE formation exist. The merger of very gas-rich dwarfs could lead to BCDs ([Bekki, 2008]), which might then become dEs as discussed earlier. Interactions of giant spiral galaxies could form “tidal dwarfs” that become dEs, a scenario that, under certain assumptions — could explain the number of dEs in clusters ([Okazaki & Taniguchi, 2000]). All these scenarios could ideally be investigated by comparing the measurements from multiwavelength observations to models of the chemical and structural evolution of dwarf galaxies or their progenitors (e.g. [Boselli et al., 2008; Hensler et al., 2004; Valcke et al., 2008]).

### 7 Discussion

#### 7.1 Early versus late formation

Most dEs in cluster regions of high density are pressure supported (Fig. 6), whereas in intermediate and low-density regions, more galaxies seem to be flattened by rotation or be rotationally supported ([Toloba et al., 2009; van Zee et al., 2004a]). Does this, by itself, tell us something about the formation history of those dEs? Simulations show that relatively flat low-mass cluster galaxies experiencing repeated strong tidal interactions become dynamically hotter: their \( v/\sigma \) decreases and they become “rounder” i.e. their axial ratio increases ([Mastropietro et al., 2005]). Such interactions are more frequent in the central region of a cluster. Thus, if all dEs once had similar levels of rotational support, those in the central cluster region would have become dynamically hotter, in agreement with the observational findings (I call this case 1). Likewise, if those that are now closer to the center have resided in the cluster for a longer time, they experienced more such interactions, leading to the same result (case 2). Similar scenarios apply to the observation that galaxies in the central cluster regions have higher stellar population ages on average ([Smith et al., 2008]): ram-pressure stripping, and also tidal stripping, are stronger in the central region, thus quenching star formation earlier in the galaxies that reside there. But without further considerations, it cannot be decided whether those galaxies have spent a longer time in the cluster, and were therefore stripped earlier (case 2), or whether they were simply stripped more efficiently (case 1).

From case 2, one might be tempted to conclude a later infall and transformation of the progenitors of those dEs that are now in the cluster outskirts and are significantly flattened by rotation. However, case 1 does not imply anything about when the dEs, or their progenitors, have entered the cluster, or whether they have always been part of the cluster since its formation phase. This is the point at which input from the theoretical side is essential: for case 2, we need to have an understanding of the timescale between the infall of a group of progenitor galaxies and the point when these galaxies (or their remnants) reach a stage in which they are concentrated towards the cluster center and show a peaked and fairly regular distribution of heliocentric velocities. For case 1, probably even more complex input physics is needed, since semi-analytical model predictions for “cosmological dwarfs” that form in dense environments need to be tested against the observations. Equally important are observational studies of dEs at significantly earlier epochs, and comparisons to the local population (cf. [Andreon, 2008; Harsono & DePropris, 2009, also this issue]).

#### 7.2 Multiple origins?

Would it be possible, despite the complex characteristics and several different subclasses, to explain all dEs by just a single formation channel? One could, for example, imagine that dEs with disks (dE(di)s) do not form an intrinsically different subclass, but instead they simply constitute the flat tail of the other dEs, with their disk components having not been destroyed yet. The fraction of dE(di)s with nuclei (~75%, [Lisker et al., 2008]) agrees with the overall fraction of nucleated dEs in the (bright) magnitude range of the dE(di)s. However, while bright non-nucleated dEs (without disks or blue centers) are significantly flatter than faint ones, this is not the case for the nucleated dEs (again without disks or blue centers). Given the lower stellar population age of dE(nN)s ([Rakos & Schomber, 2004]), and their location in regions of lower density, a possible explanation would be that the brighter dE(nN)s still need to experience further dynamical heating through tidal interactions, before they become as round as the dE(N)s. For the faint dE(nN)s,
though, one would have to assume that they were more susceptible to such interactions, and therefore already have a rounder shape. On the other hand, the correlation of the projected shape of dE(N)s and their heliocentric velocity (Lisker et al., 2009) includes both bright and faint objects, and seems to imply that the roundest shapes are achieved only when the galaxies’ orbits are significantly circularized.

To pursue the “unification” of dE subclasses, another requirement is that the dE(nN)s would need to form nuclei rather soon, before their stellar population ages are comparable to today’s dE(N)s. (Or, alternatively, there might have been some mechanism in the past that supported nucleus formation, but is not as efficient anymore today.) Perhaps nuclei are currently being formed in the centers of the dEs with blue cores, where we are witnessing ongoing star formation (Lisker et al., 2006). This would lead to nuclei with younger stellar populations than those of their host galaxies. However, Côté et al. (2006) found dE nuclei to have intermediate to old ages, and Lotz et al. (2004) measured similar colours of nuclei and dE globular clusters (GCs). Alternatively, most nuclei could form through coalescence of GCs, which would indeed be a more efficient process in the central cluster regions (Oh & Lin, 2000). Still, some effect would have to explain why the ratio of dE(N)s and dE(nN)s increases strongly with increasing dE luminosity (Sandage et al., 1985), especially if the dE(nN)s were to be the immediate progenitors of the dE(N)s.

Similar to the above argument about nucleus formation, the spatial distribution of dE(nN)s would soon have to become significantly more centrally concentrated. Conselice et al. (2001) derived a two-body relaxation time for Virgo dEs of much more than a Hubble time. However, two-body relaxation might be too simple for the real situation. These issues are probably best investigated with cosmological simulations, by “flagging” different groups or individual galaxies when they enter a cluster, and following the evolution of their combined (observable) state over various timescales. Current and future generations of simulations (e.g. Boylan-Kolchin et al., 2009) certainly provide such a possibility.

Obviously, many ifs and thens are necessary to explain all dEs by a single formation channel, and several authors have argued in favour of multiple channels (Lisker et al., 2008; Poggianni et al., 2001; Rakos & Schombert, 2004; van Zee et al., 2004b). Nevertheless, several aspects of dEs still need to be explored both theoretically and observationally, like the presence and characteristics of their globular clusters and what they can tell us about their evolutionary history (see the discussion in Boselli et al., 2008).

7.3 A plea for the study of early-type dwarfs

Galaxy mass is one of the main drivers of galaxy evolution and appearance. Internal physical processes like supernova feedback (Dekel & Silk, 1986) or the dynamical response to gas loss (Yoshii & Arimoto, 1987) have a stronger impact on dwarf galaxies than on giants, making dwarfs valuable test objects for galaxy formation models (Janz & Lisker, 2008, 2009). Nevertheless, if we want to use them as probes of the physical mechanisms that govern galaxy evolution, we need to understand the origin(s) of this most abundant galaxy population of clusters — which is a difficult task. The intriguing complexity of dEs is contrasted with the moderate amount of high-quality observational data. Now that the largest cosmological simulations and their semi-analytic models begin to reach significantly into the dwarf regime, it is essential to build complete observational samples providing a thorough characterization of fundamental scaling relations at low masses, involving structure, kinematics, and stellar population properties. These will provide indispensable benchmarks for new generations of galaxy models, as well as for future studies of dEs at significantly earlier epochs with extremely large telescopes.

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