

THE SIZES OF EARLY-TYPE GALAXIES

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ABSTRACT

In this letter we present a study of the size luminosity relation of 475 early-type galaxies in the Virgo Cluster with Sloan Digital Sky Survey imaging data. The analysis of our homogeneous, model-independent data set reveals that giant and dwarf early-type galaxies do not form one common sequence in this relation. The dwarfs seem to show weak or no dependence on luminosity, and do not fall on the extension of the rather steep relation of the giants. Under the assumption that the light profile shape varies continuously with magnitude, a curved relation of size and magnitude would be expected. While the galaxies do roughly follow this trend overall, we find that the dwarf galaxies are significantly larger and the low-luminosity giants are significantly smaller than what is predicted. We come to the conclusion that in this scaling relation there is not one common sequence from dwarfs to giants, but a dichotomy which can not be resolved by varying profile shapes. The comparison of our data to a semi-analytic model supports the idea of a physical origin of this dichotomy.

Subject headings: galaxies: elliptical and lenticular, cD — galaxies: dwarf — galaxies: fundamental parameters — galaxies: clusters: individual: (Virgo Cluster)

1. INTRODUCTION

Scaling relations have ever been an important tool not only to study galaxy properties but also to link those properties to their formation and evolution. Since early-type galaxies are the most numerous galaxy type in cluster environments, they play an outstanding role in understanding galaxy clusters and therefore structure formation in general. But still today it remains an open question whether the giant early-type galaxies and their lighter counterparts share the same origin and formation mechanisms. Of the morphological scaling relations, so far mostly the relation between surface brightness and size (“Kormendy relation”, Kormendy 1985), and between surface brightness and luminosity (e.g. Binggeli & Cameron 1991) were studied to tackle this question. Combined with velocity dispersion, the Faber-Jackson relation (Faber & Jackson 1976) and the extension to the Fundamental Plane (Dressler et al. 1987; Djorgovski & Davis 1987) were studied, mostly for giant early types. But even with the now available facilities velocity dispersions are still rare for dwarf galaxies.

Until the early 1990’s sizes of nearby early-type galaxies were studied for example by Kormendy (1977), Guzman et al. (1993), and for the Virgo Cluster in particular by Binggeli & Cameron (1991) for dwarfs and by Caon et al. (1993) for giants. An often cited source of a homogenous data set of sizes for dynamically hot systems over the whole luminosity range is Bender et al. (1992). The conclusion of that time was that giant and dwarf early-type galaxies show a distinct size distribution, and that the dwarfs show less change of size with luminosity than the giants. This together with other scaling relations was interpreted as evidence for a different origin of dwarf and giant early-type galaxies.

Towards the turn of the millenium, however, it became more widely realized that the light profile shapes of early types vary continuously with luminosity. Nei-

ther do dwarf galaxies simply follow exponential profiles, nor do all giants exhibit de Vaucouleurs profiles. Instead, all early types are well described by the generalized Sérsic profile (Sérsic 1963) with different Sérsic indices n (Young & Currie 1994; Ferrarese et al. 2006). Several authors reasoned that the scaling relations naturally follow what is predicted by n changing linearly with magnitude, and that all these galaxies can indeed be of the same kind (Jerjen & Binggeli 1997; Binggeli & Jerjen 1998; Graham & Guzmán 2003; Gavazzi et al. 2005). While this latter interpretation is, for example, not shared by Boselli et al. (2008), who argue that dwarf and giant early-type galaxies have different origins, these authors do agree that they can be seen as one structural family with a gradual variation of n with luminosity. Recently, Kormendy et al. (2008) conclude that dwarfs and giants are *structurally* distinct, notwithstanding the Sérsic continuum, which they consider insensitive to the physics dividing the two. In our analysis below we quantitatively pin down this structural distinction by taking the variation of profile shapes explicitly into account.

2. SAMPLE SELECTION AND IMAGING DATA

Our sample is selected based on the Virgo Cluster Catalog (VCC; Binggeli et al. 1985). Only certain cluster members with $m_B < 18.0$ mag are taken into account, which is the same magnitude limit up to which the VCC was found to be complete. This translates into $M_B < -13.0$ mag with our adopted distance modulus of $m-M=31.0$ mag ($d=15.85$ Mpc, Graham et al. 1999).

Galaxies listed as “S0:”, “E/S0”, “S0/Sa”, and “SB0/SBa” are taken as S0, and one S0 (VCC1902) is excluded, since it shows clear spiral arm structure. For the dwarfs, we selected galaxies classified as dE, dS0, and “dE:”, whereas “dE/Im” as well as possible irregulars based on visual inspection are excluded (Lisker et al. 2007). We excluded 13 dwarfs where the Petrosian aperture (see below) could not be obtained, as well as 13 dwarfs and four giants that are too strongly contam-

inated by the light of close neighbour objects. This leads to a working sample of 475 galaxies: 397 early-type dwarfs (“dEs”), 9 M32-type candidates (as listed in Table XIII of Binggeli et al. 1985), and 67 E and S0 galaxies.

The Sloan Digital Sky Survey (SDSS) Data Release Five (Adelman-McCarthy et al. 2007) covers all but six early-type dwarf galaxies of the VCC. The pixel scale of 0.396 corresponds to a physical size of 30 pc. For the analysis below, we use the r -band, which has the highest S/N. Since the quality of sky level subtraction of the SDSS pipeline is insufficient, we use sky-subtracted images as provided by Lisker et al. (2007), based on a careful subtraction method. The images were flux-calibrated and corrected for Galactic extinction (Schlegel et al. 1998).

The image analysis is done largely in the same way as in Lisker et al. (2008): For each galaxy, we determined a “Petrosian semimajor axis” (Petrosian 1976, a_p), i.e., we use ellipses instead of circles in the calculation of the Petrosian radius (see, e.g., Lotz et al. 2004). The total flux in the r band was measured within $a = 2a_p$, yielding a value for the half-light semimajor axis, $a_{hl,r,uncorr}$. This Petrosian aperture still misses some flux, which is of particular relevance for the giant galaxies (Trujillo et al. 2001). As improvement of Lisker et al. (2008), luminosities and half light radii are corrected for this missing flux according to Graham et al. (2005). Axial ratio and position angle were then determined through an isophotal fit at $a = 2a_{hl,r}$. The effective radius is then given by $r_{eff} = a_{hl,r}\sqrt{b/a}$ with the axis ratio b/a . Additionally we fitted Sérsic profiles. We omitted intensities at radii $r < 2''$ in order to avoid seeing effects.

Our data set is a very homogeneous set of parameters for galaxies in one cluster, based on data taken with the same instrument and reduced and analyzed with the same procedure. We point out that our derived radii are model independent.¹

3. SIZES OF EARLY-TYPE GALAXIES

In Fig. 1 we present the size luminosity diagram for our sample. At first glance the sequence from dwarf to giant early-type galaxies does not look very continuous: the giants follow a steep relation with a well-defined edge on the bright end of their distribution. The bunch of dwarfs apparently lie with a larger scatter around an effective radius of $r_{eff} = 1$ kpc, their sizes showing weak to no dependence on luminosity.²

Without applying the correction for the missing flux within the Petrosian aperture, the separation between the two sequences even widens (not shown) since the less compact objects of the same luminosity show less concentration and therefore a smaller correction.

It is important to notice that the different behaviour of dwarfs and giants does not depend on whether objects

¹ The corrections for the missing flux are based on the concentration parameter of the galaxies; therefore they implicitly depend on the assumption of a (Sérsic) light profile model (cf. Graham et al. 2005).

² The almost constancy of the dwarfs is just a coincidence when taking the half light radius containing 50 % of the light. For example, for the radius containing 90 % of the light, the relation for dwarfs steepens. This can be understood when taking the gradual variation of profile shapes with luminosity (see below) into account.

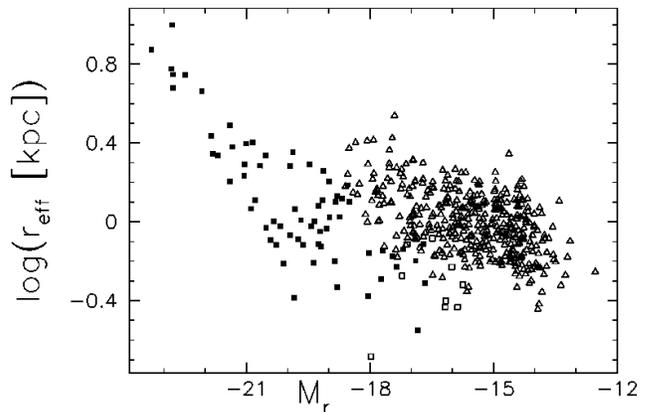


FIG. 1.— Absolute magnitude in r versus logarithm of half light radius. dEs are shown with open triangles and E and S0 with filled squares. M32-type candidates are drawn with open squares.

with disk components are omitted. This can be seen from Fig. 2, where gray symbols indicate objects with disk components or disk-like structure.

Instead of adopting one distance for all galaxies, the Virgo cluster can alternatively be described as a sub-structured system, with the different components partly having different distances (Gavazzi et al. 1999). Since this can affect the apparent size of a galaxy, we checked whether the distribution of galaxies within the size luminosity diagram correlates with projected position in the cluster. We do not find any such correlation. Therefore, while distance variations could explain the larger scatter of the sizes of early types in the Virgo Cluster as compared to other clusters (Boselli et al. 2008), it cannot explain the observed dichotomy: Boselli et al.’s Fig. 6 indicates the apparent separation of dwarfs and giants and they use different distance moduli for different subparts of the Virgo cluster.

The same impression can also be obtained from other previous studies, e.g. Binggeli & Cameron (1991), Fig. 1b; Bender et al. (1992), Table 1; Kormendy et al. (2008), Fig. 37. It is, however, not as clearly seen in the compilation of sizes of elliptical galaxies from several different studies presented by Graham & Worley (2008) (Fig. 10). In this more heterogeneous dataset, the relative number of small low-luminosity giants as well as that of large bright dwarfs appears to be somewhat smaller.

3.1. Varying profile shapes ?

Graham & Guzmán (2003) suggested that the apparent dichotomy between dwarfs and giants in scaling relations can be explained just by the fact that the profile shape of a galaxy scales with magnitude. They describe the light profiles with Sérsic profiles and show the effect of a linear relation between magnitude and logarithm of the Sérsic index n on the other scaling relations. As a result, the dependence of effective radius on magnitude becomes stronger at higher luminosities and the brightest galaxies are naturally larger (Fig. 11 in Graham & Worley 2008).

For investigating whether our galaxies display the predicted behavior, we fitted their azimuthally averaged light profiles with Sérsic models (see Sect. 2). The derived Sérsic indices n and central surface brightnesses μ_0

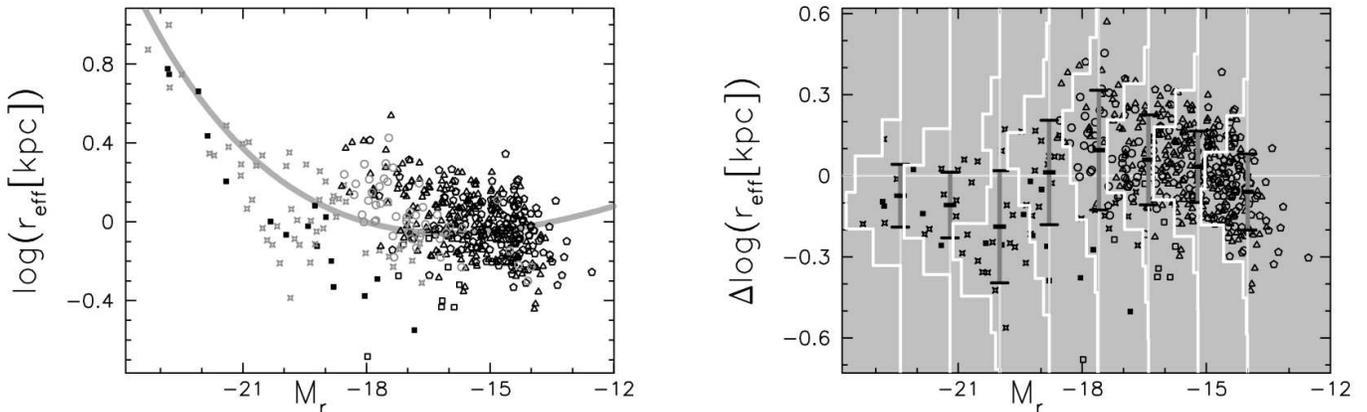


FIG. 2.— *Left panel:* Same as Fig. 1, with prediction for Sérsic profiles with the Sérsic index n given as a function of luminosity. Now the sub-classifications according to Lisker et al. (2007) are taken into account. The symbols mean: filled squares - E, gray stars - S0, open squares - M32 candidates, open triangles - dE,N, open pentagons - dE,nN and gray open circles for dwarf galaxies with probable disk-like structure (dE(di) or dE(bc)). *Right panel:* The residuals in $\log(r)$ about the predicted relation. The vertical histograms show the galaxy distributions in magnitude bins of 1.2 mag. Their zero levels are indicated by the thin gray lines. Thick gray lines measure the scatter around the mean (black marks), with the standard deviation indicated in black at the ends of the lines.

were then used to obtain linear fits to the μ_0/M_r and n/M_r relations, using a least squares fitting algorithm. For those fits we exclude systems with a (probable) disk component, namely galaxies classified as S0, dEs with disk features, and dEs with blue centers (Lisker et al. 2006b,a). This is to ensure that the light profiles can be well parametrized by Sérsic profiles. Our fits together with equation (16) of Graham & Worley (2008) predict a non-linear sequence in the r_{eff}/M_r diagram.

The predicted relation is shown together with the observed galaxies in the left panel of Fig. 2. With the visual guidance of the line, it appears more likely that the data points follow one common continuous relation. And the gross trend in the diagram can indeed be explained by varying profile shapes. However, at luminosities brightwards of the transition between dwarfs and giants, a substantial amount of galaxies fall below the relation, while faintwards most of the dwarfs lie above it.

We note that M32-type candidates play a minor role just by their small number, and furthermore, they are fainter than the “compact giants” in question. Whether both of these are special enough to justify their own classification is out of the scope of this letter, and will be investigated in a future study.

To quantify the departure of the observed galaxies from the predicted relation we show in the right panel of Fig. 2 the size residuals about the curve shown in the left panel. While at both ends of the luminosity range the observed galaxies fall onto the relation, it can now be seen even more clearly that towards intermediate luminosities, they depart more and more from the relation in opposite directions. Brightwards of the transition region, most galaxies are only half the predicted size, while faintwards, many galaxies are larger than predicted by $\geq 50\%$.

Furthermore, we divide the data into magnitude bins and investigate the distribution of galaxies in those bins with histograms (Fig. 2, right panel). The scatter and the shapes of the histograms confirm the coexistence of two separate relations. In the two bins in which the transition occurs, the scatter increases, and is even larger than for the faintest galaxies, for which one would naively expect

the largest scatter. Moreover, the distribution around the mean changes from the Gaussian-like shape seen at the bright and faint end to a much broader, even double-peaked shape. For those two bins, a K-S test yields a probability for the null hypothesis that the two samples follow the same distribution of 2.11%, which means that the break is statistically significant.

Only the bright end of the predicted curve shows strong sensitivity to the fitted relations. At intermediate luminosities, it is stable against small changes of the fits. Moreover, a change of the curve would not reduce the significant difference between the bright dwarfs and low-luminosity giants.

Thus our analysis shows two things. First, the residuals do not resemble a quite large random scatter around the relation. And therefore the size luminosity relation can not be fully explained by varying profile shapes. Second, the abrupt change in the behavior of faint and bright galaxies is even emphasized through the above examination, and this break is a real discontinuity of the sequence from lowest to highest luminosities.

4. COMPARISON TO SEMI-ANALYTIC MODEL

The Numerical Galaxy Catalog of Nagashima et al. (2005) is based on a high resolution N -body simulation in a Λ CDM universe (Yahagi 2005). The dark-halo merger trees of the N -body simulation are taken as input for a semi-analytic model of the physical processes governing galaxy formation and evolution (here a modified version of the Mitaka Model, Nagashima & Yoshii 2004).

In particular, this model takes into account the dynamical response to starburst-induced gas removal after gas-rich mergers (also for cases intermediate between a purely baryonic cloud and a baryonic cloud fully supported by surrounding dark matter as in Yoshii & Arimoto 1987). This process plays a crucial role for the sizes of early-type dwarf galaxies. Their gravitational well is shallower and thus they suffer a more substantial gas loss than giants. The subsequent variation of the potential results in an increase in size. If it is not taken into account the dwarf galaxies are modelled to be systematically smaller.

We identify model galaxies as early-type galaxies if

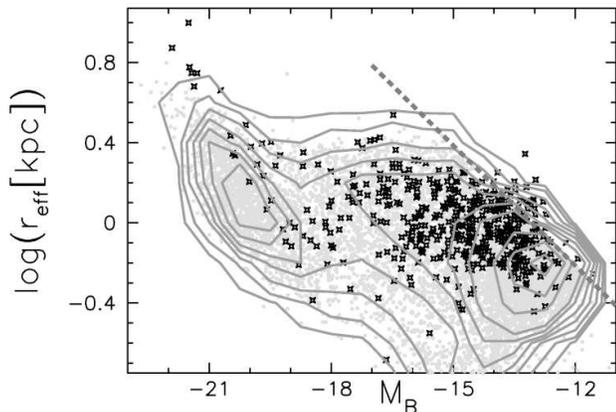


FIG. 3.— Absolute B magnitude versus logarithm of half light radius for observed (black) and model galaxies (gray) from Nagashima et al. (2005). Model galaxies with fainter surface brightnesses than a limit of $\langle \mu_B \rangle < 25.5 \text{ mag/arcsec}^2$ (dashed line) are excluded. Contours were calculated using model galaxy abundances in bins of 0.75 mag and 0.2 dex. The contour levels, relative to the lowest, are 2.5, 5, 8, 11, 15, 20, 35, 50

they are bulge dominated (bulge to total ratio > 0.6). To compare our data with the model we transformed SDSS g magnitudes into B according to Smith et al. (2002), using the galaxies’ $g - r$ color measured within $a_{hl,r}$. In Fig. 3 one can see that the model galaxies show a bimodality similar to what we observe, with low galaxy density between the two regions. In those dwarfs which form by gas-rich major mergers a starburst follows and the dwarfs are enlarged by the dynamic response to the subsequent gas loss. This mechanism is not at work in gas-deficient mergers, and the resulting galaxies are smaller.

Note that Nagashima et al. assume de Vaucouleurs profiles to calculate projected half-light radii from half-mass radii. For exponential profiles, which would be more appropriate for dwarfs, the model galaxies would shift upwards in the diagram by 0.11 dex (Nagashima & Yoshii 2003).

It is interesting, that they compared their model to the data of Bender et al. (1992) and concluded that a substantial fraction of model dwarfs is too large to match the observed galaxies. With our dataset, a much better agreement is found (also see de Rijcke et al. 2005).

5. SUMMARY AND DISCUSSION

We studied the size luminosity relation of Virgo cluster early-type galaxies, based on model-independent size measurements from SDSS imaging data. We find that the dwarfs do not fall on the extension of the rather steep sequence of the giants. While the gross trend in the size luminosity relation can be explained by light profile shapes becoming steeper for more luminous galaxies, a closer look reveals that there is a clear discontinuity in the behaviour of faint and bright galaxies.

Dabringhausen et al. (2008) compare dynamical masses and projected half-light radii of elliptical galaxies, bulges of spiral galaxies, dwarf spheroidals, massive compact objects (MCOs), and globular clusters (GCs). These authors also find a bimodality in the size distribution of elliptical galaxies. The “compact low-mass ellipticals” and the giant ellipticals lie on one sequence down to the MCOs and GCs, while the ellipticals of intermediate brightness in the larger branch lie on one sequence with the dwarf spheroidals. The interpretation of Okazaki & Taniguchi (2000), based on calculations of galaxy interactions, is that those latter galaxies are mostly of tidal origin and that the “compact low-mass ellipticals” should be interpreted as the real counterparts of the more massive elliptical galaxies. This is an alternative interpretation to the one based on semi-analytic models (Sect. 4), and represents further evidence for the physical relevance of the observed dichotomy.

Our findings are a new piece to the puzzle of the connection between dwarf and giant early-type galaxies and may hint at different origins. A further analysis of the scaling relations and comparison with models seems a promising approach to bring more light to this question. In particular it will be interesting to investigate correlations with velocity dispersion, since it should be closely related to size evolution in the framework of dynamical response. We will pursue this idea in a forthcoming paper.

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