

A FUNDAMENTAL LINE FOR ELLIPTICAL GALAXIES

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ABSTRACT

Recent studies have shown that massive galaxies in the distant universe are surprisingly compact, with typical sizes about a factor of three smaller than equally massive galaxies in the nearby universe. It has been suggested that these massive galaxies grow into systems resembling nearby galaxies through a series of minor mergers. In this model the size growth of galaxies is an inherently stochastic process, and the resulting size–luminosity relationship is expected to have considerable environmentally dependent scatter. To test whether minor mergers can explain the size growth in massive galaxies, we have closely examined the scatter in the size–luminosity relation of nearby elliptical galaxies using a large new database of accurate visual galaxy classifications. We demonstrate that this scatter is much smaller than has been previously assumed, and may even be so small as to challenge the plausibility of the merger-driven hierarchical models for the formation of massive ellipticals.

Key words: galaxies: fundamental parameters – galaxies: photometry – galaxies: structure

Online-only material: color figures

1. INTRODUCTION

Galaxies exhibit a bewildering variety of shapes and sizes, but elliptical galaxies are the simplest of all extragalactic objects, and their structural uniformity suggests that they might be easier to understand than more complex later-type galaxies. Most recent attempts to understand the evolution of elliptical galaxies have been in the context of hierarchical models for structure formation (Toomre 1977; White & Rees 1978; Khochfar & Burkert 2003; Bower et al. 2006; De Lucia et al. 2006; Hopkins et al. 2010). In these models the formation of elliptical galaxies is linked to mergers, where the galaxy’s environment is the central parameter which determines its merger history (Mo & White 1996). The predominance of old stellar populations in nearby massive elliptical galaxies is inconsistent with large episodes of recent star formation, which suggests that the mergers that formed elliptical galaxies either occurred very long ago (at redshifts $z > 2$), or else that they can best be described as the coalescence of pre-existing old stellar populations (“dry mergers”; Thomas et al. 2005; Renzini 2006; Graves et al. 2009a, 2009b). Such dry mergers do not form many new stars; instead they simply rearrange the existing stars. It has been argued that such dry merging may also be responsible for the observed large size growth in massive, compact, elliptical galaxies over the last 10 Gyr (Cimatti et al. 2004; Daddi et al. 2005; Trujillo et al. 2006; Longhetti et al. 2007; van Dokkum et al. 2008; McGrath et al. 2008; Damjanov et al. 2009; Rettura et al. 2010; Hopkins et al. 2009; Naab et al. 2009; van der Wel et al. 2008), though this scenario requires considerable fine tuning to reproduce local scaling relations (Nipoti et al. 2009). This growth is also expected to be dependent on environment, with galaxies in higher density environments undergoing more mergers and hence showing a larger scatter in their size–luminosity relation.

Recent studies (Gavazzi et al. 1996; van den Bergh 2008; Nair et al. 2010) have found that the size–luminosity relation provides the tightest of all the purely photometric correlations used to characterize galaxies. However, the environmental dependence

of this relation is highly debated, with some groups finding a large scatter as well as a strong environment-dependent curvature in the size–luminosity relation for elliptical galaxies (Giuricin et al. 1988; Shen et al. 2003; Bernardi et al. 2007; Desroches et al. 2007; von der Linden et al. 2007; Hyde & Bernardi 2009a), while others do not (Guo et al. 2009; Nair et al. 2010). The purpose of this Letter is to show that the size–luminosity relation of elliptical galaxies is well defined by a fundamental line with no environmental dependence. We demonstrate that this scatter is much smaller than has been previously assumed, and may even be so small as to challenge the plausibility of the merger-driven hierarchical models for the formation of massive ellipticals.

Throughout this Letter, we assume a flat dark energy-dominated cosmology with $h = 0.7$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$.

2. SAMPLE

2.1. Main Sample

Our sample of 2861 elliptical galaxies is a subset of the 14,034 visually classified bright galaxies (model $g' < 16$, $0.01 < z < 0.1$) presented in Nair & Abraham (2010, hereafter NA10) with valid measures of environment (described below) and no overlapping companions. The NA10 sample is in turn derived from the Sloan Digital Sky Survey (SDSS) spectroscopic catalog (Strauss et al. 2002). Visual classification was carried out by one of the authors (P.N.) and found to agree with those from the RC3 within one Hubble type (on average) for the 1793 galaxies in common to both samples. It is important to emphasize that, unlike samples derived from automated classifications, our sample is expected to contain only minimal contamination by S0 and Sa galaxies. For this analysis, we updated the photometry and spectroscopy to use the SDSS Data Release 7 (DR7) derived sizes, luminosities, and velocity dispersions.

The sizes of galaxies are parameterized by (1) the radius enclosing 90% of the galaxy’s light contained within twice the Petrosian radius (Petrosian 1976; Stoughton et al. 2002),

referred to as R_{90} ; (2) the corresponding radius containing 50% of the galaxy’s light, referred to as R_{50} ; and (3) the seeing-corrected de Vaucouleurs radius, also known as the half-light radius, R_e . The de Vaucouleurs radii are corrected for the known problem originating in slight errors in SDSS sky-subtraction of large galaxies, as specified by Hyde & Bernardi (2009a, hereafter HB).

We explored two estimators of galaxy luminosity. The total magnitude of each galaxy was specified by (1) the Petrosian luminosity and (2) the de Vaucouleurs luminosity, both corrected for extinction, k -correction (Blanton et al. 2005), and luminosity evolution (HB), and the latter also corrected for the known problems of SDSS sky-subtraction as prescribed by HB. All magnitudes in this Letter are in the AB system.

It is important to understand the size of the intrinsic scatter in our measurements. As will be shown, the tightest relations are obtained using R_{90} . From simulations, we estimate the fractional uncertainties in R_{90} to be several times the fractional uncertainty in the sky level. On SDSS images the sky background around galaxies is generally known to about $\pm 1\%$, so the corresponding fractional uncertainties in R_{90} estimates are typically 4%–5%. Other error terms are added in quadrature to this, so that a typical R_{90} measurement carries around a 5% uncertainty. The effect of seeing correction on R_{90} is negligible (see Appendix A in Nair et al. 2010). In comparison to the errors on the size measurements, the errors on both magnitude estimators are small (< 0.01 mag).⁴

Finally, we note that in the plots presented below we isolate subsets of galaxies based on central velocity dispersion. These velocity dispersions have been corrected for aperture effects as specified by Jørgensen et al. (1995).

2.2. Environment Measures

To study trends with environment, we use two publicly available metrics, an N th nearest neighbor approach computed by Baldry et al. (2006), and a group catalog algorithm by Yang et al. (2007). Baldry et al. (2006) measured the environmental density for SDSS galaxies with $r' < 18$, $0.01 < z < 0.1$, and photometrically selected galaxies with surface brightness $18.5 < \mu_{r,50} < 24.0$. The density is defined as $\Sigma = N/(\pi d_N^2)$, where d_N is the projected comoving distance (in Mpc) to the N th nearest neighbor. The best estimate density (to account for spectroscopic incompleteness) was obtained by calculating the average density for $N = 4$ and 5 with spectroscopically confirmed members only and with the entire sample. The mean $\log \Sigma$ for our sample is -0.32 .

Yang et al. (2007) used an iterative halo-based group finder on the SDSS NYU-Value Added Galaxy Catalog (Blanton et al. 2005) for objects with $r' < 18$, and $0.01 < z < 0.2$ with a redshift confidence $C_z > 0.7$. Tentative group members were identified using a modified friends-of-friends algorithm. The group members were used to determine the group center, size, mass, and velocity dispersion. New group memberships were determined iteratively based on the halo properties. The final catalog yields additional information identifying the brightest galaxy in the group, the most massive galaxy in the group (both used as proxies for central galaxies), estimated group mass, group luminosity, and halo mass. We use the group occupation

number N as a proxy for environment. We are primarily interested in relative evolution between field and cluster galaxies, and hence define low-density regions as galaxies with $N \leq 2$ and Baldry $\log \Sigma < -0.32$, while high-density regions are defined as galaxies in groups with more than two members $N > 2$ and Baldry $\log \Sigma > -0.32$ (the mean N and $\log \Sigma$ for our sample).

3. SIZE–LUMINOSITY RELATION OF ELLIPTICAL GALAXIES

We determined the best-fitting size–luminosity relations for our sample by (1) minimizing the scatter in size (direct method) and (2) minimizing the scatter orthogonal to the best-fit line (orthogonal method). While there is a slight change in fit parameters between the two methods, our overall conclusions are not affected. In all cases we found that Petrosian-based quantities yielded considerably tighter relations than those obtained with the “traditional” relations defined using de Vaucouleurs profile fits.

Figure 1 (top panel) shows the Petrosian- R_{90} -size–Petrosian-luminosity relation for the 756 elliptical galaxies that are located in sparse environments (left panel), and the 1315 ellipticals in dense environments (right panel). The points are keyed to central velocity dispersion quartiles where black points are the galaxies with the highest velocity dispersion in each panel and green points have the lowest velocity dispersion. Orange and yellow points are the intermediate quartiles. The black line shows the best-fit relation for all (~ 3000) elliptical galaxies. The blue lines/regions and red lines/regions in each panel denote the best-fit (orthogonal) relation in sparse and dense environments, respectively, with the shaded region denoting the 1σ uncertainties in the slope (determined by 100 bootstraps). The parameters of the best-fit orthogonal relation are inset in each panel and are summarized in Table 1. The lower panels of Figure 1 show the residuals in size about the (direct) size–luminosity relation in small bins of luminosity. The parameters of the best-fit direct relation are inset in each panel. The error bars show the median error in size including a 1% error in sky. The dashed contours indicate the 25th–75th percentile range, while the dotted lines indicate the range spanned by the 10th–90th percentiles. The figure shows the following striking features: (1) the radii and the luminosities of elliptical galaxies exhibit a very tight power-law relationship (linear in log–log space) over a range of ~ 100 in luminosity. (2) Within the statistical errors the elliptical galaxies in dense and in sparse environments appear to follow the same power-law relationship, though the scatter in this relation is slightly smaller in higher density environments. (3) The intrinsic scatter in the relationship is comparable to the measurement errors in R_{90} .⁵ Thus, *the size–luminosity diagram of elliptical galaxies defines a “fundamental line” in log–log space with negligible intrinsic scatter over two orders of magnitude in galaxy luminosity.*

It is interesting to compare our results with those obtained by HB, who found curvature in the size–luminosity relationship. The HB sample is a factor of 20 larger than ours, but the sample was chosen on the basis of automated classifications and is contaminated by S0 and Sa galaxies. The authors analyzed their sample using conventional galaxy sizes parameterized by

⁴ We ignore the systematic offset in magnitude caused by SDSS underestimating sky for bright galaxies ($r < 14$ mag). However, if we apply the HB correction formula (which is an overestimate) directly to the Petrosian luminosity, the trends are similar).

⁵ The measurement errors in R_{90} are expected to be larger in higher density environments where SDSS suffers from overestimation in sky background levels. This error is not included in the estimated errors.

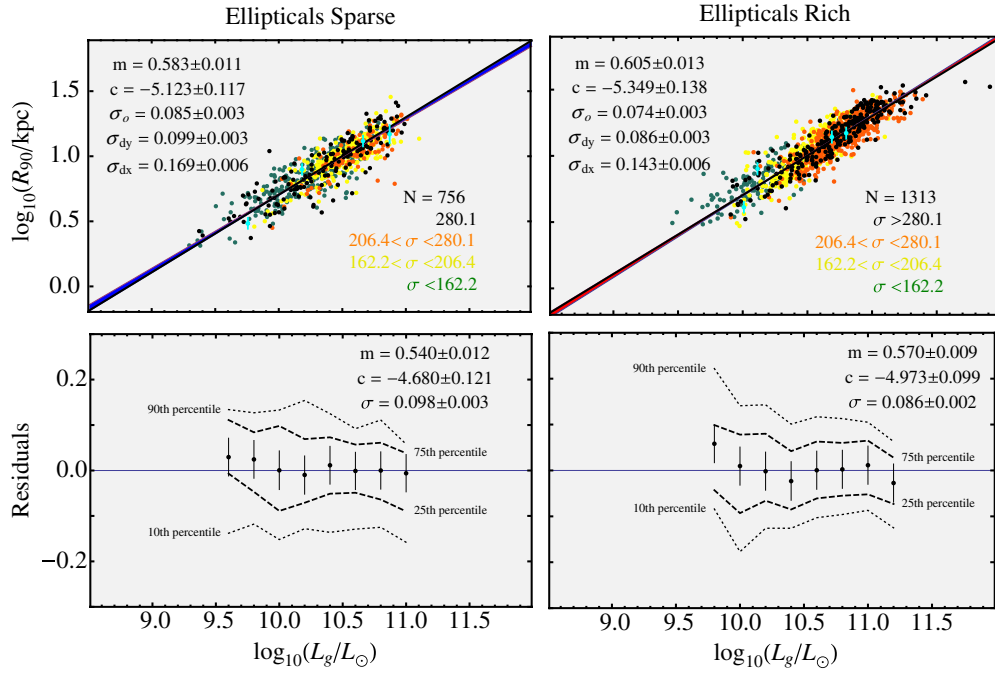


Figure 1. Petrosian size–luminosity relationships for nearby elliptical galaxies. The top row shows the relationships obtained from the Nair & Abraham (2010) elliptical galaxy sample where the size of each galaxy is parameterized by the radius enclosing 90% of the galaxy’s light contained within twice the Petrosian radius, R_{90} (see the text for details). The left-hand panel corresponds to galaxies in the field, while the right-hand panels correspond to galaxies in dense environments. Symbol colors are keyed to corrected central velocity dispersion of the galaxies, in four broad bins. In cyan are error bars for four random points. In each panel the best-fit orthogonal linear model (blue/red lines) is superposed on the data, with the parameters for the model inset. σ_{dx} and σ_{dy} are the scatter in the x and y parameters. The black line shows the best-fit relation for all elliptical galaxies. The bottom row shows the residuals in size from the direct best-fit analysis, with the parameters for the model inset. The dashed lines show the 25th–75th percentile range, while the dotted lines show the 10th–90th percentile range. The error bars show the median error in size, including 1% error in sky, in small bins of luminosity.

(A color version of this figure is available in the online journal.)

Table 1
Size–Luminosity Relationships

Class	N	Slope [log(L_{\odot})]	Intercept $\frac{\log(L_{\odot})}{\log(\text{kpc})}$	Dispersion [log(L_{\odot})]	Orthogonal Fit	
					Dispersion R [log(kpc)]	Dispersion L [log(kpc)]
Elliptical galaxies R_{90} vs. $L_{\text{petrosian}}$						
All	2861	0.596 ± 0.006	-5.256 ± 0.062	0.077 ± 0.001	0.090 ± 0.002	0.151 ± 0.003
Sparse	756	0.583 ± 0.011	-5.123 ± 0.117	0.085 ± 0.003	0.099 ± 0.003	0.169 ± 0.006
Rich	1313	0.605 ± 0.013	-5.349 ± 0.138	0.074 ± 0.003	0.086 ± 0.003	0.143 ± 0.006
Elliptical galaxies R_{50} vs. $L_{\text{petrosian}}$						
All	2861	0.596 ± 0.006	-5.746 ± 0.062	0.080 ± 0.001	0.093 ± 0.002	0.156 ± 0.003
Sparse	756	0.580 ± 0.013	-5.576 ± 0.132	0.088 ± 0.003	0.102 ± 0.003	0.176 ± 0.006
Rich	1313	0.616 ± 0.013	-5.950 ± 0.136	0.075 ± 0.003	0.088 ± 0.004	0.144 ± 0.006
Elliptical galaxies R_p vs. $L_{\text{petrosian}}$						
All	2861	0.6114 ± 0.007	-5.515 ± 0.070	0.088 ± 0.001	0.103 ± 0.002	0.169 ± 0.004
Sparse	756	0.598 ± 0.014	-5.376 ± 0.146	0.097 ± 0.003	0.113 ± 0.004	0.189 ± 0.007
Rich	1313	0.630 ± 0.014	-5.711 ± 0.149	0.083 ± 0.003	0.098 ± 0.004	0.156 ± 0.008
Elliptical galaxies R_e vs. L_{dev}						
All	2861	0.739 ± 0.013	-6.992 ± 0.140	0.135 ± 0.003	0.168 ± 0.004	0.227 ± 0.006
Sparse	756	0.695 ± 0.026	-6.538 ± 0.265	0.148 ± 0.006	0.180 ± 0.008	0.259 ± 0.011
Rich	1313	0.815 ± 0.023	-7.792 ± 0.239	0.123 ± 0.005	0.158 ± 0.006	0.194 ± 0.011

the half-light radius R_e . Figure 2 presents the size–luminosity relationship of our sample analyzed using the Petrosian half-light radius (R_{50}) versus Petrosian luminosity (top row) and R_e versus de Vaucouleurs luminosity (bottom row) keyed to central velocity dispersion quartiles. The color coding is the same as in Figure 1. The dashed black line shows the best-fit relation from

Figure 1. A number of features are apparent: (1) The slope, scatter, and environmental dependence of elliptical galaxies using R_{50} is nearly the same as R_{90} . For elliptical galaxies R_{50} is just a factor of three smaller than R_{90} . Thus, the ratio R_{90}/R_{50} is not sensitive to the internal structure (Sérsic index) of elliptical galaxies. (2) The curvature noted by HB (and clearly seen in

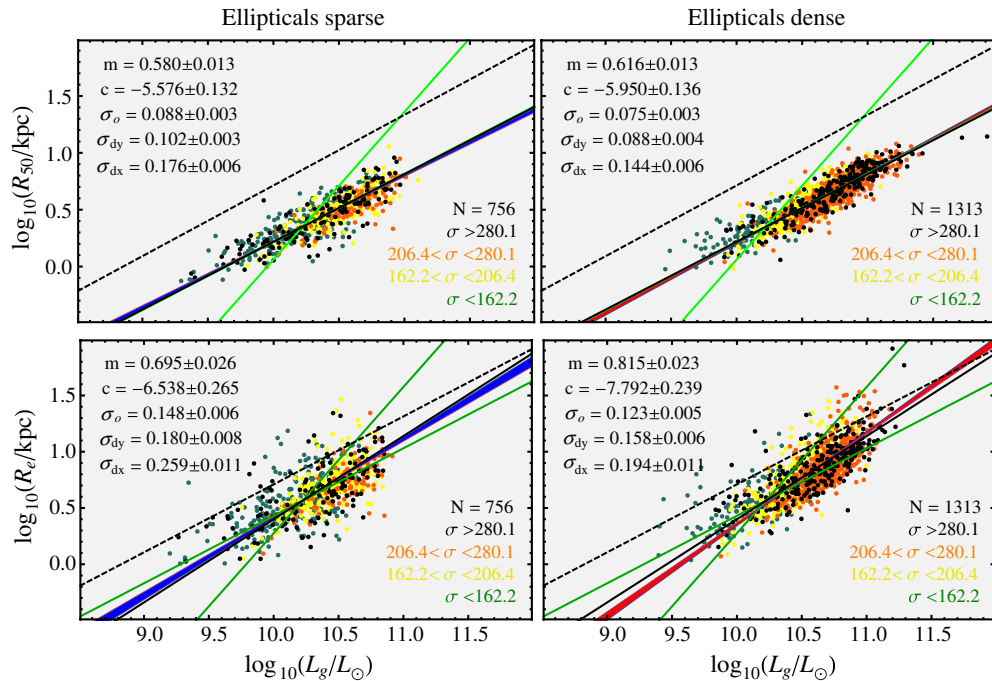


Figure 2. Decrease in scatter and curvature of the size–luminosity relation obtained by using Petrosian R_{90} (R_{50}) sizes instead of conventional sizes. The top row shows the relationships obtained using the radii enclosing 50% of the Petrosian flux, R_{50} , vs. Petrosian luminosity, while the bottom row shows the relationships obtained using de Vaucouleurs half-light radii, R_e , vs. de Vaucouleurs luminosity. The left-hand panels correspond to galaxies in the field, while the right-hand panels correspond to galaxies in dense environments, such as groups. Symbol colors are keyed to corrected central velocity dispersions of the galaxies, in four broad bins. In each panel the best-fit orthogonal linear model is superposed on the data, with the parameters for the model inset. σ_{dx} and σ_{dy} are the direct scatter in the x and y parameters. The solid black line shows the best-fit relation for all elliptical galaxies. The dashed black line shows the best-fit relation from Figure 1. The green lines indicate the predicted slopes from dry major merging assuming various orbital configurations from Boylan-Kolchin et al. (2006). The steeper line is for bound radial orbits, while the shallower line is for the bound orbit with the largest pericentric distance (Boylan-Kolchin et al. 2006).

(A color version of this figure is available in the online journal.)

the lower panels) is not seen when using R_{90} or R_{50} .⁶ This is because R_e , the half-light radius, is sensitive to the profile shape (Sérsic index) of galaxies, as has been shown in Appendix A of Nair et al. (2010). (3) The scatter in the size–luminosity relation using R_{90} (or R_{50}) is $\sim 40\%$ lower than that obtained with R_e .

4. DISCUSSION

The size–luminosity relation of elliptical galaxies is closely related to the fundamental plane (Djorgovski & Davis 1987; Faber et al. 1987; Kormendy & Djorgovski 1989), which describes a rather tight relationship between the size, surface brightness, and central velocity dispersion of elliptical galaxies. The “tilt” (with respect to canonical relationships predicted by the virial theorem) and scatter about the fundamental plane are thought to be due to variations in either age, metallicity, or structural non-homology. It is remarkable that the scatter in the Petrosian R_{90} size–luminosity relationship (~ 0.090 dex in size for all elliptical galaxies) is tighter than the scatter recently reported in the fundamental plane (~ 0.097 dex in size R_e ; Hyde & Bernardi 2009b). How is it possible that the size, luminosity, and velocity dispersion information embedded in the fundamental plane formulation does not provide a more accurate fit to the observations than does the fundamental line defined by the size and luminosity data alone? Recent work on nearby Virgo cluster galaxies (Kormendy et al. 2009) makes a strong case for the conclusion that the *internal structure* of early-type galaxies depends on their minor merger history. If true, one might perhaps

expect the dispersion about the fundamental plane to depend on the galaxy radius that is chosen to define the plane. Figure 2 suggests that at least some of the tilt, scatter, and curvature in the conventional fundamental plane may be due to structural (or kinematic) non-homology in the elliptical galaxy population with R_e , and that this may disappear if the fundamental plane is defined using a metric of size which is not as sensitive to the galaxy profile shape. Note that this suggests that the record of the galaxy’s merger history may be most strongly imprinted in a galaxy’s profile, rather than in its overall size, which is what is being probed by our investigation.

It is interesting to consider whether the small scatter in the size–luminosity relationship for elliptical galaxies poses a challenge for theory. The merger theory of elliptical galaxies needs to account for both the tightness of the fundamental plane (and the tighter size–luminosity relation) and the growth of compact elliptical galaxies which account for up to $\sim 50\%$ of the galaxy population at redshifts of 2–3 (van Dokkum et al. 2008). We compare our results to predictions from published simulations of dry mergers (Boylan-Kolchin et al. 2006). Figure 2 shows the predicted size–luminosity relationships in green for 1:1 mass dry mergers with various orbits which preserve a fundamental plane (although not necessarily with the observed slope). The size calculated by Boylan-Kolchin et al. (2006) is not a profile radius but the circular aperture enclosing half of the projected stellar mass, i.e., it is more comparable to R_{50} . The steepest relation (slope = 1.2) is for the most radial orbit, while the shallower relation (slope = 0.6) has the largest pericentric separation between the merging pair. While the curvature in R_e can be explained by radial dry merging,

⁶ This is also true when using the complete HB sample which probes higher luminosities.

the lack of curvature in R_{90} and R_{50} further suggests that R_e is more influenced by profile changes induced by mergers. The observed scatter (0.09 dex, see Table 1) in the R_{90} (R_{50})–luminosity relationship seems much too small to be consistent with the predictions of dry merger simulations. In fact, the observed scatter is consistent with the scatter due solely to orientation effects predicted by simulations (0.1 dex with 10^4 viewing angles, see Boylan-Kolchin et al. 2006). (Note that the scatter in luminosity is negligible assuming the galaxies are optically thin.) More worryingly, dry minor mergers are expected to introduce a similar and possibly larger scatter in size as do dry major mergers for a similar increase in mass (or luminosity; Nipoti et al. 2009). Variable gas fractions of the progenitors can introduce a further scatter in size (Robertson et al. 2006). It thus seems highly unlikely that major or minor mergers (either dry or wet) could be growing elliptical galaxies while preserving the slope and small scatter observed in the size–luminosity relation in both low- and high-density environments. In fact, current semianalytic hierarchical models of galaxy formation (Bower et al. 2006) are unable to reproduce the slope and scatter in the elliptical galaxy size–mass relationship in the local universe (Shankar et al. 2010).

The current prevailing theory of size growth of distant galaxies can be described as the development of an outer envelope which grows about a central dense “red nugget” (Damjanov et al. 2009), whose stellar density remains unchanged as the galaxy inflates (Hopkins et al. 2009; Bezanson et al. 2009; Damjanov et al. 2009). The most straightforward expectation (Bezanson et al. 2009) based on the virial theorem suggests that a minor merger will grow the size of a galaxy in direct proportion to the additional mass added to the total system by the galaxy being absorbed. There will be considerable scatter in the growth depending on the relative orbital configurations of the galaxies (Boylan-Kolchin et al. 2006). If minor mergers are driving this process, not only must the relative masses and orbital configurations of the merging systems be fine tuned in order to grow galaxies while maintaining the slope of the size–luminosity relationship at all redshifts (Nipoti et al. 2009), but the outcome must also preserve a negligible scatter about the fundamental line over two orders of magnitude in galaxy luminosity. Assuming a scatter of 0.07 dex in the size–mass relation, Nipoti et al. (2009) find their simulations rule out size growth larger than a factor of 1.9 by dry mergers.

In summary, it is concluded that the elliptical galaxy size–luminosity scaling relation determined using Petrosian R_{90} (or R_{50} or R_p) has a much smaller scatter than the same relation determined using the half-light radius R_e . The relation between the Petrosian luminosities and Petrosian-based radii of elliptical galaxies is a simple power law: $R_{90} \propto L^{0.6}$. The dispersion about this “fundamental line” in log–log space is found to be only 0.09 dex in size (0.36 mag in luminosity) in the local universe, smaller than that of the fundamental plane defined using the effective radius R_e . The “fundamental line” appears to be driven mainly by luminosity (or mass) and seems to be independent of environment with no curvature at higher luminosities. The observation that the structural properties of elliptical galaxies is both simple and independent of environment suggests that the theory of hierarchical growth of elliptical galaxies via mergers is not understood. Is our paradigm for galaxy formation merely cracked or is it broken?

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