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ON THE SIZE AND COMOVING MASS DENSITY EVOLUTION OF EARLY-TYPE GALAXIES

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ABSTRACT

We present a simple, empirically motivated model that simultaneously predicts the evolution of the mean size and the comoving mass density of massive ($> 10^{11}$ $M_\odot$) early-type galaxies from $z = 2$ to the present. First we demonstrate that some size evolution of the population can be expected simply due to the continuous emergence of early-type galaxies. The Sloan Digital Sky Survey (SDSS) data reveal that in the present-day universe more compact early-type galaxies with a given dynamical mass have older stellar populations. This implies that with increasing look-back time, the more extended galaxies will be more and more absent from the population. In contrast, at a given stellar velocity dispersion, SDSS data show that there is no relation between size and age, which implies that the velocity dispersion can be used to estimate the epoch at which galaxies stopped forming stars, turning into early-type galaxies. Based on this, we define an empirically motivated, redshift-dependent velocity dispersion threshold above which galaxies do not form stars at a significant rate, which we associate with the transformation into early-type galaxies. Applying this 'formation' criterion to a large sample of nearby early-type galaxies, we predict the redshift evolution in the size distribution and the comoving mass density. The resulting evolution in the mean size is roughly half of the observed evolution. Then we include a prescription for the merger histories of galaxies between the 'formation' redshift and the present, based on cosmological simulations of the assembly of dark matter halos. Such mergers after the transformation into an early-type galaxy are presumably dissipationless ('dry'), where the increase in size is expected to be approximately proportional to the increase in mass. This model successfully reproduces the observed evolution since $z \sim 2$ in the mean size and in the comoving mass density of early-type galaxies with mass $M > 10^{11}$ $M_\odot$. We conclude that the recently measured, substantial size evolution of early-type galaxies can be explained by the combined effect of the continuous emergence of galaxies as early types and their subsequent growth through dry merging.

Subject headings: galaxies: elliptical and lenticular, cD—galaxies: evolution—galaxies: formation—galaxies: fundamental parameters—galaxies: general

1. INTRODUCTION

Over the past five years it has become clear that early-type galaxies do not constitute a passively evolving population. Their predominantly old stellar populations notwithstanding, substantial evolution occurs up until the present day. The main evidence for such evolution is the increase in comoving mass density by a factor of about three from $z \sim 1$ to the present (e.g., Bell et al. 2004b; Brown et al. 2007; Faber et al. 2007). Recently, additional evidence for continuing structural evolution of the early-type galaxy population was provided by the observation that distant ($z > 1.5$), quiescent galaxies have much smaller sizes than early-type galaxies of the same stellar mass in the present-day universe (Daddi et al. 2005; Trujillo et al. 2006; Zirm et al. 2007; Toft et al. 2007; van Dokkum et al. 2008; Cimatti et al. 2008; Buitrago et al. 2008). This surprising result, raising questions about the evolutionary connection of these compact galaxies with present-day descendants, was recently put on firmer footing by van der Wel et al. (2008): using early-type galaxies with accurate dynamical masses, thus removing the most important systematic problem that may hamper the $z \sim 2$ results (the absolute uncertainty in the mass estimates), they inferred substantive size evolution, by a factor of ~ 2, at a given mass, between $z = 1$ and present. Recently, also Bernardi (2009) showed that size evolution continues up until the present day, and must be a smooth function of redshift. Although the remaining uncertainties are not negligible (see, e.g., Hopkins et al. 2009a), it has become clear that the observed size evolution cannot be explained by systematic uncertainties.

Because halos that collapsed at earlier epochs were denser, and gas-rich, dissipative processes were more important for galaxy formation, it has been argued that galaxies that formed early are smaller (e.g., Robertson et al. 2006; Khochfar & Silk 2006). In this scenario, because the number of early-type galaxies increases with cosmic time, and the more recently formed galaxies are larger, there is a direct connection between the size and comoving mass density evolution in the early-type galaxy population. This is true even without individual galaxies changing in size over time.

This paper explores the extent to which the growth of the population can account for the observed size evolution, and/or whether additional mechanisms to increase the size evolution of individual galaxies are required. As a proof of concept, we first investigate the present-day early-type galaxy population for clues that indicate that evolution in the mass-size relation may be expected purely due to evolution of the population, not size growth of individual galaxies. Are small/compact early-type galaxies older in terms of their stellar populations than large/extended early-type galaxies with the same mass? In Section 3 we show that this is indeed the case. Is there a parameter for which age and size are independent? Continuing along the track of previous work (e.g., Bernardi et al. 2005; Chang et al. 2006; Graves et al. 2008), which demonstrated that stellar velocity dispersion (σ_*) is the fundamental parameter behind well-known correlations such as the color-magnitude and mass-metallicity relations, we show that σ_* also correlates with, and perhaps drives, the age of the stellar population. This suggests that formation epoch and σ_* are related.

We cast this idea as an empirical relationship between the velocity dispersion of an early-type galaxy and the redshift $z_{\rm ET}$ at which it emerged as an early-type galaxy. This model to describe the population evolution of early-type galaxies allows us to predict which portion of the present-day early-type galaxy population already existed at a given redshift z. In turn, such a $\sigma_* - z_{\rm ET}$ relationship in conjunction with the present-day σ_* distribution thus describes the evolution with redshift of the properties of the population as a whole, in particular its size distribution. This is akin to the concept of 'progenitor bias' (van Dokkum & Franx 2001). As it turns out, a significant size evolution is expected even in the absence of size evolution of individual galaxies.

Then we continue and include a prescription for subsequent merging based on the cosmological simulations of the dark matter halo assembly by Li et al. (2007). The merger rates that we derive are in agreement with those found empirically (e.g., Bell et al. 2006; Lotz et al. 2008; Lin et al. 2008). Because we examine the merger history after the last, major episode of star-formation activity and the transformation into an early-type galaxy, by definition, these mergers are dissipationless or 'dry' (van Dokkum 2005; Bell et al. 2006; Naab et al. 2006). Under reasonable assumptions for the relationship between the properties of progenitors and descendants based on numerical simulations of merging, gas-poor progenitors (e.g., Ciotti & van Albada 2001; González-García & van Albada 2003; Nipoti et al. 2003; Boylan-Kolchin et al. 2005; Robertson et al. 2006), we can predict how individual galaxies grow. This evolution of individual galaxies is then superimposed on the evolution of the population (Section 4). A comparison with the observations allows us to investigate whether the continuous growth of the early-type galaxy population, with galaxies experiencing 'puffing' through dry mergers, is able to explain the observed size evolution with redshift, or whether other, perhaps unknown, physical mechanisms must play a significant role. Potential caveats, known problems, and testable predictions of our model are discussed in Sections 5 and 6. We adopt as cosmological parameters $(\Omega_{\rm M},\ \Omega_\Lambda,\ h, \sigma_8) = (0.3,\ 0.7,\ 0.7,\ 0.9)$.

2. SUMMARY OF HIGH-REDSHIFT OBSERVATIONS

Before describing and testing our model, we summarize the relevant high-redshift measurements that we seek to explain. These are the evolutions of the characteristic size and the comoving mass density of early-type galaxies from $z = 1$ and $z = 2$ to the present.

2.1. *The Early-Type Galaxy Population at $z \sim 1$*

Size evolution between $z \sim 1$ and the present has recently been measured by van der Wel et al. (2008), who found, at a given dynamical mass, $R_{\rm eff}(z) \propto (1+z)^{-0.98\pm0.11}$ for galaxies with masses $M > 10^{11}\ M_\odot$. This corresponds to $\delta R_{\rm eff}(1) \equiv R_{\rm eff}(1)/R_{\rm eff}(0.06) = 0.54 \pm 0.04$ ($z = 0.06$ is the center of the redshift bin in which we select our sample of nearby early-type galaxies described in Section 3 and will be used throughout as a benchmark).

The second observational quantity we compare our model with is the evolution of the comoving mass density ρ. We derive the change in the comoving mass density of early-type galaxies with masses larger than $10^{11}\ M_\odot$ from the evolution of the normalization (ϕ^*) of the luminosity function for red galaxies as measured by Faber et al. (2007). Even though not all massive, red galaxies have early-type morphologies, the fraction of early-type galaxies among these changes little between $z = 1$ and the present (e.g., Bell et al. 2004a; van der Wel et al. 2007). We assume that the characteristic mass at the 'knee' of the mass function $M^* = 7.1 \times 10^{10}\ M_\odot$ does not change, implying that the evolution in ϕ^* is identical to that in ρ. This assumption should hold because the evolution of the M/L, as derived from evolution of the fundamental plane zero point and the observed evolution of L^* cancel. However, it cannot be ruled out at this stage that M^* changes by ~ 0.1 dex. From the results presented by Faber et al. (2007), we derive that $\delta\rho(1) \equiv \rho(1)/\rho(0.06) = 0.35 \pm 0.13$ for galaxies with mass $M > 10^{11}\ M_\odot$, where the error includes an uncertainty of 0.1 dex in the evolution of M^*.

2.2. *The Early-Type Galaxy Population at $z \sim 2$*

The observational constraints at higher redshifts are far less secure than at $z \lesssim 1$ due to limited sample sizes and systematic uncertainties. Simply extrapolating the $z = 1$ size evolution measurement mentioned above to $z = 2$, without regard to other measurements, gives $\delta R_{\rm eff}(2) = 0.36 \pm 0.04$. Compiling all available data sets at higher redshifts (up to $z = 2.5$), van der Wel et al. (2008) found marginally faster evolution of $R_{\rm eff}(z) \propto (1+z)^{-1.20\pm0.12}$, i.e., $\delta R_{\rm eff}(2) = 0.29 \pm 0.04$. Assuming that the difference between the robust, but generously extrapolated, $z \sim 1$ results, and the direct, but systematically uncertain, $z \sim 2$ results is indicative of the true, systematic error, we conservatively adopt $\delta R_{\rm eff}(2) = 0.3 \pm 0.1$ as the most realistic estimate of the size evolution between $z = 2$ and the present. We note that all measurements have been obtained for galaxies with masses $M > 10^{11}\ M_\odot$. At lower masses samples are non-existent or severely biased.

The observational constraints on ϕ^* and hence ρ are less secure at $z \sim 2$ than at $z \sim 1$, again because of systematic uncertainties. The latest estimate by Marchesini et al. (2008) yields $\delta\rho(2.4) = 0.14^{+0.05}_{-0.08}$ for all galaxies with stellar masses larger than $10^{11}\ M_\odot$[1]. Other recent determinations (Elsner et al. 2008; Pérez-González et al. 2008) are consistent with this estimate. Kriek et al. (2008) have shown that already at

[1] The mass estimates in that study assume the Salpeter (1955) initial mass function for which, given the other uncertainties, the difference between stellar mass and dynamical mass is negligible for the mass range of interest here (van der Wel et al. 2006; Borch et al. 2006; Cappellari et al. 2006).

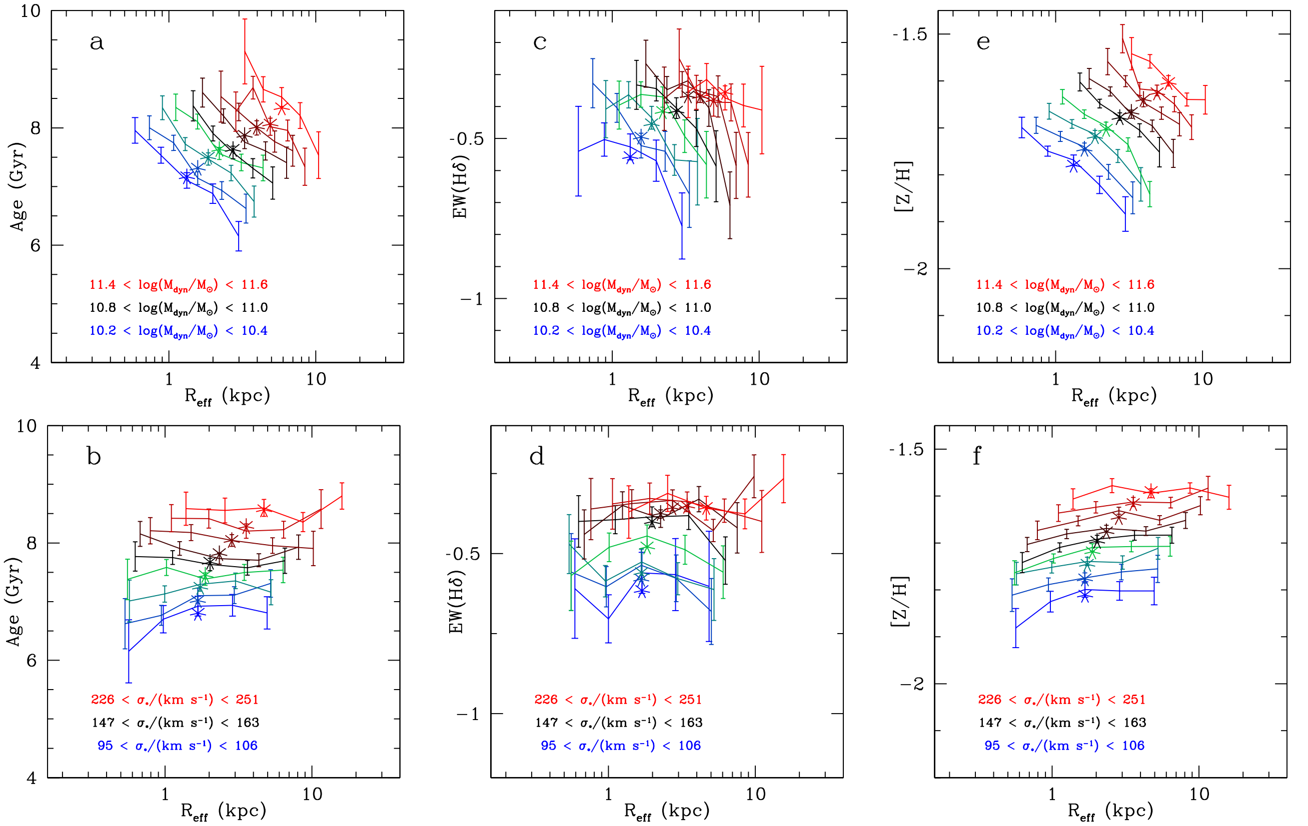

FIG. 1.— *(a)*: The age-size relation for present-day early-type galaxies in nine different dynamical mass bins. The age is the light-weighted stellar population age. The distance between the same-colored error bars is equal to the scatter (1σ) in size. The median size and age in each bin, indicated by the stars, both increase with mass (from blue to red), reflecting the well-known mass-age and mass-size relations. However, at fixed mass small galaxies are older than large galaxies. *(b)*: The age-size relation as in panel *(a)*, but here in nine bins of stellar velocity dispersion instead of $M_{\rm dyn}$. The same overall trend is seen in the sense that galaxies with high σ_* are, on average, larger and older than galaxies with low σ_*. However, at *fixed* σ_* the age-size trend differs importantly from that seen at fixed $M_{\rm dyn}$: age does not depend on size (or size does not depend on age) at fixed σ_*. *(c)* and *(d)*: The same as panels *(a)* and *(b)*, respectively, but with Hδ line strength instead of age along the y-axis. The trends are similar as those seen with age, albeit with larger uncertainties. Since Hδ is a robust age indicator, the similar behavior in this figure of Hδ and age demonstrates that the trends seen with age are not caused by model uncertainties in the age estimates, and cannot be artificial. *(e)* and *(f)*: The same as panels *(a)* and *(b)*, respectively, but with metallicity instead of age along the y-axis. As with age, there is no correlation between size and metallicity at fixed σ_*. We note that the size of the SDSS spectroscopic aperture cannot explain the observed trends (see Section 3.1 for details).

$z \sim 2.4$ the majority ($56\%^{+8\%}_{-12\%}$) of such massive galaxies have red colors, and that those show no or little evidence for star-formation activity. This number is somewhat lower than for the nearby massive galaxy population which has a red sequence fraction of 77%. In addition, despite the quiescent nature of the red $z \sim 2$ galaxies, it is as yet unclear what their morphologies are. They are barely spatially resolved, such that it is impossible to tell whether they have smooth surface brightness profiles, and constraints on the shape of their surface brightness profiles are rather poor, even though Toft et al. (2007) showed that exponential profiles are perhaps a better representation than De Vaucouleurs profiles. Given these constraints on the evolution of the red/early-type fraction among the massive galaxies at $z \sim 2$, we arrive at $\delta\rho(2.4) = 0.10^{+0.04}_{-0.06}$ as our best estimate of the comoving mass density of early-type galaxies at $z = 2.4$ with mass $M > 10^{11}\ M_\odot$.

3. A SIMPLE EMPIRICAL MODEL I: DENSITY REFLECTS FORMATION EPOCH

We develop an empirical estimate of the formation epoch of early-type galaxies based on the correlations between the global properties of the present-day population of early-type galaxies. In this approach, individual early-type galaxies are assumed not to evolve after their formation in either mass or size. A sample of 17,483 nearby early-type galaxies at redshifts $0.04 < z < 0.08$ has been constructed by Graves et al. (2008) from the Sloan Digital Sky Survey (SDSS) database (DR6, Adelman-McCarthy et al. 2008). Only galaxies with measured velocity dispersions, on the red sequence, either without emission lines or with high [OII]-to-Hα ratios and with concentration parameters $C > 2.5$ are included in the sample. These criteria effectively exclude star-forming galaxies, but include genuine early-type galaxies with nuclear activity (see Yan et al. 2006). For the description of the velocity dispersions and the determination of effective radii, as well as our dynamical mass estimator ($M_{\rm dyn} \propto R\sigma_*^2$), we refer to van der Wel et al. (2008). In addition, we require that luminosity-weighted stellar ages are available from Gallazzi et al. (2005); 16,279 out of 17,483 galaxies have such an age estimate.

3.1. *Correlations between Global Properties of Early-Type Galaxies*

It is well known that early-type galaxies with large masses and velocity dispersions have older stellar popula-

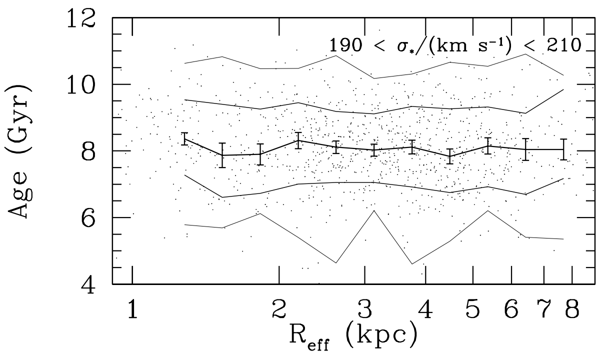

FIG. 2.— Size vs. stellar population age for present-day early-type galaxies in a narrow range of velocity dispersion. The line with the errorbars is a running median, while the other lines indicate the scatter (1σ and 2σ). The scatter is of order 10% and the residual from the running median does not correlate with any other parameter.

tions than those with low masses and velocity dispersions (Trager et al. 2000; Thomas et al. 2005; Gallazzi et al. 2006; Graves et al. 2007). In Figure 1a we also show that in our SDSS sample massive galaxies have older stellar populations. In the same figure, it can also be seen that, naturally, size increases with mass. As a corollary, we have that, loosely speaking, galaxies with large sizes have older stellar populations than galaxies with small sizes.

For these broad, global trends it does not matter what tracer of mass is adopted. Dynamical mass and velocity dispersion both show similar correlations with size and age (compare Figures 1a and 1b). However, the difference between the dynamical mass and the velocity dispersion comes to light when we dissect the sample, and look at the relation between age and size at fixed dynamical mass or at fixed velocity dispersion. At a fixed dynamical mass, there is an anti-correlation between size and age: large galaxies have younger stellar populations than small galaxies (Figure 1a). This trend persists over a mass range of almost two orders of magnitude, from $\sim 10^{10}\ M_\odot$ to $\sim 10^{12}\ M_\odot$, and there is no clear indication that the slope of the age-size relation depends on mass.

The correlation between age and size at fixed mass implies that the zero point and scatter of the mass-size relation will evolve with redshift, even if we assume that individual galaxies do not change in size. This is simply due to the fact that larger, younger galaxies did not exist yet at earlier epochs. This is, in essence, the model prediction made by Khochfar & Silk (2006). The result shown in Figure 1a provide the first empirical evidence for this process.

It is perhaps surprising that the picture changes quite dramatically if we look for an age-size relation for galaxies with a given velocity dispersion. In Figure 1b, it can be seen that at a given velocity dispersion there is no evidence that small galaxies are older than large galaxies. On the other hand, if one realizes that $M_{\rm dyn} \propto R_{\rm eff}\sigma_*^2$, the size-age relation has to be flatter at fixed σ_* than at fixed $M_{\rm dyn}$ (or may even be reversed). The fact that the relation should disappear altogether at fixed σ_* is, however, not obvious. In Figure 2, we show for one particular narrow bin around $\sigma_* = 200\ \ {\rm km\,s^{-1}}$ the size-age distribution. Again, there is no sign that age depends on size (or vice versa). Moreover, the scatter is remarkably uniform and rather small ($\sim 10\%$). We could not identify a parameter that correlates with the residual in the size-age relation at fixed σ_*. This includes environment: using the Yang et al. (2007) SDSS group catalog, we find that the scatter in age does not correlate with group membership, the mass of the group, the distance to the group center, or whether galaxies are centrals or satellites (see also, van den Bosch et al. 2008b).

The age estimates are unavoidably model dependent, and may therefore be hampered by systematic uncertainties. In Figure 1c and 1d we replace stellar population age by Hδ absorption line strength. The strength of this Balmer line is relatively insensitive to metallicity and is therefore a good tracer of age. Although the random uncertainties are substantially larger, the picture remains the same: at fixed dynamical mass the Hδ line is stronger for larger galaxies, implying a younger stellar population, whereas at fixed velocity dispersion there is no correlation between size and line strength. We conclude that the trends with stellar population age in Figure 1a and 1b are robust and not artificial.

In Figures 1e and 1f, we show the correlation between size and metallicity. As with age, for the population as a whole there is a positive correlation between size and metallicity, as expected from the combination of the mass-metallicity relation and mass-size relations. At fixed velocity dispersion (Figure 1f), however, there is no correlation between size and metallicity, which is consistent with the idea that the velocity dispersion traces the potential well depth. By necessity, we also find that at fixed dynamical mass, the metallicity is smaller for large galaxies (see Figure 1e).

The SDSS spectroscopic aperture does not sample the entire galaxy; therefore, some aperture effects may be expected: age and metallicity gradients could introduce artificial trends in Figure 1. However, aperture effects would cause a positive correlation between age/metallicity and size, not the observed anticorrelation. Therefore, we conclude that aperture effects do not strongly affect our analysis.

The emerging picture is consistent with previous work. It has been shown that at fixed σ_* there is no color-magnitude relation (Bernardi et al. 2005; Graves et al. 2008), which indicates that velocity dispersion, more so than luminosity, determines the properties of the stellar population, unless some sort of conspiracy renders trends invisible. However, this possibility is excluded by the lack of a trend in Figures 1b, 1d, and 1f. In addition, Chang et al. (2006) find that, at fixed velocity dispersion, there is almost no correlation between stellar mass and absorption line indices.

Very recently, several authors have noted similar trends (or lack thereof) as in our Figure 1. Graves et al. (2009) show that, at fixed velocity dispersion, age and metallicity do not correlate with galaxy size (see our Figures 1b and 1f). Moreover, Shankar & Bernardi (2009) derive the same trend that we show in Figure 1a: at fixed mass, old galaxies are smaller than young galaxies.

Furthermore, Bell & de Jong (2000) and Kauffmann et al. (2004) showed that for any type of galaxy, stellar mass surface density is a better predictor than stellar mass of the star-formation history and current star-formation activity, and surface density is closely related to velocity dispersion. This was made explicit by Kauffmann et al. (2006), who showed that there is a sharp transition in the fraction of quiescent versus star-forming galaxies at particular values of both surface density and velocity dispersion.

These previous results and our result that age and size at a given σ_* are uncorrelated (Figure 1b) tell us something about the significance of σ_* as a (and perhaps *the*) fundamental characteristic of a galaxy. We now pursue the idea that σ_* can be used as a predictor of the epoch when star formation was truncated and an early-type galaxy emerged.

3.2. *The Formation Epoch of Early-Type Galaxies*

As a starting point, we take the observation by Kauffmann et al. (2006) that at the present epoch the transition between star-forming and quiescent galaxies takes place at $\sigma_* \sim 125\,\mathrm{km\,s^{-1}}$. Truncation of star formation may be associated with the morphological transformation to an early-type galaxy, and so we may suppose that newly formed early-type galaxies in the present-day universe have a velocity dispersion of $\sigma_{\rm ET} = 125\,\mathrm{km\,s^{-1}}$. This transition is not infinitely sharp; in reality there are late-type galaxies with higher σ_* and early-type galaxies with lower σ_*. We ignore this scatter in our model, but in Section 5.1 we will briefly comment on the consequences for our model predictions.

Given such a velocity dispersion threshold for star-formation activity in the present-day universe, we may expect that such a threshold existed at earlier epochs as well, but not necessarily with the same value. The relation between age and velocity dispersion (Figure 1b) implies that $\sigma_{\rm ET}$ would have had to be higher in the past. Observational evidence for the existence of $\sigma_{\rm ET}$ at high redshifts was recently found by Franx et al. (2008), who used data extending to $z \sim 3$ to show that there exists a surface mass density threshold, $\Sigma_{\rm ET}$, above which star-formation activity drops suddenly and significantly. Interestingly, this threshold was shown to be larger at higher redshifts. We parametrize the velocity dispersion threshold for the truncation of star formation and the transformation into an early-type galaxy as follows:

$$\sigma_{\rm ET}(z) = 125\,\mathrm{km\,s^{-1}}\ (1+z)^{\alpha}. \tag{1}$$

Consequently, given the velocity dispersion of a galaxy we can estimate the redshift at which its star formation was truncated and it attained its early-type morphology:

$$z_{\rm ET}(\sigma_*) = \left(\frac{\sigma_*}{125\,\mathrm{km\,s^{-1}}}\right)^{1/\alpha} - 1. \tag{2}$$

Although precise constraints on the amount of evolution are still lacking due to systematic errors and small sample sizes, the results from Franx et al. (2008) imply that α must lie in the range $1/4 \lesssim \alpha \lesssim 3/4$. In the following, we will adopt $\alpha = 3/4$ as the standard value, which turns out to provide the best results. We will discuss the dependence of our results on the chosen value and the range allowed by the data in Section 5. We note that the redshift dependence of $\sigma_{\rm ET}$ is consistent with the long-standing result from fundamental plane studies at high redshift that high-mass galaxies have stellar populations with high formation redshifts ($z \gtrsim 2$, see van Dokkum & van der Marel 2007, and references therein), and also with the observation that this formation redshift depends on mass, low-mass galaxies having younger stellar populations epochs (van der Wel et al. 2005; Treu et al. 2005). In addition, this is in agreement with archaeological studies of nearby early-type galaxies (e.g., Thomas et al. 2005; Gallazzi et al. 2008).

To quantify the model predictions for earlier epochs, we apply Equation 1 to our nearby galaxy sample, only retaining those with $\sigma_* > \sigma_{\rm ET}(z)$ as galaxies that were early types already at redshift z. In Figure 3 we show how the early-type galaxy population would build up at different present-day masses for $\alpha = 3/4$. Half of the galaxies with present-day masses exceeding $10^{12}\ M_\odot$ had become early types by $z \sim 2$, while half of those with masses exceeding $10^{11}\ M_\odot$ had become early types by $z \sim 1$. This behavior is reminiscent of the predictions by, e.g., De Lucia et al. (2006) and Neistein et al. (2006), who also predict that massive galaxies formed their stars earlier than less massive galaxies.

In addition to comoving mass density evolution, Equation 2 also implies size evolution at fixed dynamical mass: at a given mass, large galaxies have smaller velocity dispersions and therefore became early-type galaxies more recently. Figure 4 shows the predicted evolution in the size distribution from the present to $z = 1$ and $z = 2$. The behavior of the model is straightforward: at progressively higher redshifts the minimum velocity dispersion of a galaxy (the dotted lines in Figure 4) is higher, as defined by Equation 1. The resulting evolution in both the number of galaxies and their size distribution can readily be seen. How does this model compare with the observations described in Section 2? For $z = 1$, we find $\delta\rho(1) = 0.61$ and $\delta R_{\rm eff}(1) = 0.81$, both for galaxies with mass $M > 10^{11}\ M_\odot$, and where the latter is the average offset from the local mass-size relation, computed in log-space. The actually observed evolution is faster (see Section 2.1 and Figure 5), significantly for the evolution in average size and marginally for the mass density evolution. For $z = 2$ the model predicts $\delta\rho(2) = 0.09$ and $\delta R_{\rm eff}(2) = 0.71$. The comoving mass density in this case agrees well with the observed value. The observed size evolution, however, is much stronger than this model predicts (see Section 2.2 and Figure 5).

Despite the quantitative disagreements, it is encouraging that this model, which only prescribes a redshift-dependent σ-threshold when galaxies stop forming stars and become early types, implies trends in the right direction. These results suggest that the continuous 'top-down' emergence of new early-type galaxies can explain roughly half of the observed size evolution, with individual galaxies not changing after their initial transformation. However, an indication that individual galaxies must change as well was recently found by Trujillo et al. (2009): the local abundance of galaxies with the same properties as the compact, high-redshift objects is very low, implying that such galaxies did not survive in their original form. It is clear that size evolution of individual galaxies has to occur as well.

4. A SIMPLE EMPIRICAL MODEL II: GROWTH THROUGH MERGERS

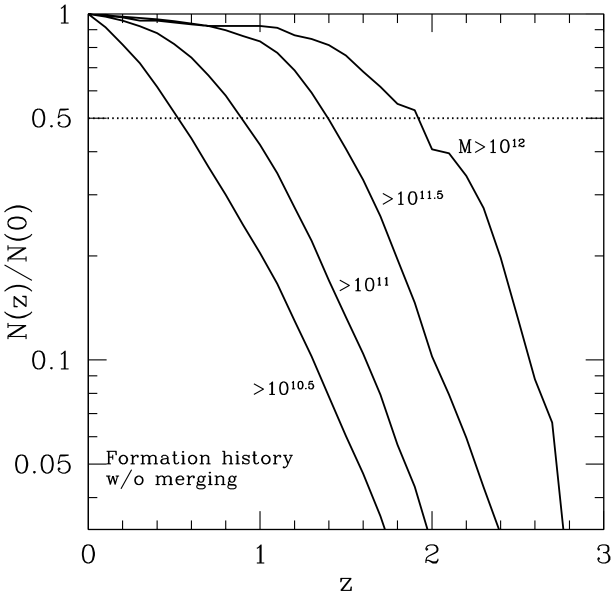

FIG. 3.— Predicted evolution with redshift of the comoving number density of early-type galaxies with different masses based on the velocity dispersion threshold specified in Equation 2. The horizontal dotted line indicates a fraction of 50%. High-mass galaxies emerged as early-type galaxies earlier than low-mass galaxies. Note that this evolutionary picture does not include merging, as described in Section 4.

We now augment the simplistic model from Section 3 by a prescription to include subsequent merger activity of galaxies after the epoch of transformation into early types. After constructing merger histories, we describe how mergers affect, in our model, the masses, sizes, and velocity dispersions of early-type galaxies.

4.1. *Merger Histories*

After they become early types, galaxies still undergo subsequent evolution in terms of merging and/or minor episodes of star-formation activity, without changing their overall morphological properties, apart from, perhaps, brief periods of time after accretion events. That this can lead to substantial size evolution has been shown by Naab et al. (2007). To include such evolution schematically into our model we implement merger histories based on simulations of dark matter halo assembly from Li et al. (2007).

Following Li et al. (2007), we define n as the inverse of the fractional mass increase in a merger. In other words, if the mass of the main progenitor is M_i, then the mass of the merger remnant is $M_f = (1 + 1/n)M_i$. The Li et al. (2007) simulations demonstrate that the number of mergers does not depend on n, i.e., the probability distribution of n is flat. To realize merger histories we can therefore assume a series of accretion events with randomly chosen n. We verify this simplified approach by attempting to reproduce the merger histories that Li et al. (2007) inferred, starting with seed halos that have 1% of their present-day mass. When we allow mergers in the range $1 < n < 100$, we construct an ensemble of merger histories with the same number of mergers with $n < 3$, $n < 4$, and $n < 6$ as found by Li et al. (2007); see their Figures 11 and 12. In addition, our scatter in the number of such mergers is also close to that found by Li et al. (2007). We conclude that it is sensible to approximate the merger histories of dark matter halos by assuming a series of merger events with randomly chosen n in the range $1 < n < 100$.

Since we are not interested in the merger history of a halo growing from 1% of its present-day mass, but rather in the merger history of a halo between $z = 1$ or $z = 2$ and the present, we need to know by how much halos grow over that period of time. Contrary to the distribution of n, the growth with time depends on halo mass (van den Bosch 2002; Wechsler et al. 2002). We focus on halo masses in the mass range $M_{\rm halo} = 10^{12} - 10^{13} M_\odot$, which corresponds to the halo masses of galaxies with masses in the range $M \sim 10^{11} - 10^{12} M_\odot$. In the Li et al. (2007) simulations, halos in this mass range had assembled $\sim$ 50% of their present-day mass by $z = 1$ ($M_{z=1} = M_{z=0}^{-0.30\pm0.09}$, where 0.09 is the scatter), and $\sim$ 30% by $z = 2$ ($M_{z=2} = M_{z=0}^{-0.55\pm0.28}$).

Combining the elements discussed so far, we have the following practical method to construct the possible merger history between $z = 1$ and the present for a halo with present-day mass M. We assume a series of mergers with mass ratios $1/n_i$, with $1 < n_i < 100$ a sequence of randomly chosen real numbers. For example, the most recent merger involved a main progenitor with mass $n_1 M/(n_1 + 1)$ and a minor (or, accreted) progenitor with mass $M/(n_1 + 1)$. The main progenitor is, in turn, assumed to be the product of a merger with ratio $1/n_2$. The main progenitor is followed in this manner, assuming a sequence of mergers with ratio $1/n_i$, up until the point that the expected mass for the main progenitor at $z = 1$ is reached. This expected mass is $M_{z=1} = M_{z=0}^x$, where x is drawn from a Gaussian distribution with a mean -0.30 and a standard deviation 0.09. To construct the merger history between $z = 2$ and the present, the only difference is that we choose x from a Gaussian distribution with mean -0.55 and a standard deviation 0.28. In practice, in order to conserve mass, the mass ratio of the final event is rounded such that the $M_{z=1}$ is precisely $M_{z=0}^x$. In case $x > 0$, which we formally allow, we assume that no mergers have occurred.

This process describes the merger history of a halo. van den Bosch et al. (2008a) found that the vast majority of the galaxies in the mass range of interest here should be central galaxies. We, therefore, assume that the merger history of the halo directly corresponds to the merger history of the galaxy. We incorporate one exception to this rule into the model: mergers involving halos with mass $M_{\rm halo} < 10^{11}\ M_\odot$ do not increase the mass of the galaxy, but only the mass of the halo. This takes into account that such small halos contain a much smaller fraction of stars (e.g., Cooray & Sheth 2002; van den Bosch et al. 2007). The growth in galaxy mass is therefore somewhat slower than the growth in halo mass. As it turns out, our model predictions are not strongly affected by this. In Section 5.2, we discuss the effect of possible delays between mergers between halos and mergers between their occupying galaxies.

For each galaxy in the nearby sample, we construct a Monte Carlo realization of its merger history as described above, which predicts by how much the mass of the main galaxy grows between $z = 1$ ($z = 2$) and the present, and how the accreted mass is distributed over a number of ad-

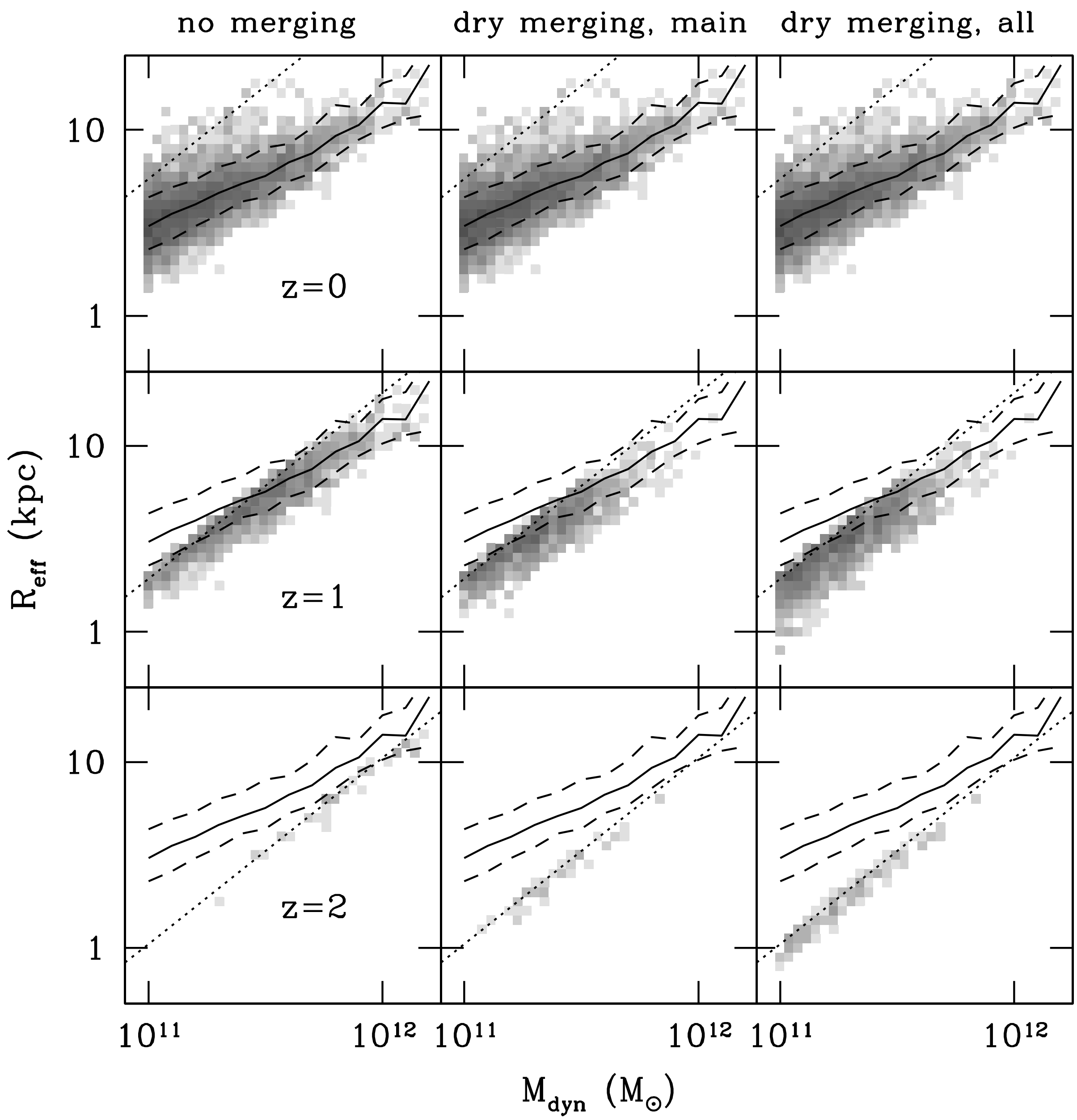

FIG. 4.— Predicted redshift evolution of the mass-size relation. The left-hand column of panels shows the predicted evolution for the model described in Section 3.2, i.e., without merging. The model presented in the middle column includes merging as described in Section 4.3, only considering the main progenitors of present-day early-type galaxies. The model presented in the right-hand column includes, in addition, all progenitors, as described in Section 4.4. The top row (in which all panels are identical) shows the observed, local mass-size relation, which is the starting point of our model, the gray-scale corresponding to the number of galaxies. The solid line is a running median, and the dashed lines indicate the scatter (1σ). These lines are repeated in every panel to guide the eye. The diagonal dotted line corresponds to $\sigma_* = 125\ \mathrm{km\,s^{-1}}$, which is the present-day velocity dispersion threshold, σ_{ET}, for the formation of early-type galaxies according to Equation 1. The middle row shows the predicted mass-size relation for $z = 1$. The dotted line now corresponds to $\sigma_* = 210\ \mathrm{km\,s^{-1}}$, which is σ_{ET} at $z = 1$. The lighter gray scale reflects the evolution in the number of galaxies. In addition, their size distribution is different. The bottom row shows the predicted mass-size evolution for $z = 2$, where $\sigma_{\mathrm{ET}} = 285\ \mathrm{km\,s^{-1}}$. In our model, the effect of dry mergers is that galaxies move parallel to the dotted lines, i.e., σ remains constant (see Section 4).

ditional progenitors at $z = 1$ ($z = 2$). Hence, we have two sets of merger trees: one that describes the $z = 1$ progenitors and another that describes the $z = 2$ progenitors. The average number of mergers per galaxy with mass ratios exceeding 1:2 is ~ 0.25 between $z = 1$ and the present (~ 0.55 between $z = 2$ and the present); the average number of mergers with mass ratios exceeding 1:4 is ~ 0.40 (~ 0.90). Note that whereas the dry merger rate per unit time *per early-type galaxy* was higher in the past, the dry merger rate per unit time and *per unit comoving volume* was smaller due to the strong evolution in the comoving density of early-type galaxies. The merger rates in our model are consistent with or lower than the available observational constraints on the dry merger rate between $z \sim 1$ and the present (Bell et al. 2006; Lotz et al. 2008; Lin et al. 2008).

4.2. *The Effect of Dry Mergers on Galaxy Sizes*

A crucial part of the model is the effect of merging on the sizes of galaxies. Because we are interested in the merger history of galaxies that are already early types, we focus on dissipationless (dry) merging. According to most numerical simulations the remnants of gas-poor mergers of equal-mass progenitors situated in dark halos have roughly twice the size of those progenitors (e.g., Ciotti & van Albada 2001; González-García & van Albada 2003; Nipoti et al. 2003; Robertson et al. 2006); yet Boylan-Kolchin et al. (2005) find that the size of the remnant is typically only 1.5 times that of the progenitors. This difference may, in some cases, be explained by the assumed orbits: the bound orbit used by Boylan-Kolchin et al. may be responsible for remnants that are smaller than found by, e.g., Ciotti et al., who use a parabolic orbit. However, not all simulations with bound orbits lead to small remnants (e.g., Robertson et al. 2006), such that the reason for the discrepancy is not completely clear. In agreement with the majority of the predictions, we assume that equal-mass, dry merger products have double the size of the progenitors (see Section 5 for further discussion). The virial theorem then implies that the velocity dispersion remains constant, supported by the numerical simulations. Moreover, the results of González-García & van Albada (2003) and Nipoti et al. (2003) suggest that for a dry merger with any mass ratio the size of the main progenitor increases linearly with mass, keeping its velocity dispersion constant. The implied decrease in surface brightness is such that mergers of this kind move galaxies roughly, but not precisely, along the fundamental plane (see, e.g. Robertson et al. 2006). This is reassuring because scenarios in which this is not the case are difficult to reconcile with the observed tightness of this scaling relation (e.g., Rix et al. 1994). These considerations allow us to directly and linearly link the growth in mass and size in our merger scenario.

4.3. *The Evolution of the Main Progenitors*

First, we investigate the evolution of the main progenitors in the merger scenario described above, ignoring the smaller progenitors. Because we assume that mergers do not alter the velocity dispersion of the main progenitor, it is straightforward to combine the predicted merger history from Section 4.1 with the formation redshift criterion described in Section 3.2. Figure 4 shows how the evolution in the number of early-type galaxies and their size distribution is altered when we augment the $\sigma_{\rm ET}$ model from Section 3 by dry merging, only considering the main progenitors. Relative to the scenario without merging, the number of high-mass galaxies decreases more rapidly with redshift, while the number of lower-mass galaxies decreases less rapidly. The average difference in size is predicted to be somewhat larger than in the absence of merging. The agreement with the observations improves considerably (see Figure 5): The merger model now predicts a redshift evolution of $\delta R_{\rm eff}(1) = 0.68$ and $\delta R_{\rm eff}(2) = 0.45$ for the average size at a given mass, and $\delta\rho(1) = 0.38$ and $\delta\rho(2) = 0.03$ for the comoving mass density. The agreement with the observations is not perfect though; the observed evolution of the mean size is still $\sim 30\%$ faster than predicted.

4.4. *The Properties of Accreted Progenitors*

At redshifts $z \lesssim 1$, when few major mergers occur and the growth of halos is relatively slow, it is probably sufficient to consider only the main progenitors, as we did in the previous section. However, at higher redshifts, when major mergers are more frequent and halos grow fast, this simplification may become inappropriate. It is, therefore, also necessary to include the smaller progenitors in the analysis and assess the question how their masses and sizes affect the evolution of the population averages. In the following we do not consider merger activity of the smaller progenitors before their accretion onto a larger object; thus, some of the uncertainty remains.

We make two assumptions regarding the properties of the minor progenitors. First, because we are mainly interested in dry merging, we assume that all progenitors are early-type galaxies. Second, we assume that the velocity dispersions of all progenitors are equal to the dispersion of the main progenitor, and therefore also equal to that of the final descendant (see Section 4.2). The second assumption is seemingly quite extreme and is obviously not valid for minor mergers. However, since the goal is to predict only the abundance and sizes of progenitors with mass $M > 10^{11}\ M_\odot$, this is not necessarily a problem. Moreover, Equation 1 implies that, in our model, all early-type galaxies at any epoch have a minimum velocity dispersion, $\sigma_{\rm ET}$. At redshifts $z \sim 2$, where smaller progenitors matter, the number of early-type galaxies is a rapidly declining function of velocity dispersion such that most galaxies available for dry merging will have comparable velocity dispersions. Thus, given the characteristics of our model so far, it is defensible that galaxies that partake in mergers at $z \sim 2$ with mass ratios 1:3 or 1:4 have similar velocity dispersions.

The population of smaller progenitors by definition have smaller masses than the population of main progenitors. Their inclusion will mostly affect the predicted comoving mass density evolution at $z = 2$ (see Figure 4). Quantitatively, the model predicts $\delta\rho(1) = 0.45$ and $\delta\rho(2) = 0.05$, both consistent with the data (see Figure 5). The effect on the predicted evolution in average size at fixed mass is less pronounced: the model predicts $\delta R_{\rm eff}(1) = 0.63$ and $\delta R_{\rm eff}(2) = 0.40$, not much slower than observed (the remaining disagreement is of order $1 - 2\sigma$).

Overall, it is quite remarkable that such a simplistic estimate of the redshift at which galaxies transform into

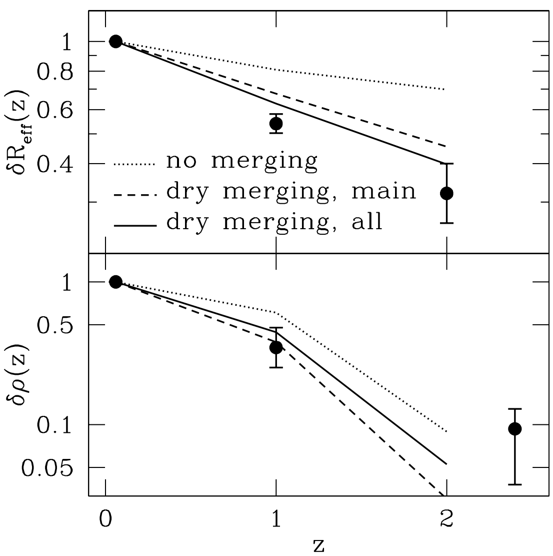

FIG. 5.— Comparison of the observations described in Section 2 (points with error bars) with the model predictions for redshift evolution of the average size and fixed mass (the top panel) and the total, comoving mass density (the bottom panel) for all early-type galaxies with mass $M(z) > 10^{11}\ M_{\odot}$. The dotted, dashed, and solid lines refer to different versions of our model, as in Figure 4. The dotted line represents the model without merging (Section 3.2); the dashed line represents the model with merging, only considering the main progenitors (Section 4.3); and the solid line represents the standard version of our model, including merging and considering all progenitors (Section 4.4). Our dry-merging model successfully reproduces both size and mass density evolution from $z = 2$ to the present.

early types and the simple assumptions regarding their subsequent merger activity can come so close to reproducing the observations.

5. MODEL UNCERTAINTIES

The model presented in Sections 3 and 4 is a drastically simplified description of the formation and evolution of early-type galaxies. In this section we describe some of the uncertainties that arise from the simplifications and their potential impact on the model predictions.

5.1. *Uncertainties in the Estimate of the Formation Epoch*

As stated in Section 3.2, the value of the exponent in Equations 1 and 2 was chosen *a posteriori*, $\alpha = 3/4$ producing the best results. The model predictions are quite sensitive to the choice of α. Trying a range of values for α, we find that, for the 'standard' version of our model as described in Section 4, in order to be consistent with all data at the 2σ level, the exponent has to have a value in the range $0.65 < \alpha < 0.85$. This is consistent with the results of Franx et al. (2008). For lower values of α we find, in particular, that the predicted evolution of the mean size is slower than observed. For higher values the predicted comoving mass density at $z \sim 2$ is lower than observed. Clearly, if we change the prescription for merging (see Sections 5.2 and 5.3), the allowed range for α also changes; however, in order for the model to remain consistent with the observed evolution of the comoving mass density, α has to be close to 0.75.

A related problem is a possible systematic uncertainty in the velocity dispersions of nearby early-type galaxies. This remains to be an issue, especially for the most massive galaxies (Bernardi 2007). Even a 5% systematic error has major consequences for the $z = 2$ predictions because the number of galaxies with high dispersions declines very rapidly with increasing dispersion. This implies that the formation-redshift distribution is rapidly, and perhaps artificially, truncated as well. Increasing all velocity dispersions by 5% leads to a higher comoving mass density at $z = 2$ by as much as a factor of 3 (while the increase at $z = 1$ is just 10%), whereas size evolution is only slowed down by less than 5% over the entire redshift range. We conclude that the predictive power of our model regarding the comoving mass density evolution at $z \sim 2$ is likely limited by systematic uncertainties in the velocity dispersions of massive nearby galaxies.

A further simplification in our model is that there is no scatter in the relationship between velocity dispersion and formation redshift. As a result, the predicted comoving mass density evolution will be overestimated, particularly at $z \sim 2$ where the model predictions depend strongly on the steepness of the mass function. It is beyond the scope of this paper to properly implement such scatter, as this would require a more advanced synthesis between the formation epoch and merger history of the galaxies in our simulated samples.

Finally, we assume that the truncation of star formation coincides with a morphological transformation. Even though those events may have the same cause, they need not occur simultaneously.

5.2. *Uncertainties in the Estimated Merger Histories*

We make the approximation (see Section 4.1) that the merging of dark matter halos is followed by the merging of the galaxies within $\Delta t << t_{\rm Hubble}$ due to dynamical friction. In reality, galaxies occupying merging halos may merge not at all, such as in the case of infall of a galaxy-sized halo into a cluster-sized halo, or they may merge quickly, such as in the case of two galaxy-sized, equal-mass halos. Generally speaking, the larger the mass-ratio of a halo-halo merger, the longer the delay of the galaxy-galaxy merger (see, e.g., Boylan-Kolchin et al. 2008; Kitzbichler & White 2008). It may, therefore, be necessary to invoke a delay for galaxy mergers with respect to halo mergers. To obtain an upper limit, we test the effect of a long, 2.5 Gyr delay on our model predictions, which is of the same order as the Hubble time at high redshift, and amounts to a few times the dynamical time scale of large clusters. In practice, this means that the galaxy merger activity between $z = 1$ and the present reflects halo merger activity between $z = 2$ and $z = 0.2$. As a consequence, major merger activity (with mass ratios of 1:2 or less) is boosted substantially from 0.25 to 0.5 mergers per galaxy between $z = 1$ and the present. This results in the stronger size evolution ($\delta R_{\rm eff}(1) = 0.57$ and $\delta R_{\rm eff}(2) = 0.35$) which would be in excellent agreement with the data (see Figure 5). Both the observational and model uncertainties are too large, however, to draw the conclusion that a delay in galaxy merger activity is preferable, especially because the mass dependence of this phenomenon is not taken into account.

A merger delay for the galaxies under consideration may indeed not be of great importance, as cosmological simulations that explicitly treat galaxy mergers as separate from halo mergers find similar merger rates for galaxies as we find for halos (Maller et al. 2006; Khochfar & Silk 2008). This, along with our finding that any merger delay only increases the redshift evolution of the mean sizes (i.e., our model in this sense provides a lower limit), implies that our conclusions are not compromised by the simple assumption that galaxies mergers are instantaneous reflections of halo mergers.

5.3. *Uncertainties in the Properties of Progenitors*

Our modeling assumes that in a dry merger, the size of the main progenitor grows proportionally to its mass increase. We justify this choice in Section 4, but it is useful to discuss its effect on the model predictions. If a substantial amount of orbital energy were transferred from the stellar component to the dark halo, the descendant would be more tightly bound than the progenitors. This would result in a fractional size change less than that in mass, which is what Boylan-Kolchin et al. (2005) find in their simulations. The results from Boylan-Kolchin et al. (2005) in fact suggest that dry mergers move galaxies along the slope of the present-day mass-size relation, in which case no redshift evolution in size at fixed mass due to merging would be expected. Our approach implies that no energy is transferred to the halo, resulting in large, relatively loosely bound merger remnants (with an unchanging velocity dispersion), in agreement with most other simulations (see Section 4.2). This is why mergers play an important role in shaping the early-type galaxy population in our modeling. Conversely, we would infer that the strong redshift evolution of the mean size implies that the amount of energy transferred to the halo must be small.

The above arguments make it very clear that our model would not work without the assumption that galaxies, at least the main progenitors, grow in size more or less proportional to their mass. The properties of the smaller progenitors before merging with the main progenitors are a separate, but related issue. In Section 4.4 we justified our assumption that all progenitors partaking in a merger have nearly the same velocity dispersion. This breaks down at lower redshifts, where a reservoir of galaxies with a large range in mass (and dispersion) is available for merging. It is therefore useful to test the sensitivity of the model predictions on this assumption. To do so, we consider the following alternative scenario: the smaller progenitors follow the present-day mass-size relation with respect to the main progenitor, i.e., we assume that their size ratios are $(M_{\rm accr}/M_{\rm main})^{0.56}$ (Shen et al. 2003; van der Wel et al. 2008). The virial theorem requires lower velocity dispersions for the smaller progenitors than for the main progenitor. By comparing this lower velocity dispersion with the threshold associated with the particular redshift that is being simulated (i.e, $z = 1$ or $z = 2$), we can decide in a very natural manner within the context of our model whether the smaller progenitor is a late-type galaxy or an early-type galaxy. If it has such a low dispersion that the implied formation redshift according to Equation 2 is lower than the simulated redshift, it is omitted from the sample, otherwise it is retained. Despite the substantially different approach, this exercise has a limited effect on the model predictions. The predicted size evolution is $\sim 10\%$ slower, and the predicted comoving mass density evolution $\sim 10\%$ faster. We conclude that the assumptions regarding the properties of the smaller progenitors are not of crucial importance to the model predictions.

It is, in principle, possible that in a (minor) merger the relative increase in size is larger than the relative increase in mass. In the case of virialized progenitors and remnants, homology, and zero energy transfer between the stars and the dark matter halo, following the analytical work of Boylan-Kolchin et al. (2005), we derive that the ratio of the radii of the merger remnant (R_r) and the main progenitor (R_m) is

$$\frac{R_r}{R_m} = \frac{(1+n)^2}{n^\alpha + n^2}, \tag{3}$$

where n, as before, is the mass ratio of the main progenitor and the accreted progenitor, and α is the slope of the mass-size relation for the progenitors ($R \propto M^\alpha$). For $n \to \infty$, we have that $R_r/R_m \to 1 + 2/n$ (for $\alpha < 1$), implying that for minor accretion events, the relative increase in size is close to twice the increase in mass (see also, Naab et al. 2009). This may provide an explanation for the evolution of the most compact galaxies in the observed $z > 2$ samples (e.g., Zirm et al. 2007; van Dokkum et al. 2008), which our model does not reproduce. The difficulty in the context of our model, however, is that knowledge of the nature of very small accreted galaxies, which in this scenario would be the main contributors to size evolution, becomes essential. It seems unrealistic to suppose that low-mass galaxies are not gas rich and are not forming stars. As a consequence, mergers will be dissipative, with a different effect on the evolution of the scaling relations (see, e.g., Robertson et al. 2006; Ciotti et al. 2007; Hopkins et al. 2009b). A more complete description of the merger history of galaxies, including a prescription for dissipation, will be required to fully explore the role of mergers with large mass ratios. However, if energy transfer to the halo is a minor factor, the large number of expected minor accretion events could be a viable explanation for the most compact, observed galaxies at $z > 2$.

If minor mergers that are gas poor dominate the growth of early-type galaxies, size evolution can be regarded as the assembly of a low-density envelope around a high-density central region. In such a scenario, the compact, high-redshift galaxies survive as the centers of present-day, massive galaxies. The properties of the centers of local early-type galaxies and the distant compact galaxies are, indeed, not significantly different (Bezanson et al. 2009; Hopkins et al. 2009a). On the other hand, there is no indication that the outer envelopes of early-type galaxies, the wings of De Vaucouleurs-type surface brightness profiles, have evolved since $z \sim 1$ (van der Wel et al. 2008). We conclude that it is thus far unclear, from an empirical perspective, what the relative contributions of major and minor merging are.

Summarizing, there are two elements of the model that are essential to any success in explaining the observations: first, the evolving velocity dispersion threshold which is associated with the formation of early-type galaxies; second, the growth of the main progenitor of present-day early-type galaxies by means of the accretion of mass through dry mergers in such a manner that size grows proportionally to mass.

6. TESTABLE PREDICTIONS

Our model predicts mass-dependent size evolution, with the high-mass end of the mass-size relation changing least with redshift (see Figure 4). This is mainly due to the higher formation redshifts of more massive galaxies. Such a trend is furthermore strengthened by the presumed properties of the accreted progenitors described in Section 4.4. This prediction is exactly opposite to the prediction by Khochfar & Silk (2006) that massive galaxies will display the strongest evolution. This seeming discrepancy may be explained if the star-formation histories of galaxies in the Khochfar & Silk (2006) model are closely linked to the assembly histories of their halos. We explicitly separate these processes by invoking a criterion for galaxies transforming into early types that is unrelated to the assembly history, only considering further assembly through dry merger events after the epoch of their initial emergence as early-type galaxies.

Unfortunately, the current observations are not of sufficient quality to decide this matter. The $z \sim 1$ mass-radius relation of the sample of early-type galaxies with dynamical mass measurements used by van der Wel et al. (2008) has a somewhat steeper slope than the local mass-size relation (see also Ferreras et al. 2009), but this is a marginal effect (of order 2σ), and which, in addition, could also be explained as a difference between cluster and field galaxies. Interestingly, the $z \sim 2$ samples show a hint that the reverse may be the case (van der Wel et al. 2008), with samples with the largest masses showing the largest offsets from the local mass-size relation, in qualitative (but not quantitative) agreement with the predictions by Khochfar & Silk (2006).

Another feature predicted by our model is a decrease with redshift in the scatter in size at fixed mass (see Figure 4) . This is simply because at fixed mass the larger galaxies are younger: at earlier epochs the larger galaxies at a given mass were not yet members of the early-type galaxy population, such that the scatter was smaller than it is nowadays. How rapidly the scatter is predicted to evolve with redshift depends on the implementation of merger activity, but regardless of the details a decrease with redshift is expected. Therefore, a measurement of the scatter in the high-redshift mass-size relation mainly tests our idea that there is a relation between age and size at fixed mass, which we already know to exist given the archaeological properties of present-day early-type galaxies (see Figures 2 and 1). The effect of dry mergers on the scatter is, in our model, of secondary importance. The $z \sim 1$ observations are consistent with a non-evolving scatter (within 2σ), but the best-fitting value points toward smaller scatter at earlier epochs (see van der Wel et al. 2008), in agreement with our model. Clearly, larger samples are required to confirm this tentative result.

Our study here concerns several fundamental scaling relations for early-type galaxies. It is therefore interesting to consider the implications of our model for another fundamental scaling relation that we have not mentioned so far: the connection between super-massive black holes and their host galaxies (e.g., Kormendy & Richstone 1995; Magorrian et al. 1998; Ferrarese & Merritt 2000; Gebhardt et al. 2000; Graham et al. 2001). In our dry-merger scenario, the growth of galaxies is obviously connected to the growth of the mass of the central black hole ($M_\bullet$). We assume that σ_* remains constant in dry mergers (Section 4.2), whereas the mass of the halo, the galaxy, and that of the black hole grow more or less proportionally. Hence, the evolution of $M_\bullet$ is more closely linked to the evolution of the total mass of both the halo and the galaxy than to σ_*. However, note that this is not an argument against a fundamental relationship between σ_* and $M_\bullet$ that may have determined the initial shape of the scaling relations between black-hole and bulge properties. It is as yet unclear what the intrinsic scatter in these scaling relations is, or whether one of the relations is fundamental in the sense that the intrinsic scatter is zero (e.g., Tremaine et al. 2002; Ferrarese & Ford 2005). Nor is it clear if and in which direction the $M_\bullet$ scaling relations evolve with redshift for non-active galaxies, despite recent progress for galaxies with active nuclei (e.g., Salviander et al. 2007; Woo et al. 2008). In the context of our model, evolution with redshift is expected, and the intrinsic scatter is unlikely to be zero. Scatter and redshift evolution in the $M_\bullet$-σ_* relation is expected due to continuous dry merging and the variety of the merger history of galaxies with a given σ_* (see Section 4.1). The scatter should then correlate with the size of the galaxy (bulge). Furthermore, assuming that σ_* and $M_\bullet$ are initially related, scatter and evolution in the $M_\bullet$-$M_{\rm dyn}$ (bulge mass) relation is expected due to the σ_*-dependent formation redshift of galaxies, and the scatter in the relationship between σ_* and $M_{\rm dyn}$ (see Section 3.2). The scatter should then correlate with size and the age of the stellar population. However, the current observational constraints on both the scatter of the present-day black-hole scaling relations and their evolution with redshift are not sufficiently accurate to provide evidence against or in favor of our model. Indications that the scatter indeed correlates with a third parameter have been found (e.g., Marconi & Hunt 2003), but the statistical significance of these results is quite marginal and their interpretation still debated (e.g., Graham 2008).

In addition to the $M_\bullet$-σ_* relation, the model presented here also predicts some characteristics of other scaling relations, such as the Faber-Jackson (Faber & Jackson 1976) and $Mg_2 - \sigma_*$ (Dressler et al. 1987) relations. Equal-mass, dry mergers have little effect on the $Mg_2 - \sigma_*$ relation, as both the metallicity and the velocity dispersion remain unchanged. The scatter may decrease somewhat, as merging will lead to regression to the mean metallicity at fixed velocity dispersion. Unequal-mass mergers will slightly decrease the metallicity of the merger remnant compared to the metallicity of the main progenitor (because of the mass-metallicity relation), which may somewhat increase the scatter in the $Mg_2 - \sigma_*$ relation. If we assume that luminosity is a proxy for mass, our model predicts scatter in the Faber-Jackson relation. This reflects the variety in the merger history of galaxies and is equivalent to the expected scatter in the $M_\bullet$-σ_* relation. Hence, our model predicts a correlation between the scatter in the $M_\bullet$-σ_* relation and the Faber-Jackson. Both of these should also correlate with galaxy size. The correlation between the scatter in Faber-Jackson relation and galaxy size is, of course, well known. The existence of the fundamental plane is, therefore, consistent with a scenario in which dissipationless merging plays an important role.

7. SUMMARY AND CONCLUSIONS

We present a simple, empirically motivated model that simultaneously predicts the evolution in the mean size and the comoving mass density of early-type galaxies between $z = 2$ and the present. A large sample of nearby early-type galaxies extracted from the Sloan Digital Sky Survey serves as the starting point. The redshifts at which galaxies transform into early-type galaxies (i.e., their 'formation' redshifts) are estimated based on an evolving velocity dispersion threshold, $\sigma_{\rm ET}$, above which galaxies have low specific star-formation rates. This is motivated in part by the observation that the stellar population age of present-day early-type galaxies is a simple function of their velocity dispersion. In addition to a prescription for estimating formation epochs, several merging scenarios between the formation epoch and the present are explored. Merger trees are generated such that they match the results from simulations of the mass assembly history of dark matter halos. Assuming dissipationless ('dry') merging and a simulation-inspired prescription for the effect of such mergers on the size of galaxies, we successfully reproduce both the observed evolution in the mean size and in comoving mass density of early-type galaxies with mass $M > 10^{11}\ M_\odot$ between $z = 2$ and the present. Our model quantitatively explains the recently measured, substantial size evolution of early-type galaxies. Our model does so by combining the continuous emergence of early-type galaxies, starting with systems with the highest velocity dispersion, with subsequent merging. Recently, and from the very different perspective of hydrodynamical simulations, Hopkins et al. (2009b) also considered such a combination of growth of the population and growth of individual galaxies, and arrived at similar conclusions.

We emphasize that our model for estimating the 'formation' redshifts of early-type galaxies is entirely phenomenological. We have, so far, not addressed the question why the velocity dispersion would be closely related to the formation redshift. Surely, this is related to the formation of bulges, perhaps regulated by feedback mechanisms. An obvious connection can be made between the crucial role that velocity dispersion plays in our model and the importance of black hole growth. It will be interesting to see whether a theoretical framework can be constructed that explains from first principles that early-type galaxies which form during a certain epoch have velocity dispersions that are independent of mass.

The most troubling issue of our model, which affects the merger part, is the effect of mergers on the sizes of the descendants. As mentioned in Section 4.2, some confusion remains in the literature describing the results from numerical simulations. Even if this issue is resolved, it will remain unclear how a multitude of minor accretion events will affect size evolution. In principle, a stronger effect on the sizes of the main progenitors than we assume in our model is physically possible. This may explain the presence of very compact galaxies in the $z > 2$ samples; however, dissipation will have to be incorporated in our model to make realistic predictions, which is beyond the scope of this study.

Besides the possibly underestimated effect of minor accretion events in our model, there are other potential solutions to the puzzle that the most compact galaxies present. First, the systematic uncertainties in the observations may still be underestimated; the ultimate test would be a direct measurement of the velocity dispersion. Initial steps in this direction were recently taken by Cenarro & Trujillo (2009). They find, based on an analysis of stacked spectra, that the velocity dispersions of quiescent galaxies at $z \sim 1.5$ may be somewhat higher than those of present-day galaxies with the same stellar mass. Second, physical mechanisms besides merging may play a role. A recently proposed idea is that quasar feedback is perhaps responsible for the observed size evolution, through the ejection of gas, simultaneously providing an explanation for the cessation of star formation, and the increase in size (Fan et al. 2008). An indication that this cannot be the mechanism that fully explains the observed size evolution is that a substantial fraction of this evolution took place between $z = 1$ and the present; over this period, massive early-type galaxies are known not to undergo phases of intensive nuclear activity. On the other hand, quasar feedback could contribute at higher redshifts, providing an explanation for the remaining discrepancy between our model predictions and the most compact galaxies found at $z > 2$.

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REFERENCES

Adelman-McCarthy, J. K. et al. 2008, ApJS, 175, 297
Bell, E. F., & de Jong, R. S. 2000, MNRAS, 312, 497

Bell, E. F. et al. 2004a, ApJ, 600, L11
Bell, E. F., et al. 2006, ApJ, 640, 241
Bell, E. F. et al. 2004b, ApJ, 608, 752
Bernardi, M. 2007, AJ, 133, 1954
—. 2009, MNRAS, in press, arXiv:0901.1318
Bernardi, M., Sheth, R. K., Nichol, R. C., Schneider, D. P., & Brinkmann, J. 2005, AJ, 129, 61
Bezanson, R., van Dokkum, P. G., Tal, T., Marchesini, D., Kriek, M., Franx, M., & Coppi, P. 2009, ApJ, in press, arXiv:0903.2044
Borch, A. et al. 2006, A&A, 453, 869
Boylan-Kolchin, M., Ma, C.-P., & Quataert, E. 2005, MNRAS, 362, 184
—. 2008, MNRAS, 383, 93
Brown, M. J. I. et al. 2007, ApJ, 654, 858
Buitrago, F., Trujillo, I., Conselice, C. J., Bouwens, R. J., Dickinson, M., & Yan, H. 2008, ApJ, 687, L61
Cappellari, M. et al. 2006, MNRAS, 366, 1126
Cenarro, A. J., & Trujillo, I. 2009, arXiv:0902.4893
Chang, R., Gallazzi, A., Kauffmann, G., Charlot, S., Ivezić, Ž., Brinchmann, J., & Heckman, T. M. 2006, MNRAS, 366, 717
Cimatti, A. et al. 2008, A&A, 482, 21
Ciotti, L., & van Albada, T. S. 2001, ApJ, 552, L13
Ciotti, L., Lanzoni, B., & Volonteri, M. 2007, ApJ, 658, 65
Cooray, A., & Sheth, R. 2002, Phys. Rep., 372, 1
Daddi, E. et al. 2005, ApJ, 626, 680
De Lucia, G., Springel, V., White, S. D. M., Croton, D., & Kauffmann, G. 2006, MNRAS, 366, 499
Dressler, A., Lynden-Bell, D., Burstein, D., Davies, R. L., Faber, S. M., Terlevich, R., & Wegner, G. 1987, ApJ, 313, 42
Elsner, F., Feulner, G., & Hopp, U. 2008, A&A, 477, 503
Faber, S. M., & Jackson, R. E. 1976, ApJ, 204, 668
Faber, S. M. et al. 2007, ApJ, 665, 265
Fan, L., Lapi, A., De Zotti, G., & Danese, L. 2008, ApJ, 689, L101
Ferreras, I., Lisker, T., Pasquali, A., Khochfar, S. & Kaviraj, S. 2009, arXiv:0901.4555
Ferrarese, L., & Ford, H. 2005, Space Science Reviews, 116, 523
Ferrarese, L., & Merritt, D. 2000, ApJ, 539, L9
Franx, M., van Dokkum, P. G., Foerster Schreiber, N. M., Wuyts, S., Labbe, I., & Toft, S. 2008, ApJ, 688, 770
Gallazzi, A., Brinchmann, J., Charlot, S., & White, S. D. M. 2008, MNRAS, 383, 1439
Gallazzi, A., Charlot, S., Brinchmann, J., & White, S. D. M. 2006, MNRAS, 370, 1106
Gallazzi, A., Charlot, S., Brinchmann, J., White, S. D. M., & Tremonti, C. A. 2005, MNRAS, 362, 41
Gebhardt, K. et al. 2000, ApJ, 539, L13
González-García, A. C., & van Albada, T. S. 2003, MNRAS, 342, L36
Graham, A. W. 2008, ApJ, 680, 143
Graham, A. W., Erwin, P., Caon, N., & Trujillo, I. 2001, ApJ, 563, L11
Graves, G. J., Faber, S. M., & Schiavon, R. P. 2008, ApJ, 693, 486
Graves, G. J., Faber, S. M., & Schiavon, R. P. 2009, ApJ, in press, arXiv:0903.3603
Graves, G. J., Faber, S. M., Schiavon, R. P., & Yan, R. 2007, ApJ, 671, 243
Hopkins, P. F., Bundy, K., Murray, N., Quataert, E., Lauer, T., & Ma, C.-P. 2009a, arXiv:0903.2479
Hopkins, P. F., Hernquist, L., Cox, T. J., Keres, D., & Wuyts, S. 2009b, ApJ, 691, 1424
Kauffmann, G. et al. 2006, MNRAS, 367, 1394
Kauffmann, G. et al. 2004, MNRAS, 353, 713
Khochfar, S., & Silk, J. 2006, ApJ, 648, L21
Khochfar, S., & Silk, J. 2008, arXiv:0809.1734
Kitzbichler, M. G., & White, S. D. M. 2008, MNRAS, 391, 1489
Kormendy, J., & Richstone, D. 1995, ARA&A, 33, 581
Kriek, M., van der Wel, A., van Dokkum, P. G., Franx, M., & Illingworth, G. D. 2008, ApJ, 682, 896
Li, Y., Mo, H. J., van den Bosch, F. C., & Lin, W. P. 2007, MNRAS, 379, 689
Lin, L. et al. 2008, ApJ, 681, 232
Lotz, J. M. et al. 2008, ApJ, 672, 177
Magorrian, J. et al. 1998, AJ, 115, 2285
Maller, A. H., Katz, N., Kereš, D., Davé, R., & Weinberg, D. H. 2006, ApJ, 647, 763
Marchesini, D., van Dokkum, P. G., Forster Schreiber, N. M., Franx, M., Labbe', I., & Wuyts, S. 2008, arXiv:0811.1773
Marconi, A., & Hunt, L. K. 2003, ApJ, 589, L21
Naab, T., Johansson, P. H., & Ostriker, J. P. 2009, arXiv:0903.1636
Naab, T., Johansson, P. H., Ostriker, J. P., & Efstathiou, G. 2007, ApJ, 658, 710
Naab, T., Khochfar, S., & Burkert, A. 2006, ApJ, 636, L81
Neistein, E., van den Bosch, F. C., & Dekel, A. 2006, MNRAS, 372, 933
Nipoti, C., Londrillo, P., & Ciotti, L. 2003, MNRAS, 342, 501
Pérez-González, P. G. et al. 2008, ApJ, 675, 234
Rix, H.-W., Maoz, D., Turner, E. L., & Fukugita, M. 1994, ApJ, 435, 49
Robertson, B., Cox, T. J., Hernquist, L., Franx, M., Hopkins, P. F., Martini, P., & Springel, V. 2006, ApJ, 641, 21
Salpeter, E. E. 1955, ApJ, 121, 161
Salviander, S., Shields, G. A., Gebhardt, K., & Bonning, E. W. 2007, ApJ, 662, 131
Shankar, F., & Bernardi, M. 2009, MNRAS, in press, arXiv:0903.3964
Shen, S. et al. 2003, MNRAS, 343, 978
Thomas, D., Maraston, C., Bender, R., & de Oliveira, C. M. 2005, ApJ, 621, 673
Toft, S. et al. 2007, ApJ, 671, 285
Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, AJ, 119, 1645
Tremaine, S. et al. 2002, ApJ, 574, 740
Treu, T. et al. 2005, ApJ, 633, 174
Trujillo, I., Cenarro, A. J., de Lorenzo-Cáceres, A., Vazdekis, A., de la Rosa, I. G., & Cava, A. 2009, ApJ, 692, L118
Trujillo, I. et al. 2006, MNRAS, 373, L36
van den Bosch, F. C. 2002, MNRAS, 331, 98
van den Bosch, F. C. et al. 2008a, MNRAS, 387, 79
van den Bosch, F. C., Pasquali, A., Yang, X., Mo, H. J., Weinmann, S., McIntosh, D. H., & Aquino, D. 2008b, arXiv:0805.0002
van den Bosch, F. C. et al. 2007, MNRAS, 376, 841
van der Wel, A., Franx, M., van Dokkum, P. G., Rix, H.-W., Illingworth, G. D., & Rosati, P. 2005, ApJ, 631, 145
van der Wel, A., Franx, M., Wuyts, S., van Dokkum, P. G., Huang, J., Rix, H.-W., & Illingworth, G. 2006, ApJ, 652, 97
van der Wel, A. et al. 2007, ApJ, 670, 206
van der Wel, A., Holden, B. P., Zirm, A. W., Franx, M., Rettura, A., Illingworth, G. D., & Ford, H. C. 2008, ApJ, 688, 48
van Dokkum, P. G. 2005, AJ, 130, 2647
van Dokkum, P. G., & Franx, M. 2001, ApJ, 553, 90
van Dokkum, P. G. et al. 2008, ApJ, 677, L5
van Dokkum, P. G., & van der Marel, R. P. 2007, ApJ, 655, 30
Wechsler, R. H., Bullock, J. S., Primack, J. R., Kravtsov, A. V., & Dekel, A. 2002, ApJ, 568, 52
Woo, J.-H., Treu, T., Malkan, M. A., & Blandford, R. D. 2008, ApJ, 681, 925
Yan, R., Newman, J. A., Faber, S. M., Konidaris, N., Koo, D., & Davis, M. 2006, ApJ, 648, 281
Yang, X., Mo, H. J., van den Bosch, F. C., Pasquali, A., Li, C., & Barden, M. 2007, ApJ, 671, 153
Zirm, A. W. et al. 2007, ApJ, 656, 66