MASSIVE ELLIPTICAL GALAXIES: FROM CORES TO HALOS

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ABSTRACT

In the context of recent observational results that show massive ellipticals were in place at high redshifts, we reassess the status of monolithic collapse in a ΛCDM universe. Using a sample of over 2000 galaxies from the Sloan Digital Sky Survey, by comparing the dynamical mass and stellar mass (estimated from colors) we find that ellipticals have “cores” that are baryon-dominated within their half-light radius. These galaxies correspond to 3 σ peaks in the spherical collapse model if the total mass in the halo is assumed to be 20 times the dynamical mass within the half-light radius. This value yields stellar mass–to–total mass ratios of 8%, compared to a cosmological baryon fraction of 18% derived from the first 3 years of WMAP observations alone. We further develop a method for reconstructing the concentration halo parameter c of the progenitors of these galaxies by utilizing adiabatic contraction. Although the analysis is done within the framework of monolithic collapse, the resulting distribution of c is lognormal with a peak value of c ∼ 3–10 and a distribution width similar to the results of N-body simulations. We also derive scaling relations between stellar and dynamical mass and the velocity dispersion, and find that these are sufficient to recover the tilt of the fundamental plane.

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

1. INTRODUCTION

The large new galaxy surveys such as 2dF (Colless et al. 2001) and the Sloan Digital Sky Survey (SDSS; York et al. 2000) have transformed the way we can study galaxy properties statistically. Here we focus on a sample of elliptical galaxies derived from those selected from the SDSS by Bernardi et al. (2003a, hereafter B03). Our motivation is to revisit fundamental issues of galaxy formation from the perspective afforded by a modern data set.

A theory of galaxy formation in a universe dominated by cold dark matter was first set out in a seminal paper by Blumenthal et al. (1984, hereafter BFPR) that considers the monolithic collapse of isolated dark matter halos. According to this picture, the redshift at which a halo collapses is determined only by its mass, for a given cosmology and choice of amplitude of fluctuation. The baryons follow the dark matter distribution until the radius of the collapsing halo reaches the virial radius and is halted. Studies of the evolution of the fluctuations in density, however, suggest that galaxy formation is dominated by merging of small dark matter halos (White & Rees 1978), and this picture is supported by simulations (Springel et al. 2005). There have been many attempts to discriminate between these two pictures of the formation of galaxies, referred to respectively as monolithic or spherical collapse and hierarchical merging. Simulation results notwithstanding, the small scatter of the observed color-magnitude relation and its evolution with redshift provides evidence that massive ellipticals were already in place at a redshift of z ≈ 1–2 with little subsequent merging (e.g., Stanford et al. 1998), whereas less massive ellipticals present features characteristic of recent star formation (e.g., Ferreras & Silk 2000a). This “inverted hierarchy” or “downsizing” effect (Cowie et al. 1996) illustrates the complexity of galaxy formation compared with a simple picture of the assembly of dark matter halos. In this paper we use the predictions of the spherical collapse scenario as a benchmark, which can then be challenged with further comparisons with observations and detailed simulations.

A new aspect of our analysis is the estimation of the stellar mass of each of the B03 ellipticals, allowing us to distinguish between baryonic and total mass. We also update the calculations of BFPR for a “concordance cosmology” (matter density Ωm = 0.3, dark energy density Ωλ = 0.7, Hubble constant h = 0.7, and amplitude of fluctuations σ8 = 0.9) and place the observed ellipticals on a revised cooling diagram. Despite the attention BFPR has received, this relatively simple generalization to ΛCDM has not previously appeared in the literature. Our analysis of the B03 galaxies also appears to be the first attempt to incorporate data for individual galaxies (as opposed to schematic data) in this parameter space. From the first 3 years of WMAP observations of the cosmic microwave background alone (Spergel et al. 2006), Ωm = 0.24 ± 0.04 and Ωλ = 0.73 ± 0.05. For simplicity, we use a “cosmological” baryon fraction of 1/3 unless otherwise stated.

On galactic scales, Klypin et al. (2002) model the Milky Way within the virial radius (∼250 kpc) and find that a substantial “feedback” mechanism that removes baryons from the galaxy itself must have operated. Do similar processes operate in massive ellipticals? Are their cores dominated by baryonic matter? Romanowsky et al. (2003) and Dekel et al. (2005) have reached conflicting conclusions to this important question, based on the analysis of planetary nebulae in elliptical galaxies out to 5 times the effective radius Re. By using the central velocity dispersion and stellar mass out to Re we seek to answer the same question by focusing on the central region only. We find that the cores of the galaxies are baryon-dominated, at least to a distance of Re from the center.

By making the straightforward assumption that the total mass of the galaxy is proportional to the mass of the galaxy cores we have studied, we reproduce the BFPR results for a modern
concordance cosmology and investigate the regime in which
their benchmark model of spherical collapse is consistent with
the data. We also recover the profile of the undisturbed dark
matter halo from present-day observables via the procedure
of adiabatic contraction, which enables us to compare our derived
profile concentration with both simulations and observations.
Defining \( \alpha = M_{\text{tot}}/M_{\text{dyn}}(R_e) \)—the total mass of the collapsing
halo divided by the dynamical mass within \( R_e \)—we find a
strong constraint that \( \alpha \geq 10 \); \( \alpha \approx 20 \) provides a good fit to the
data.

The outline of the paper is as follows: § 2 presents the B03
sample and a volume-limited subset of 2040 galaxies selected
from it. Section 3 describes the derivation of stellar masses of
these ellipticals from the SDSS colors. Section 4 derives dynamical
masses and § 5 covers the relations between luminosity,
velocity dispersion, stellar mass, and dynamical mass, extending
the classic Faber & Jackson (1976) relation. In § 6 we comment
on the acceleration of stars in the ellipticals and the connection
to modified Newtonian dynamics. Section 7 extends the bench-
mark spherical collapse model for the concordance \( \Lambda \)CDM cos-
6

mology and uses it to contrast the observed ellipticals with the
level of rms fluctuations on the cooling diagram. Finally, in
§ 8 we present a new reconstruction method that recovers the
initial halo of dark matter from the present-day observables us-
ing the adiabatic contraction. We summarize the results and out-
line future work in § 9.

2. THE SAMPLE

We use galaxies selected from the sample of B03 extracted
from the SDSS. The sample comprises almost 9000 early-type
galaxies, with spectroscopic redshifts in the range \( 0.01 \leq z \leq 0.3 \)
in the heliocentric reference frame. In B03 the authors describe
the selection criteria for their sample and the catalog itself; as
the photometry in each of the bands is used in our subsequent
analysis, it is important to note that these criteria do not include
selection by color. Their sample is magnitude-limited with all
galaxies at a redshift of \( z > 0.3 \) excluded. For the work pre-
sented in this paper we have used the data as presented in B03,
with the exception of photometry where we have used the recent
Sloan Data Release 4, (Adelman-McCarthy et al. 2005), which
resolves many of the problems with photometry identified in
earlier releases.

Unlike the work presented in B03 and its companion papers,
we have further restricted the sample to provide a volume-limited
sample. The mass function of the subset of galaxies selected by
B03, with \( z < 0.1 \) and absolute magnitude in the \( r \) band \( M_r < -20.75 \),
is shown in Figure 1.

As the figure shows, restricting our sample to massive ellipti-
cals, with \( M_{\text{star}}(R_e) > 7.94 \times 10^{10} M_\odot \), produces a volume-
limited sample of 2040 galaxies with \( z < 0.1 \) that appears free
from selection effects. Unless otherwise stated, this is the sample

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States Naval Observatory, and the University of Washington.

Fig. 1.—Stellar mass function of our volume-limited sample of early-type
galaxies extracted from B03. As shown in the inset (in which we plot the full
sample of \( \sim 8700 \) galaxies), we initially make cuts in redshift and absolute
magnitude, plotting the mass function for the remaining galaxies as the jagged
line. In order to check that these cuts produce a useful sample, we compare the
result with the LF derived for all SDSS early-type systems (type \( 0 < T < 1 \)
obtained independently by Nakamura et al. (2003). For the purposes of this com-
parison, we assume a characteristic \( M_{\text{tot}}/L_r = 4 \) (see Fig. 4). Our sample is com-
plete for systems with stellar masses greater than \( 7.94 \times 10^{10} M_\odot \) (dashed line),
and so we make a final cut at this mass to leave our final sample of 2040 galaxies.

we use for subsequent results. The definition of stellar mass, as
shown in the figure, is given in the next section.

3. STELLAR MASS

For massive elliptical galaxies with little gas content, the
baryonic mass is approximately equal to the stellar mass, at least
within the effective radius \( R_e \). We compute the stellar mass con-
tent within the effective radius by comparing the available SDSS
photometry with a wide range of star formation histories (SFHs).
We assume an exponentially decaying star formation rate, so
that each SFH is uniquely defined by three parameters: stellar
metallicity (constant with time), star formation timescale, and
formation redshift (allowed in the range \( 10 > z_f > 2 \)). These
models can represent either a short, sharp burst of star formation
or a more extended episode. For every choice of SFH we calcu-
late the resulting synthetic stellar populations of Bruzual &
Charlot (2003), generating a composite spectrum. A Chabrier
(2003) initial mass function (IMF) is used throughout. We use
four SDSS passbands to compare the flux in each of three colors
\((g-r), (r-i), (i-z)\) with the observations of each source. The
best fit is used to determine the stellar mass-to-light ratio, which
allows us to estimate the stellar mass content of each source
from the absolute \( r \)-band magnitudes given in Data Release 4.

It seems initially that the use of the full spectral energy dis-
tribution would produce a stellar mass content that might be
more accurate. However, we must emphasize that our results
indicate that the stellar mass-to-light ratio in the \( r \) band does not
change much with respect to the star formation histories allowed
in early-type galaxies. All photometric observables of
local early-type galaxies correspond to old, passively evolving
stellar populations (Bernardi et al. 2003b), which results in a
very weak dependence of the $M/L$ for the allowed ages and metallicities (see Fig. 4, top right). The largest systematic error in the stellar mass is due to the choice of the IMF, which amounts to a factor $\sim 0.1$–$0.2$ dex in $\log \frac{M}{L}$ for a range of standard IMFs (see, e.g., Bruzual & Charlot 2003).

4. DYNAMICAL MASS

We can use the projected size and central velocity dispersion along with a simple model of the dynamics of early-type galaxies to estimate the total matter content. Assuming that the velocity dispersion and the anisotropy of the velocity distribution do not vary with radius, one can solve Jeans’ equation (see, e.g., Binney & Tremaine 1988).

Padmanabhan et al. (2004) perform a careful analysis of the profiles of massive galaxies and find that

$$M_{\text{dyn}}(<R_e) = A \frac{\sigma^2 R_e}{G},$$

(1)

where $R_e$ is the effective (or projected half-light) radius, $\sigma$ is the velocity dispersion as measured at the center, and $A$ is a constant that depends weakly on the anisotropy of the velocity field. We adopt the Padmanabhan value of $A \approx 2.72$ throughout the present work, noting that they assume a systematic error of 30%. The dominant source of scatter is, as Padmanabhan et al. note, measurement errors.

Figure 2 presents a comparison of the dynamical mass and stellar mass. It is clear that dark matter is underabundant (compared to the cosmological abundance) in the central regions of these systems. In other words, the core region is baryon-dominated, in agreement with observations (e.g., Mamon & Lokas 2005). The slope is in agreement with independent estimates of total mass using strong gravitational lensing (Ferreras et al. 2005) and suggests that dark matter is more important in massive galaxies. It also is comparable to the results of Loewenstein & White (1999), although they use an unrealistic model for anisotropy in their sources.

Romanowsky et al. (2003) measure $\sigma$ through observations of bright planetary nebulae in three local ellipticals and derive a mass-to-light ratio within $5R_e$ compatible with those of purely stellar populations. Dekel et al. (2005) explain this result by suggesting that “the stellar orbits in the outer regions . . . are very elongated.” Our results, derived for the innermost $R_e$, suggest that results similar to those obtained by Romanowsky et al. would be expected even in large samples of ellipticals. In addition, realistic assumptions about the velocity structure of the cores of these systems do not provide an explanation of the deviation observed from the cosmological baryon fraction.

5. SCALING RELATIONS

Figure 3 shows the scaling relations of the $(r$ band) luminosity and stellar and dynamical mass as a function of velocity dispersion. The bottom panel shows the well-known Faber-Jackson relation (Faber & Jackson 1976).

Note that the truncation imposed by the choice of a volume-limited sample results in a constraint nearly aligned with the correlation (dashed line). Hence, a strong bias is expected if we use this reduced sample for the fits (see, e.g., Appendix B in Lynden-Bell et al. 1988). Therefore we use the complete sample for the fits in this figure.

In order to reduce the effect of outliers in the calculation of the best-fitting parameters, in common with all fits in this paper we use a robust M-estimator based on the minimization of the mean absolute deviation (Press et al. 1992), as standard least-squares methods were found to be very sensitive to outliers in this sample. Given the uncertainties in determining the errors in velocity dispersion and radius, we have chosen to weight all points equally rather than take into account their quoted errors. A bootstrap method is used to determine the uncertainty in the
The Faber-Jackson relation is a direct consequence of the dynamics of the systems being studied. Early-type galaxies are hot dynamical systems whose support comes mostly from the velocity dispersion of the constituent stars. Hence, a correlation is expected between the central velocity dispersion and the mass of the system. The different slope between stellar and dynamical mass estimates is mostly related to either stellar population effects, to structural differences, or to a significant correlation between the dark matter fractional contribution and total galaxy mass. This effect has been commonly invoked to explain the tilt of the observed so-called fundamental plane with respect to the prediction from the virial theorem (see, e.g., Guzmán et al. 1993; Ferreras & Silk 2000b; Trujillo et al. 2004).

Figure 4 shows the correlation between velocity dispersion and $M/L$ (stellar or total). Local early-type galaxies are dominated by stars which are older than about 7–8 Gyr, which implies that the contribution of stellar populations to the tilt of the fundamental plane cannot be too large, as previously suggested (Dressler et al. 1987).

There is a remarkable difference between stellar and dynamical $M/L$ in Figure 4. The fits were done using a bootstrap minimization of the mean absolute deviation on the volume-limited sample. The slope of the dynamical $M/L$ is sufficient to explain the tilt of the fundamental plane. Note that equation (1) assumes homology for all galaxies. Hence, we recover the tilt without invoking structural non-homology. Furthermore, recent estimates using strong gravitational lensing (Ferreras et al. 2005) suggest dark matter is the main cause of the tilt, a view supported by these results.

6. ACCELERATION

Our analysis so far has been done within the framework of Newtonian dynamics. We showed that the cores (i.e., within radius $R_c$) of massive early-type ellipticals are dominated by baryons, rather than by dark matter. The alternative model of modified Newtonian dynamics (MOND) of Milgrom (1983) suggests a modification to the acceleration if it is below $a_0 = 10^{-8}$ cm s$^{-2}$. This modification can then explain the rotation curves of spiral galaxies without the need for dark matter. It is intriguing indeed to see a correlation between the Newtonian $M/L$ and the centrifugal acceleration ($a = v^2/r$) at the last measured radial point $r$ in spiral galaxies (Sanders & McGaugh 2002). Their points are reproduced in our Figure 5 (as circles). It is clear from the start that such low acceleration is not expected at the cores of ellipticals, which have much smaller radii than...
the outer parts of spiral galaxies. However, it is interesting to look for any such correlation in the sample of ellipticals. Figure 5 shows (in dots) the dynamical $M/L_K$ ratio versus the acceleration, defined as $a = v^2/R_e = 3\sigma^2/R_e$. We see no obvious correlation and no continuity between the spirals and the ellipticals. As expected the ellipticals have accelerations that are $\sim 10$ times larger than that required by MOND to show departure from the Newtonian dynamics. If indeed ellipticals have large halos it would be an important test to measure the acceleration at these large radii.

7. SPHERICAL COLLAPSE IN A ΛCDM UNIVERSE

We have already mentioned the renewed interest in spherical collapse models as part of the complexity of galaxy formation. How do the predictions of this simple model compare to the modern data we have available, and how do the predictions change in a cosmological model incorporating a cosmological constant?

There have been many attempts to study spherical collapse in a cosmological model (e.g., Lahav et al. 1991; Wang & Steinhardt 1998), but we will follow the analysis of BFPR more closely, using the virial theorem to obtain the final overdensity (relative to the critical density at the collapse redshift) for universes in which $\Omega_m + \Omega_{\Lambda} = 1$:}

$$
\Delta_c = 18\pi^2 + 82d - 39d^2,
$$

where $d = \Omega_m^z - 1$ and

$$
\Omega_m^z = \frac{\Omega_m(1+z)^3}{\Omega_m(1+z)^3 + \Omega_\Lambda + \Omega_k(1+z)^2}.
$$

A halo will therefore collapse at a redshift $z$ determined only by its total mass and by cosmology. Via the virial theorem its radius will be given by (Barkana & Loeb 2001)

$$
r_{\text{vir}} = 0.784 \left( \frac{M_{\text{tot}}}{10^8 \, h^{-1} M_{\odot}} \right)^{1/3} \left( \frac{\Omega_m}{\Omega_m^* 18\pi^2} \right)^{-1/3} \left( \frac{1+z}{10} \right)^{-1} \, h^{-1} \, \text{kpc}.
$$
A halo of given mass will collapse later in a universe with a non-zero cosmological constant, leading to the differences between the two sets of calculations presented here. The EdS universe calculations were first presented by BFPR, and here we have updated their diagram to reflect a modern cosmological model together with data for individual galaxies, which to the best of our knowledge has not been done before.

In order to compare with data, it is necessary to convert the $M_{\text{dyn}}$ defined by equation (1) to a total mass. A naive solution would be to assume that $M_{\text{tot}} \approx 2M_{\text{dyn}}(< R_c)$, but this ignores factors including variation in the mass-to-light ratio and the profile of the velocity dispersion. Instead, we use the Ansatz that the total mass of a galaxy will be proportional to the dynamical mass within $R_c$:

$$M_{\text{tot}} = \alpha M_{\text{dyn}}(< R_c).$$

(7)

There will exist a scatter in $\alpha$ in the population of galaxies, and we may expect $\alpha$ to be a function of the total mass of the galaxy. However, if we approximate by considering a single value of $\alpha$, we can then consider for what values of $\alpha$ the spherical collapse model discussed above is appropriate. Consider the example of $\alpha = 2$, the naive value discussed above. The slope of the data is encouraging, being in good agreement with the theoretical prediction. However, for a given mass, the velocity dispersion is so large that the galaxies correspond to 4 $\sigma$ fluctuations in an EdS model and a 7 $\sigma$ fluctuation in $\Lambda$CDM. These are extremely unlikely fluctuations, not compatible with the observed number density of massive galaxies.

In order to get a rough estimate for the level of fluctuations that correspond to massive galaxies, we use the morphologically segregated luminosity functions (LFs) from SDSS (Nakamura et al. 2003). Integrating the LF of E/S0s from $L_*$ to some bright upper limit, say 20$L_*$ (the choice does not matter given the exponential cutoff of the LF), we get a comoving number density of ellipticals similar to those in our sample (see Fig. 1). The numbers from the SDSS LF give $n(E/S0) = 0.11 \times 10^{-2} h^3 \text{Mpc}^{-3}$. A similar integral for the LF of all galaxies in the sample in the range $0.005 < L/L_* < 20$ gives the comoving number densities of galaxies, $n(\text{all}) = 9.02 \times 10^{-2} h^3 \text{Mpc}^{-3}$. The ratio of the two number densities $[n(E/S0)/n(\text{all}) = 0.012]$ corresponds to a Gaussian fluctuation around $2.5 \sigma$. Hence, we can assume that a spherical collapse model from 2 to 3 $\sigma$ level fluctuations is compatible with the observed number density of early-type galaxies today. A choice of $\alpha = 20$ produces a good correlation between the data and the predicted $M$-$\sigma$ relation for $3 \sigma$ fluctuations given $\Lambda$CDM.

It is interesting to note that this choice of $\alpha$ produces a value for the stellar mass—total mass ratio that is approximately half the cosmological baryon fraction; i.e., half the baryons in the halo are found in the form of stars. Models with large $\alpha$ are also consistent with the large mass-to-light ratios found by studies of massive ellipticals in X-rays (Griffiths et al. 1996).

8. THE EVOLUTION OF THE DARK MATTER

In order to further investigate the distributions of total and stellar mass within the spherical collapse framework, we need to take into account the evolution of the dark matter as the baryons dissipate energy and sink toward the center of the halo. We use the procedure of adiabatic contraction of the dark matter halo, following Blumenthal et al. (1986). We assume that the dark matter has an initial density profile of the form given by Navarro, Frenk, & White (1997, hereafter NFW profile). The concentration is defined as $c = r_{\text{vir}}/r_s$, where $r_{\text{vir}}$ is the virial radius—usually considered to be the edge of the halo—and $r_s$ is the scale radius. This method is strictly valid only for halo particles moving on circular orbits. Gnedin et al. (2004) show that the predicted density profile is more dense than that found in $N$-body simulations. However, the deviation is small (Sellwood & McGaugh 2005) and we use the method here as a first approximation.

The initial mass profile and the final dark matter and baryonic profiles are related by two equations:

$$r [M_b(< r) + M_h(< r)] = r_i M_i(< r_i),$$

(8)

and

$$M_h(< r) = (1 - f_{\text{cool}}) M_i(< r_i).$$

(9)

Here $M_i(< r)$ is the initial mass enclosed within the radius $r$; $M_b(< r)$ and $M_h(< r)$ are the final baryonic and dark matter profiles, respectively; $f_{\text{cool}}$ is the fraction of the system’s mass that is contained in baryons that cool to form the galaxy and is related to $\alpha$ via the relation

$$f_{\text{cool}} = \frac{2M_{\text{star}}(< R_c)}{\alpha M_{\text{dyn}}(< R_c)},$$

(10)

where the stellar mass within $R_c$ is assumed to be half the cooled baryonic mass (Padmanabhan et al. 2004). For $\alpha = 20$ and the ratio of $M_{\text{star}}(< R_c)$ to $M_{\text{dyn}}(< R_c)$ found in § 4, the value of $f_{\text{cool}}$ is $0.08$. This corresponds to half the cosmological baryon fraction, which suggests that half the halo’s baryons are in stars. We can also use this sort of argument to place a limit on $\alpha$ by requiring $f_{\text{cool}} < 0.5$ (where 0.5 is the cosmological baryon density). This corresponds to $\alpha > 10$.

The baryons are assumed to have a density profile of the form given by Hernquist (1990), which closely approximates the de Vaucouleurs law; see § 4. In this case the adiabatic contraction problem can be solved analytically (Keeton 2001). Each initial radius $r_i$ maps to a final radius $r$ given by

$$f_{\text{cool}} r^3 + (r + a)^2 [(1 - f_{\text{cool}}) r - r_i] m_i(< r_i) = 0,$$

(11)

where $a = 0.551 R_s$ is the scale radius of the Hernquist profile and $m_i(< r_i) = M_i(< r_i)/M_{\text{tot}}$. A halo of mass $M_{\text{tot}}$ in the monolithic picture considered here will collapse at a redshift determined only by the cosmology and the amplitude of perturbations. The virial radius is then given by equation (6). After choosing a value for $\alpha$, $f_{\text{cool}}$ is given by equation (10) using the value of $M_{\text{star}}(< R_c)/M_{\text{dyn}}(< R_c)$ for each galaxy. For any concentration $c$, we then obtain the total mass inside the initial radius $r_i$ that will evolve into a final radius $r = R_c$. The adiabatic contraction prescription implies this mass is equal to the final mass observed within $R_c$. Hence, we determine via a maximum likelihood estimator the concentration that satisfies $M_{\text{dyn}}(< R_c) = M_i(< r_i)$.  

8.1. Results

Figure 7 shows the histogram of the concentration of the initial dark matter halos for our sample, for 2 and 3 $\sigma$ perturbations and $\alpha$ of 10 or 20. The figure overlays a Gaussian distribution corresponding to this result. The fit is remarkable: our simplistic model of spherical collapse and adiabatic contraction combined with a volume-limited sample results in a lognormal distribution of concentrations.

This type of distribution is also obtained in more detailed $N$-body simulations (Bullock et al. 2001). Furthermore, the dispersion of our distribution is $\sigma(\log c) \sim 0.2$–0.25, in agreement with the simulations, which give ~0.18; note that these
Hierarchical models give concentrations around 4 only for objects that have recently undergone major mergers or for large (galaxy cluster mass) systems. The mean concentration for galaxies with mass $M_{\text{vir}} \geq 1.5 \times 10^{12} \, h^{-1} M_\odot$ is typically 13.1 (Wechsler et al. 2002).

As Figure 7 shows, our model does reproduce large values of $c$ for small values of $\alpha$ and 2 $\sigma$ fluctuations. However, a value $\alpha < 10$ would shift the data points in Figure 6 to the left, away from the predictions for 2 or 3 $\sigma$ fluctuations. We therefore conclude that the benchmark model predicts a mean concentration lower than that found in simulations.

These results are reminiscent of those of Collister & Lahav (2005), who studied the concentration of galaxy clusters and groups in the 2dF Galaxy Redshift Survey. They found concentrations from the galaxy data that were a factor of $\sim 2$ lower than the predictions of dark matter simulations (e.g., Kravtsov et al. 2004), albeit on larger scales than those considered here. Trujillo et al. (2006) present weak evidence for a change in concentration of massive elliptical galaxies (as derived from the size-mass relation) with redshift; further studies with larger samples should enable us to test their results with our methods.

### 8.2. Galaxy Formation and Cooling

In order to consider the baryonic component of the galaxies, it is convenient to plot baryon number density against temperature, following BFPR. We define number density at present as

$$n_b = \frac{3M_{\text{baryon}}(< R_e)}{4\pi R_e^3 \mu m_1}$$

and temperature as

$$T = \frac{\mu m_1 \sigma^2}{k_B},$$

where $\mu m_1$ is the mean atomic weight ($\mu = 0.6$ for a primordial mix of hydrogen and helium) and $k_B$ is the Boltzmann constant.

The result is shown in Figure 8. The sample is shown in two different ways: the black dots are the actual baryon densities (i.e., after adiabatic contraction) using equation (12), computed within the half-light radius. The gray dots represent baryon densities before adiabatic contraction and are computed as the density corresponding to a baryon mass $(f_{\text{cool}})M_{\text{tot}}$ within a radius $R_{\text{vir}}$. The gray and black lines are predictions for the spherical collapse model ($\Lambda$CDM) and are shown for 2 and 3 $\sigma$ fluctuations before and after adiabatic contraction. These models require a translation from total mass to baryon mass, for which we use the average value for $f_{\text{cool}}$ obtained from the sample, i.e., $\langle f_{\text{cool}} \rangle = 0.083$. For the “before AC” (gray) lines we use this mass and the virial radius defined by equation (6). Incidentally, we note that the early-type galaxies indicated in the original cooling diagram in BFPR correspond to our set of points before adiabatic contraction. As far as we know, this is the first time individual galaxies have been plotted in this space, as previous work has relied on “schematic” data. The (black) curves “after AC” also need to assume a ratio between the virial radius and the initial radius $r_i$ that is mapped into $R_e$. We use again the sample to find $r_i \sim 0.1 R_{\text{vir}}$ (see Fig. 9).

The figure shows consistency with our previous results. The curves tracing $t_{\text{dyn}} = t_{\text{cool}}$ use the dynamical timescale

$$t_{\text{dyn}} = \frac{3\pi}{32 G \rho},$$

where $\rho$ is the total density of baryonic and dark matter, and the cooling timescale

$$t_{\text{cool}} = \frac{3k_B T}{n \Lambda_{\text{net}}}.$$
where $n$ is the number density of nuclei and $\Lambda_{\text{net}}$ is the net cooling rate for solar (or zero) metallicity from Sutherland & Dopita (1993). As expected, the galaxies after contraction lie in the region of the plot where $t_{\text{cool}} < t_{\text{dyn}}$. Although the approach is simplistic, assuming that galaxies are uniform spheres rather than using radial profiles, it is intriguing that 2 σ fluctuations even for massive galaxies lie on the cooling curve for zero metallicity systems, and that adiabatic contraction promotes cooling of these systems. This result may be followed up with detailed simulations.

9. CONCLUSIONS

The sample of early-type galaxies selected by B03 from the Sloan Digital Sky Survey has been used to investigate the properties of baryonic and dark matter within these systems. For the work presented in this paper, the sample was further restricted to be volume-limited, containing only massive elliptical systems, leaving a total of more than 2000 systems. Using photometry from Sloan Data Release 4 and the synthetic stellar populations of Bruzual & Charlot (2003) we calculated the mass in stars of each system.

We recover the well-known Faber-Jackson relation between luminosity and observed velocity dispersion and also find a tight correlation between stellar mass and velocity dispersion, which we have called the “baryonic Faber-Jackson relation.” We find a slope of $M_{\text{star}}(< R_e) \propto \sigma^{2.33 \pm 0.18}$ (in appropriate units), less steep than previous work (Thomas et al. 2005) based on a study of an order of magnitude fewer galaxies.

In addition to determining the stellar mass, it is possible to determine a dynamical mass via the velocity dispersion and the radius of the system. Comparing the two estimates of mass reveals that dark matter is underabundant in the center of such galaxies when compared to the cosmological baryon fraction. However, our results are in good agreement with observers who have claimed that the inner regions of massive ellipticals are baryon-dominated.

In order to examine whether this large data set is sufficient to discriminate between galaxy formation via monolithic collapse or the merging of small dark matter halos, the data were compared to a simple model of spherical collapse. It was necessary to assume that the total mass of the systems under study is proportional to the mass within the baryon-rich core (within $R_e$), but given such an assumption we find that for $\alpha \approx 20$ [where $\alpha = M_{\text{tot}} / M_{\text{gas}} (< R_e)$], the data were found to be consistent with simple monolithic collapse of 3 σ perturbations (assuming CDM cosmology).

Interestingly, this choice of $\alpha$ also produces a value for the fraction of the mass that lies in the form of cooled baryons that is consistent with other work. A choice of 20 seems large but corresponds to the stellar mass contributing half of the cosmological baryon fraction. Given the other reservoirs of baryons in these systems, this is a reasonable value.

Having given the motivation for our choice of $\alpha$, we used the adiabatic contraction method first due to Blumenthal et al. (1986) to calculate the response of the dark matter to the presence of the observed baryons. We assume that the dark matter has an initial NFW profile and produce the distribution of initial concentration shown in Figure 7. The mean concentration is lower than that found in dissipationless N-body simulations.

In summary, we have shown that the B03 sample of early-type galaxies is a powerful resource for studying the distribution of matter within these objects. However, despite this excellent data set we cannot rule out spherical collapse as a mode of formation for massive ellipticals. We find that the central regions of the galaxies, which are baryon-dominated, must represent only a small fraction of the total mass of the system. In future work, we will extend our analysis to a new large sample of early-type systems and undertake a detailed comparison of simulation results in order to understand the differences between observations and semi-analytic models.

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Fig. 9.—Comparison of the virial radius $r_{\text{vir}}$ and the initial radius used in the adiabatic contraction procedure. For each galaxy $r_i$ is chosen such that the mass within $r_i$ before contraction corresponds to the dynamical mass within $R_e$ after contraction. The top panel shows the correlation with the effective radius $R_e$. In larger galaxies, more of the halo is contracted into $R_e$. No. 2, 2006

MASSIVE ELLIPTICAL GALAXIES: FROM CORES TO HALOS 833

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