I use the abundance matching ansatz, which has proven to be successful in reproducing galaxy clustering and other statistics, to derive estimates of the virial radius, $R_{200}$, for galaxies of different morphological types and a wide range of stellar masses. I show that over eight orders of magnitude in stellar mass galaxies of all morphological types follow an approximately linear relation between half-mass radius of their stellar distribution, $r_{1/2}$, and virial radius, $r_{1/2} \approx 0.015 R_{200}$, with scatter of $\approx 0.2$ dex. Such scaling is in remarkable agreement with the expectation of models that assume that galaxy sizes are controlled by halo angular momentum, $r_{1/2} \propto \lambda R_{200}$, where $\lambda$ is the spin of galaxy parent halo. The scatter about the relation is comparable with the scatter expected from the distribution of $\lambda$. Moreover, I show that when the stellar and gas surface density profiles of galaxies of different morphological types are rescaled by the radius $r_n = 0.015 R_{200}$, the rescaled profiles follow approximately universal exponential (for late types) and de Vaucouleurs (for early types) form with scatter of only $\approx 30\%–50\%$ at $R \approx 1–3 r_n$. Remarkably, both late- and early-type galaxies have similar mean stellar surface density profiles at $R \gtrsim r_n$. The main difference between their stellar distributions is thus at $R < r_n$. The results of this study imply that galaxy sizes and radial distribution of baryons are shaped primarily by properties of their parent halos and that the sizes of both late-type disks and early-type spheroids are controlled by halo angular momentum.

Key words: galaxies: formation – galaxies: halos – galaxies: structure

1. INTRODUCTION

In the standard hierarchical structure formation scenario, galaxies form in minima of potential wells formed by nonlinear collapse of peaks in the initial density field. Galaxy formation is expected to be a complex, highly nonlinear process, involving forces on a wide range of scales. Despite an apparent complexity, observed galaxies exhibit a number of tight scaling relations between their structural parameters. As first shown by Fall & Efstathiou (1980) and elaborated by Mo et al. (1998; see also Dalcanton et al. 1997; Avila-Reese et al. 1998; Mo & Mao 2000; Avila-Reese et al. 2008; Dutton et al. 2007; Dutton 2009; Fu et al. 2010), some of these scaling relations can be reproduced in a fairly simple framework, in which sizes of galaxies are determined by halo angular momentum which sets the sizes of their initial rotationally supported gaseous disks. Such models predict that galaxy sizes scale approximately linearly with the virial radius, $R_{200}$, where $R_{300}$ is defined as the radius enclosing overdensity of 200 with respect to the critical density of the universe, $\rho_c(z)$, so that $M_{200} = (4\pi/3)200\rho_c(z)R_{200}^3$.

Regularity in galaxy properties is also implied by a success of the abundance matching ansatz, in which relation between total mass of halos, $M$, and stellar mass of galaxies they host, $M_*$, is derived from a simple assumption that the relation is approximately monotonic and cumulative abundances of halos and galaxies match: $n_h(M) = n_<(M_*)$. This model is remarkably successful in reproducing clustering of galaxies of different luminosities and at different redshifts (Kravtsov et al. 2004; Tasitsiomi et al. 2004; Conroy et al. 2006; Reddick et al. 2012) and other statistics (Vale & Ostriker 2004, 2006; Behroozi et al. 2010, 2012; Guo et al. 2010; Moster et al. 2012; Hearin et al. 2012).

In this Letter, I use the abundance matching ansatz to examine relation between the sizes of stellar systems of galaxies, characterized by the three-dimensional half-mass radius, $r_{1/2}$, and the virial radii of their halos, $R_{200}$, estimated using the abundance matching ansatz. I show that over the entire observed range of stellar masses and morphologies, galaxies do indeed exhibit approximately linear scaling $r_{1/2} \propto R_{200}$ relation. Furthermore, I show that the stellar and gas surface density profiles of galaxies rescaled with the radius $r_n = 0.015 R_{200}$ follow universal profiles with a scatter as low as $\approx 30\%–50\%$ at intermediate radii within the optical extent of galaxies.

Throughout this Letter I assume a flat $\Lambda$CDM model with parameters $\Omega_m = 1 - \Omega_\Lambda = 0.27$, $\Omega_\Lambda = 0.0469$, $h = H_0/(100 \text{ km s}^{-1} \text{ Mpc}^{-1}) = 0.7$, $\sigma_8 = 0.82$, and $n_s = 0.95$ compatible with combined constraints from the Wilkinson Microwave Anisotropy Probe, Baryonic Acoustic Oscillations (BAO), supernovae, and cluster abundance (Komatsu et al. 2011).

2. ABundance Matching

To estimate the virial masses and radii of halos hosting galaxies, I use the abundance matching ansatz: $n_h(M) = n_<(M_*)$. A number of estimates of the $M_*-M$ relation using this technique have been presented in the recent literature (e.g., Moster et al. 2012; Behroozi et al. 2012). However, the relations derived in these studies are based on stellar mass functions (SMFs) known to underestimate abundance of massive galaxies (Bernardi et al. 2010) and the double power-law fit to the $M_*-M$ relation of Moster et al. (2012) does not capture the upturn in the relation at $M_* \lesssim 10^9 M_\odot$ originating from the steepening of the SMF at these masses (Baldry et al. 2008, 2012; Papastergis et al. 2012). Therefore, in this study I re-derive the $M_*-M$ relation to fix these problems.

I use the Tinker et al. (2008) calibration of halo mass function for $M_{200}$, which was calibrated using host halos only. To account for subhalos, I correct the host mass function by the subhalo
fraction, \( f_{\text{sub}}(>M) = \frac{n_{\text{sub}}(>M) - n_{\text{host}}(>M)}{n_{\text{host}}(>M)} \). \( n_{\text{host}}(>M) \) was calculated using current \( M_{200} \) masses for hosts and corresponding masses at the accretion epoch for subhalos using \( z = 0 \) halo catalog of Behroozi et al. (2013) derived from the Bolshoi simulation (Kravtsov et al. 2011). The subhalo fraction in the Bolshoi simulation is parameterized as \( f_{\text{sub}} = \min(0.35, 0.085(15 - \log_{10} M_{200})) \).

I combine two recent SMF calibrations by Papastergis et al. (2012) and Bernardi et al. (2010) to accurately characterize SMF behavior at both small and large \( M_\ast \), respectively: \( n(M_\ast) = \max[n_{P12}, n_{B10}] \). For \( n_{B10} \) I adopt the double Schechter form given by Equation (6) of Baldry et al. (2012) with the following parameters: \( \log_{10} M_\ast = 10.66, \phi_1^* = 3.96 \times 10^{-3} \text{Mpc}^{-3}, \alpha_1 = -0.35, \phi_2^* = 6.9 \times 10^{-4} \text{Mpc}^{-3}, \alpha_2 = -1.57 \). These parameters are in general agreement with the best-fit parameters derived for the local SMF by Baldry et al. (2012). Note that SMF measurements at \( M_\ast \lesssim 10^8 \, M_\odot \) are quite uncertain due to incompleteness of low surface brightness galaxies in this regime (Baldry et al. 2012); the current SMF measurements at these stellar masses should be considered as lower limits and the actual SMF may be somewhat steeper still. For \( n_{B10} \) I use the parameter values given in the bottom row of Table 4 in Bernardi et al. (2010, unbracketed values) and the Schechter parameterization of the SMF given by Equation (9) in that paper. I refer readers to the original papers for further details on how the SMFs were estimated.

3. GALAXY SAMPLES

To estimate the size–virial radius relation, I have selected several publicly available data sets chosen to span the entire range of galaxy stellar masses\(^4\) and morphologies. First, I use a compilation of stellar masses and effective radii for the spheroidal, early-type galaxies in Misgeld & Hilker (2011). These include 95 ellipticals (Es) and dwarf elliptical (dE) galaxies in the Virgo cluster with the Hubble Space Telescope (Ferrarese et al. 2006), the Very Large Telescope/ FORS1 observations of 194 dEs in the Hydra I and Centaurus clusters (Misgeld et al. 2008, 2009), and 23 dwarf spheroidal (dSph) galaxies in the Local Group. The sample of late-type galaxies includes 25 of the THINGS/HERACLES galaxies of Leroy et al. (2008) and the LITTLE THINGS sample of 34 dwarf irregular galaxies from Zhang et al. (2012). I also include the stellar mass profile of the Milky Way using a combination of the thin and thick stellar disks with parameters given in Table 2 of McMillan (2011). For the late-type samples, I used the deprojected stellar surface density profiles presented in these studies to estimate the half-mass radius, \( R_{1/2} \), directly from the profiles. \( R_{1/2} \) was determined as the radius that contains half of the stellar mass of galaxies using the cumulative mass profile of each disk: \( M_\ast(<R) = 2\pi \int_0^R \Sigma(R')R'dR' \).

In addition, I use the average relations between half-light radius and stellar mass, \( (R_{1/2}/M_\ast) \), derived for early- and late-type galaxies in the Sloan Digital Sky Survey (SDSS) from the recent study by Bernardi et al. (2012; SerExp values in their Table 4). I also use the intrinsic scatter about the mean relation calculated for both early- and late-type galaxies (M. Bernardi 2012, private communication). Finally, I use the half-mass radii and stellar masses for a sample of 220 massive SDSS galaxies at \( z < 0.1 \) presented in Szomoru et al. (2013, see their Table 1).

\(^4\) Stellar masses in all of the samples were estimated assuming the Chabrier (2003) initial mass function.
galaxies are also close to the global linear relation, although the figure indicates that late-type galaxies of the intermediate stellar masses have systematically larger half-mass radii than the early-type galaxies of the same stellar mass (e.g., Bernardi et al. 2012).

The purple-shaded band around the dot-dashed line in Figure 1 shows $\sigma_r \approx 0.3\text{--}0.5$ dex intrinsic scatter estimated for all galaxies in the sample of Bernardi et al. (2012; the scatter shown is for all galaxies in the sample; M. Bernardi, private communication). The orange error bars show scatter estimated for the mass-limited sample of massive SDSS galaxies presented in Szomoru et al. (2013). The scatter estimated for this sample is in good agreement with the scatter of the Bernardi et al. (2012) sample. Remarkably, the scatter is also approximately consistent with the scatter expected from the distribution of halo spins, $\lambda$, in models in which galaxy size is $\propto \lambda R_{200}$, shown by the dotted lines in the figure.

4.2. Stellar and Gas Surface Density Profiles of Galaxies

In this section I show that in addition to $r_{1/2}-R_{\text{200}}$ correlation, the surface density profiles of stars and neutral gas approximately follow universal profiles when scaled by $r_n = 0.015 R_{\text{200}}$, i.e., the mean normalization of the $r_{1/2}-R_{\text{200}}$ correlation.

Two panels in Figure 2 show the surface density profiles of stars and neutral gas (H$1+\text{H}_2$, where H$1$ is corrected for helium) for late-type galaxies. The radius of each individual profile was rescaled by $r_n = 0.015 R_{\text{200}}$ and surface densities were scaled by $\Sigma_n = 0.448 M/R_{\text{200}}^2$, where $M$ is the total stellar or gas mass of each galaxy and factor $0.448 = 1.678^2/(2\pi)$ assumes exponential profile ($r_{1/2} = 1.678 R_{\text{de}}$). The figure shows that both the mean stellar and gas profiles are on average well described by the exponential profile, $\Sigma(R) = \Sigma_0 \exp(-R/R_d)$, where $\Sigma_0, R_d \approx 1256 M/R_{\text{200}}^2$ and the scale length $R_{\text{de}} \approx 0.011 R_{\text{200}}$ for stars and $\Sigma_{\text{gas}} \approx 0.029 R_{\text{200}}$ for neutral gas. The gas distribution is thus on average a factor of $\approx 2.6$ more extended than the stellar distribution. Scatter around the mean profiles is rather small and is only $\approx 30\%\text{--}50\%$ at $R \approx 1\text{--}3r_n$, even though $M_*$ of galaxies shown in the $\Sigma_*(R)$ figure (top panel) spans over six orders of magnitude.

The approximate universality of the gas and surface density profiles was recently pointed out by Bigiel & Blitz (2012). These authors rescaled gas profiles of the THINGS/HERACLES galaxies using the optical Holmberg radius, $R_{\text{de}}$, and the gas surface density $\Sigma_{\text{gas}}$ at the radius where $\Sigma_{\text{gas}} \approx \Sigma_{\text{gas}}$. Thus rescaling results in the average exponential profile described by $\Sigma_{\text{gas}} \approx 2.1 \Sigma_{\text{gas}} \exp(-1.65 R/R_{\text{25}})$ with comparable scatter around the mean profile to the rescaling described above. Comparison gives $\Sigma_{\text{gas}} = 0.048 R_{\text{200}}$. Thus, the results of Bigiel & Blitz (2012) can be understood if $\Sigma_{\text{gas}}$ scales with the characteristic surface density $\Sigma_{\text{gas}}$. The scaling of $R_{\text{25}}$ is implied by the scaling $R_{\text{d, gas}} \propto R_{\text{200}}$ because for exponential disks $R_{\text{25}} \approx 4.5 R_{\text{d, gas}}$. Thus, the gas surface density profiles can be scaled by the surface density $\propto M_{\text{gas}}/R_{\text{200}}^2$ instead of $\Sigma_{\text{gas}}$. In summary, the results presented here indicate that the reason scaling employed by Bigiel & Blitz (2012) works is that surface densities of gas and stars are both exponential and their scale lengths are correlated: $R_{\text{d, gas}} \propto R_{\text{d, gas}}$. The origin of the universality of $\Sigma_{\text{gas}}$ profiles lies in the scaling of half-mass radius of both gas and stars with the virial radius of parent halo.

Figure 3 shows stellar surface density profiles of massive SDSS ($z < 0.1$) galaxies in the sample presented by Szomoru et al. (2013) rescaled using $r_n$ as above. Note that I plot not the actual measured profiles but the Sérsic profiles with parameters derived from the $M_*$ and $R_e$ values in Table 1 of that paper. The mean profile of late-type galaxies from the top panel of Figure 2 is shown for comparison. The figure shows that stellar distribution of early-type galaxies also follows an approximately universal profile. The mean profile is very close to the de Vaucouleurs profile with $R_e = 0.015 R_{\text{200}}/1.34$, where factor of 1.34 converts the three-dimensional half-mass radius to the two-dimensional $R_e$. Remarkably, the mean profiles of late-type and early-type galaxies are quite similar at $R \gtrsim 5r_n$ and are only significantly different at $R \lesssim 5r_n$. This implies that similar processes shape stellar distribution at large radii in both late- and early-type galaxies.
A restatement of the well-known relations indicates that the derived relation is not a trivial nearly linear relation emerges from a combination of nonlinear relations used are fractions of cosmic simulations (Diemer et al. 2012), the halo radius that set the galaxy size is $R_{200}(z = 2) \approx 0.37 R_{200}(z = 0)$. Using again $\lambda = 0.045$ and $c_{200} = 4$ typical for $z = 2$ halos, the prediction is $r_{1/2} \approx 0.016(j_{a}/m_{d})R_{200}(z = 0)$, in agreement with the relation derived for observed galaxies. This conjecture can, in principle, be tested via analysis similar to the one presented in this Letter but done at $z = 1-2$.

These estimates demonstrate that empirically derived $r_{1/2}/R_{200}$ relation is in very good quantitative agreement with predictions of the Mo et al. (1998) disk formation model. Remarkably, the prediction works not only for late-type disks, but also for early-type galaxies. This means that angular momentum plays a critical role in setting the sizes of galaxies of all morphological types. This fact reveals yet another remarkable regularity in properties of observed galaxies and provides a critical test for models of galaxy formation. Although predictions of galaxy formation simulations are much more uncertain, recent simulations with efficient feedback indicate that specific angular momentum of the baryonic components of galaxies does indeed correlate with that of their host dark matter halo (e.g., Zavala et al. 2008; Scannapieco et al. 2008; Sales et al. 2010; Kimm et al. 2011). Moreover, the results of Sales et al. (2010) hint at the possible explanation for the similarity of relations for early- and late-type galaxies. Morphology may be determined by how well aligned the angular momentum of matter accreted at different epoch was, rather than by the frequency of mergers. The total angular momentum of accreted matter is set by the overall torque and may be comparable in objects, even though large differences in angular momentum alignment may exist.

The derived $r_{1/2}/R_{200}$ relation may provide a useful way to estimate galaxy sizes in simulations when only halo information is available. Conversely, it can be used to derive halo extent and mass using the observed $R_e$. As shown recently by Szomoru et al. (2013), half-light radius of galaxies is offset only by $\approx 25\%$ from the half-mass radius $r_{1/2}$ regardless of galaxy stellar mass, morphology, and redshift. The relation derived in this study can thus be used to estimate $R_{200}$ of galaxy halos with $\approx 50\%$ accuracy and virial mass $M_{200}$ to within a factor of about 4 from the measurement of half-light radius alone without resorting to estimate of stellar mass. For these reasons it would be interesting to calibrate the relation and its scatter using larger, well-defined samples at a variety of redshifts.

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**Figure 3.** Normalized surface density profiles of stars for massive early-type SDSS galaxies ($r_{200} > 2.5$) from Szomoru et al. (2013). Profiles of individual galaxies are shown by the thin lines colored according to their log10 $M_*$, as indicated in the legend. Each individual profile is normalized by the radius $r_n = 0.015 R_{200}$, where $R_{200}$ is obtained using the abundance matching ansatz from galaxy’s $M_*$. The thick lines with error bars show the sample average and the rms dispersion around the mean. The thick dashed line shows the average profile of late-type galaxies from the top panel of Figure 2 for comparison.
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