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A detection of the environmental dependence of the sizes and stellar haloes of massive central galaxies

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ABSTRACT

We use $\sim$100 deg^2 of deep ($>$28.5 mag arcsec^{-2} in *i* band), high-quality (median 0.6 arcsec seeing) imaging data from the Hyper Suprime-Cam (HSC) survey to reveal the halo mass dependence of the surface mass density profiles and outer stellar envelopes of massive galaxies. The *i*-band images from the HSC survey reach $\sim$4 mag deeper than Sloan Digital Sky Survey and enable us to directly trace stellar mass distributions to 100 kpc without requiring stacking. We conclusively show that, at fixed stellar mass, the stellar profiles of massive galaxies depend on the masses of their dark matter haloes. On average, massive central galaxies with $\log_{10}(M_{\star,\,100\,\mathrm{kpc}}/\mathrm{M}_{\odot})>11.6$ in more massive haloes at $0.3 < z < 0.5$ have shallower inner stellar mass density profiles (within $\sim$10–20 kpc) and more prominent outer envelopes. These differences translate into a halo mass dependence of the mass–size relation. Central galaxies in haloes with $\log_{10}(M_{200\mathrm{b}}/\mathrm{M}_{\odot})>14.0$ are $\sim$20 per cent larger in R_{50} at fixed $M_{\star,\,100\,\mathrm{kpc}}$. Such dependence is also reflected in the relationship between the stellar mass within 10 and 100 kpc. Comparing to the mass–size relation, the $M_{\star,\,100\,\mathrm{kpc}}$–$M_{\star,\,10\,\mathrm{kpc}}$ relation avoids the ambiguity in the definition of size, and can be straightforwardly compared with simulations. Our results demonstrate that, with deep images from HSC, we can quantify the connection between halo mass and the outer stellar halo, which may provide new constraints on the formation and assembly of massive central galaxies.

Key words: galaxies: elliptical and lenticular, cD – galaxies: formation – galaxies: haloes – galaxies: photometry – galaxies: structure.

1 INTRODUCTION

A key discovery in the last decade has been the dramatic structural transformation of massive quiescent galaxies (e.g. Trujillo et al. 2006; Cimatti et al. 2008; van Dokkum et al. 2008; Damjanov et al. 2009; van der Wel et al. 2011; Szomoru, Franx & van Dokkum 2012; Patel et al. 2013) from $z \approx 2$ to the present day. These observations suggest that the progenitors of $z \sim 0$ massive early-type galaxies (ETGs) need to increase their effective radii (R_e) by a factor of 2–4 over a time span of 10 Gyr (e.g. Newman et al. 2012; van der Wel et al. 2014). This observational result spurred the development of the 'two-phase' formation scenario for massive ETGs (e.g. Oser et al. 2010, 2012), in which galaxies form a compact central region at $z\sim 2$ through highly dissipative processes (e.g. gas-rich mergers or cold gas accretion; Hopkins et al. 2008; Dekel, Sari & Ceverino 2009). They subsequently assemble extended stellar haloes via dry mergers (e.g. Khochfar & Silk 2006; Naab, Khochfar & Burkert 2006; Oser et al. 2010, 2012), which can cause significant size growth at late times. An alternative explanation for size growth, progenitor bias, hypothesizes that larger ETGs were quenched more recently; but this explanation is still under active debate (e.g. Newman et al. 2012; Carollo et al. 2013; Poggianti et al. 2013; Belli, Newman & Ellis 2015; Keating et al. 2015; Fagioli et al. 2016).

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There have been multiple observational attempts to test the two-phase formation scenario using galaxies at low redshift, by investigating surface brightness or mass density profiles (e.g. Huang et al. 2013a,b; Oh, Greene & Lackner 2017), optical colour gradients (e.g. La Barbera et al. 2010, 2012), and stellar population gradients (e.g. Coccato, Gerhard & Arnaboldi 2010; Coccato et al. 2011; Greene et al. 2015; Barbosa et al. 2016). These observations are generally consistent with the two-phase formation scenario. However, it is still not clear whether this picture correctly predicts the connection between the stellar mass distributions in massive galaxies and their dark matter haloes.

In the ΛCDM cosmology, the assembly of massive ETGs is intrinsically tied to the hierarchical growth of their host dark matter haloes (e.g. Leauthaud et al. 2012; Behroozi, Wechsler & Conroy 2013; Shankar et al. 2013). Hydrodynamic simulations suggest that the fraction of stars accreted through mergers (the *ex situ* component) in central galaxies increases with halo mass (e.g. Rodriguez-Gomez et al. 2016; Pillepich et al. 2017). The major merger rate is not a strong function of progenitor halo mass (e.g. Shankar et al. 2015) but minor mergers rate should increase with halo mass, hence play an important role in determining the structures of central galaxies (e.g. Guo et al. 2011; Yoon, Im & Kim 2017). Minor mergers are efficient at 'puffing up' the outskirts of massive galaxies (e.g. Bédorf & Portegies Zwart 2013; Oogi & Habe 2013). Because the minor merger rate increases with halo mass, the structures of massive ETGs and the well-known stellar mass–effective radius relation ($M_\star$–R_e; e.g. Shen et al. 2003; Guo et al. 2009) should depend on their 'environment'[1] (e.g. Shankar et al. 2013, 2014). However, evidence for the environment dependence of $M_\star$–R_e at low redshift is still not very solid (Nair, van den Bergh & Abraham 2010; Huertas-Company et al. 2013; but also see Yoon et al. 2017), and the results at higher redshift are even more unclear (e.g. Papovich et al. 2012; Lani et al. 2013; Delaye et al. 2014; but also see Rettura et al. 2010).

Deep images of massive galaxies can probe their outer stellar haloes of massive galaxies and test these predictions. Unfortunately, this is observationally challenging since the stellar haloes of massive galaxies can extend to >100 kpc (e.g. Tal & van Dokkum 2011; D'Souza et al. 2014), and their surface brightness profiles decline rapidly with typical values of $\mu > 26.0$ mag arcsec^{-2} in *i* band at 100 kpc and at $z \sim 0.3$. In Huang et al. (2017, Paper I hereafter), we showed that deep, multiband imaging from the Subaru Strategic Program (SSP; Aihara et al. 2017a,b) using Hyper Suprime-Cam (HSC; Miyazaki et al. 2012, 2018) allows us to extract robust surface stellar mass density ($\mu_\star$) profiles for *individual* galaxies with $\log_{10}(M_\star/\mathrm{M}_\odot)>11.4$ at $0.3 < z < 0.5$ and out to 100 kpc. In Paper I, we characterized the stellar mass profiles of massive ETGs and showed that there is a large intrinsic scatter in the stellar haloes of massive galaxies on 100-kpc scales. In this paper, we investigate whether the large scatter in the outer profiles of massive galaxies correlates with halo mass. We conclusively show that the sizes and stellar haloes of massive central galaxies depend on dark matter halo mass. In other words, we reveal the halo mass dependence of the mass–size relation for massive ETGs.

This paper is organized as follows. In Section 2 we briefly introduce the sample selection and the data reduction processes. Please refer to Huang et al. (2017) for more technical details. Our main results are presented in Section 3 and discussed in Section 4. Our summary and conclusions are presented in Section 5.

[1]There are multiple definitions of 'environment' in the literature. In this work, we use 'environment' and halo mass interchangeably.

Magnitudes use the AB system (Oke & Gunn 1983), and are corrected for galactic extinction using calibrations from Schlafly & Finkbeiner (2011). We assume $H_0 = 70\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_\mathrm{m} = 0.3$, and $\Omega_\Lambda = 0.7$. Stellar mass is denoted $M_\star$ and has been derived using a Chabrier initial mass function (IMF; Chabrier 2003). Halo mass is defined as $M_{200\mathrm{b}} \equiv M(< r_{200\mathrm{b}}) = 200\bar{\rho}\,\frac{4}{3}\pi r^3_{200\mathrm{b}}$, where $r_{200\mathrm{b}}$ is the radius at which the mean interior density is equal to 200 times the mean matter density ($\bar{\rho}$). As in Huang et al. (2017), we do not attempt to decompose or distinguish any potential 'intra-cluster' component (ICL; e.g. Carlberg, Yee & Ellingson 1997; Lin & Mohr 2004; Gonzalez, Zabludoff & Zaritsky 2005; Mihos et al. 2005).

2 SAMPLE SELECTION AND DATA REDUCTION

We refer the reader to Paper I for an in-depth description of the sample selection and data reduction processes. Here, we briefly summarize the main steps.

We use imaging data from the HSC internal data release `S15B`, which is very similar to the Public Data Release 1 (Aihara et al. 2017b) and covers ~110 deg^2 in all five bands (*grizy*) to the full depth in the wide field. The data are reduced by `hscPipe 4.0.2`, a derivative of the Large Synoptic Survey Telescope (LSST) pipeline (e.g. Axelrod et al. 2010; Jurić et al. 2015), modified for HSC (Bosch et al. 2017). The pixel scale of the reduced image is 0.168 arcsec. We use *i*-band images for extracting surface brightness profiles. HSC *i*-band images are typically 3–4 mag deeper than Sloan Digital Sky Survey (SDSS; e.g. Abazajian et al. 2009; Aihara et al. 2011; Alam et al. 2015) and have superb seeing conditions (mean *i*-band seeing has FWHM=0.6 arcsec).

In Paper I, we select a sample of 25 286 bright galaxies with spectroscopic redshifts or reliable 'red-sequence' photometric redshifts (Rykoff et al. 2014) at $0.3 < z < 0.5$. Within this redshift range, we have a large enough volume (~5×10^6 Mpc^3) to sample the galaxy stellar mass function above $\log_{10}(M_\star/\mathrm{M}_\odot)>11.6$, and we can spatially resolve galaxy profiles to ~5 kpc (1.0 arcsec corresponds to 4.4 and 6.1 kpc at $z = 0.3$ and 0.5, respectively). Massive galaxies should experience little structural evolution and size growth between $z = 0.5$ and 0.3 (~1.5 Gyr time span) based on model predictions (e.g. Shankar et al. 2015).

After carefully masking out surrounding neighbours and accounting for the subtraction of the background light, we derive *i*-band surface brightness profiles out to 100 kpc. We use the broad-band spectral energy distributions (SEDs) fitting code `iSEDFit`[2] (Moustakas et al. 2013) to measure $M_\star/L_\star$ ratios and *k*-corrections using five-band forced `cModel` magnitudes from `hscPipe`. We assume a Chabrier (2003) IMF, the Flexible Stellar Population Synthesis models[3] (FSPS; `v2.4`; Conroy & Gunn 2010a, Conroy & Gunn 2010b), the Calzetti et al. (2000) extinction law, and a simple delayed-τ model for star formation histories. Using HSC data, we can measure the $\mu_\star$ profiles of massive galaxies to ~100 kpc, and we integrate these profiles within elliptical isophotal apertures at different physical radii. As explained in Paper I, we focus on the two following metric masses:

(i) Stellar mass within 10 kpc (hereafter noted $M_{\star,\,10\,\mathrm{kpc}}$), which we use as a proxy for the stellar mass of the *in situ* stellar component. This is motivated both by observations and simulations (e.g. van Dokkum et al. 2010; Rodriguez-Gomez et al. 2016). The value of

[2]http://www.sos.siena.edu/jmoustakas/isedfit/
[3]http://scholar.harvard.edu/cconroy/sps-models