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Massive post-starburst galaxies at $z > 1$ are compact proto-spheroids

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ABSTRACT

We investigate the relationship between the quenching of star formation and the structural transformation of massive galaxies, using a large sample of photometrically selected post-starburst galaxies in the UKIDSS Ultra-Deep Survey field. We find that post-starburst galaxies at high redshift ($z > 1$) show high Sérsic indices, significantly higher than those of active star-forming galaxies, but with a distribution that is indistinguishable from the old quiescent population. We conclude that the morphological transformation occurs before (or during) the quenching of star formation. Recently quenched galaxies are also the most compact; we find evidence that massive post-starburst galaxies ($M_* > 10^{10.5} M_\odot$) at high redshift ($z > 1$) are on average smaller than comparable quiescent galaxies at the same epoch. Our findings are consistent with a scenario in which massive passive galaxies are formed from three distinct phases: (1) gas-rich dissipative collapse to very high densities, forming the proto-spheroid, (2) rapid quenching of star formation to create the ‘red nugget’ with post-starburst features and (3) a gradual growth in size as the population ages, perhaps as a result of minor mergers.

Key words: galaxies: evolution – galaxies: formation – galaxies: fundamental parameters – galaxies: high-redshift – galaxies: structure.

1 INTRODUCTION

Galaxies in the local Universe display a striking bimodality in their morphological and spectral characteristics; massive galaxies ($M_* > 10^{10.5} M_\odot$) are typically spheroidal with old stellar populations, while lower mass galaxies are typically disc-dominated with blue, younger stellar populations (e.g. Strateva et al. 2001; Hogg et al. 2002). Deep surveys have revealed that the most massive galaxies were formed at high redshift ($z > 1$; e.g. Fontana et al. 2004; Kodama et al. 2004; Cirasuolo et al. 2010), but we still do not understand why their star formation was abruptly terminated. Feedback from AGN (e.g. Silk & Rees 1998; Hopkins et al. 2005) or starburst-driven superwinds (e.g. Diamond-Stanic et al. 2012) are leading contenders for rapidly quenching distant galaxies, while jet-mode AGN feedback may be required to maintain the ‘red and dead’ phase (e.g. Best et al. 2006).

In addition to the quenching of star formation, massive galaxies must also undergo a dramatic structural transformation to produce the spheroid-dominated population that we see today. The transition appears to occur at $z > 1$ for most galaxies with $M_* > 10^{10.5} M_\odot$ (Mortlock et al. 2013; Bruce et al. 2014), but it is unclear if quenching and structural transformation occurred during the same event. Over the last 10 yr, it has also emerged that quiescent galaxies were significantly more compact in the early Universe compared to the present day (e.g. Daddi et al. 2005; Trujillo et al. 2006; van Dokkum et al. 2008; Belli et al. 2014). Plausible explanations for the dramatic size growth include minor mergers (e.g. Bezanson et al. 2009; Naab, Johansson & Ostriker 2009) or expansion due to mass-loss (Fan et al. 2008). For the population of quiescent galaxies as a whole, however, there may also be an element of progenitor bias; galaxies that quenched at lower redshift tend to be larger than their counterparts at early times, which may drive much of the observed size evolution (e.g. Carollo et al. 2013; Poggianti et al. 2013).

From a theoretical perspective, the formation of ultracompact massive spheroids requires the concentration of vast reservoirs of cool gas via dissipation, which can radiate and collapse to very

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high densities. A variety of models have arisen to explain spheroid formation in detail, with some invoking gas-rich mergers (e.g. Hopkins et al. 2009; Wellons et al. 2015) while others use the inflow of gas through cold streams, feeding an extended disc that eventually becomes unstable and contracts (e.g. Dekel et al. 2009; Zolotov et al. 2015). Outflows driven by an AGN or star formation may then terminate the star formation by expelling the remainder of the gas (e.g. Hopkins et al. 2005).

In this work, we explore the relationship between the quenching of distant galaxies and their structural transformation. We focus in particular on the rare class of ‘post-starburst’ (PSB) galaxies, which are observed a few hundred million years after a major episode of star formation was rapidly quenched. In the local Universe, PSBs are identified from characteristic strong Balmer absorption lines (Dressler & Gunn 1983; Wild et al. 2009), due to the strong contribution from A stars, but until recently very few were spectroscopically identified at $z > 1$ (e.g. Vergani et al. 2010). Two photometric methods have therefore been developed to identify this population. Whitaker et al. (2012) used medium-band photometry from the NEWFIRM Medium-Band Survey to identify ‘young red-sequence’ galaxies using rest-frame UVJ colour–colour diagrams. In Wild et al. (2014), an alternative approach was used, based on a principal component analysis (PCA) applied to the deep multiwavelength photometry in the Ultra-Deep Survey (UDS) field. Three spectral shape parameters (‘supercolours’) were found to provide a compact representation for a wide range of photometric spectral energy distributions (SEDs). In addition to cleanly separating quiescent and star-forming galaxies, the PCA method identifies ‘PSB’ galaxy candidates in a distinct region of supercolour space, corresponding to galaxies in which a significant amount of mass was formed within the last giga year but then rapidly quenched. The method was recently verified with deep 8 m spectroscopy from VLT, which established that between 60 and 80 per cent of photometric candidates are spectroscopically confirmed PSB galaxies, depending on the specific criteria adopted (Maltby et al. 2016).¹ In terms of completeness, the photometric method was found to identify approximately 60 per cent of galaxies that would be spectroscopically classified as PSBs. Overall, these figures confirm that photometric PCA techniques can be used to identify large and relatively clean samples of recently quenched galaxies. So far the spectroscopic confirmation is restricted to $z < 1.4$, given the requirement to detect $H\delta$ with optical spectroscopy. Future near-infrared spectroscopy (e.g. with the *James Webb Space Telescope*) will allow a detailed investigation of the population at higher redshift.

The identification of large PSB samples has allowed the first study of the PSB galaxy mass function and its evolution to $z = 2$ (Wild et al. 2016). Strong evolution was observed, with the implication that a large fraction of massive galaxies are rapidly quenched and pass through a PSB phase. In this paper, we use the unique PCA sample described in Wild et al. (2016) to explore the structural properties of PSB galaxies. As newly quenched systems, our primary aim is to investigate if this population is structurally similar to star-forming galaxies at the same epoch, or if they already show evidence for

the compact spheroid-dominated morphology of well-established quiescent galaxies.

We assume a cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$ and $h = 0.7$. All magnitudes are given in the AB system.

2 DATA AND SAMPLE SELECTION

2.1 The UDS K -band galaxy sample

Our study is based on deep K -band imaging from the UKIRT Infrared Deep Sky Survey (UKIDSS; Lawrence et al. 2007) UDS (Almaini et al., in preparation). The UDS is the deepest of the UKIDSS surveys, covering 0.77 square degrees in the J , H and K bands. We use the eighth UDS data release (Hartley et al. 2013), reaching depths of $J = 24.9$, $H = 24.2$ and $K = 24.6$ (AB, 5σ and 2 arcsec apertures). The final UDS data release (2016 June) achieved estimated depths $J = 25.4$, $H = 24.8$ and $K = 25.3$, and will be used to extend our PSB studies in future work.

To complement the near-infrared imaging from UKIDSS, the UDS has a deep optical coverage from Subaru Suprime-CAM to depths of $B = 27.6$, $V = 27.2$, $R = 27.0$, $i' = 27.0$ and $z' = 26.0$ (AB, 5σ and 2 arcsec), as described in Furusawa et al. (2008). Additional u' -band imaging is provided by the Canada–France–Hawaii Telescope (CFHT) MegaCam instrument, reaching $u' = 26.75$ (AB, 5σ and 2 arcsec). Deep imaging at longer near-infrared wavelengths is provided by the *Spitzer* UDS Legacy Program (SpUDS; PI: Dunlop), achieving depths of 24.2 and 24.0 (AB) using the IRAC camera at 3.6 and 4.5 μm , respectively. The resulting area with full multiwavelength coverage, following the masking of bright stars and artefacts, is 0.62 square degrees. Further details on the construction of the multiwavelength DR8 catalogue can be found in Hartley et al. (2013).

We determined photometric redshifts using the techniques outlined in Simpson et al. (2013). The 11-band photometric data were fit using a grid of galaxy templates, assembled using simple stellar populations from Bruzual & Charlot (2003; hereafter BC03), with a logarithmic spacing of ages between 30 Myr and 10 Gyr, and the addition of younger templates with dust-reddened SEDs. The additional templates consist of a mildly reddened ($A_V = 0.25$ mag) version of the two youngest templates, plus a version of the 30 Myr template with heavier reddening ($A_V = 1.0$ mag). The resulting photometric redshifts show a normalized median absolute deviation $\sigma_{\text{NMAD}} = 0.027$. The stellar masses used in this work differ slightly from those presented in Simpson et al. (2013), and instead are based on supercolour templates (see Section 2.3). As noted in Section 4.2, we investigated a range of alternative stellar masses, including those from Simpson et al. (2013), and found no significant impact on our conclusions.

2.2 Classification using PCA supercolours

We classify galaxies using a PCA method applied to the broadband photometric data, using the techniques outlined in Wild et al. (2014; hereafter W14). The aim of the PCA analysis is to describe the variation in galaxy SEDs using the linear combination of only a small number of components. The components are derived using a library of spectral synthesis models from BC03, using a wide range of stochastic star formation histories, metallicities and dust-reddening. We found that only three principal components (effectively low-resolution ‘eigenspectra’) are required, in linear combination, to account for >99.9 per cent of the variance in photometric SEDs. The amplitude of each component defines a ‘supercolour’,

¹ From a sample of 24 PSB candidates, 19 galaxies (~ 80 per cent) showed strong Balmer absorption lines ($W_{H\delta} > 5 \text{ \AA}$), dropping to 14 confirmations (~ 60 per cent) if stricter criteria are used to exclude galaxies with significant [O II] emission. The fraction of spectroscopic PSBs among the passive and star-forming PCA classes was estimated to be < 10 and < 1 per cent, respectively (Maltby; private communication).

analogous to a traditional colour but defined using all available photometric bands. Supercolours allow the comparison of SEDs without the need for model fitting, and galaxies with extreme properties are free to have colours that differ substantially from any of the input model components.

Using the supercolour technique, we separated the UDS galaxy population into three categories: passive galaxies (with low specific star formation rates), star-forming galaxies and PSB galaxies. PSB galaxies are identified as a well-defined stream of galaxies in supercolour space, consistent with quiescent stellar populations in which a large fraction (>10 per cent) of the stellar mass was formed within the last ~ 1 Gyr, with the star formation then rapidly quenched (W14; see also Wild et al. 2016). The precise boundary between the passive and PSB population is set by the ability to observe strong Balmer absorption lines in optical spectroscopy (W14; Maltby et al. 2016). As outlined in Wild et al. (2016), evolutionary tracks suggest that not all photometric PSBs may have necessarily undergone a short-lived ‘burst’ of star formation. The population may also include galaxies that have undergone more extended ($\lesssim 3$ Gyr) periods of star formation, but the key characteristic is the rapid quenching of star formation within the last ~ 1 Gyr.

In W14, four categories of star-forming galaxies were identified (SF1, SF2, SF3 and dusty), which we combine for the purposes of this work. As outlined in W14 (see also Section 4.3), the classification by supercolours is in very good agreement with the separation of galaxies using the more traditional rest-frame UVJ technique for separating star-forming and passive galaxies (Labbé et al. 2005; Wuyts et al. 2007). There is also good agreement with the UVJ method of Whitaker et al. (2012), who identified recently quenched candidates at the blue end of the passive UVJ sequence.

2.3 Stellar masses

We determined stellar masses for each galaxy using a Bayesian analysis to account for the degeneracy between physical parameters. Further details may be found in Wild et al. (2016). A library of tens of thousands of population synthesis models was created using BC03 and fit to the supercolours to obtain a probability density function for each physical property. A wide range of star formation histories, dust properties and metallicities were explored, including exponentially declining star formation rates with superimposed stochastic starbursts. Stellar masses were calculated assuming a Chabrier initial mass function, defined as the stellar mass at the time of observation, i.e. allowing for the fraction of mass in stars returned to the interstellar medium due to mass-loss and supernovae. The resulting stellar mass uncertainties from the Bayesian fits are typically ± 0.1 dex for all populations, assuming BC03 stellar population synthesis models and allowing for uncertainties in the photometric redshifts. The potential impact of stellar mass errors (random and systematic) is discussed further in Section 4.2.

Fig. 1 shows the resulting distribution of stellar mass as a function of redshift, separated into the three primary populations. Mass completeness limits (95 per cent) were determined as a function of redshift using the method of Pozzetti et al. (2010). We note that the 95 per cent completeness limit for star-forming galaxies appears to be surprisingly high in this diagram (formally slightly higher than the PSB population). This is caused by the wide range in mass-to-light ratios within the star-forming population.

As outlined in Wild et al. (2016), the PSB mass function evolves strongly with redshift, so that the comoving space density of massive PSBs ($M_* > 10^{10} M_\odot$) is several times higher at $z \sim 2$ than at $z \sim 0.5$. This trend is apparent in Fig. 1, which shows a sharp

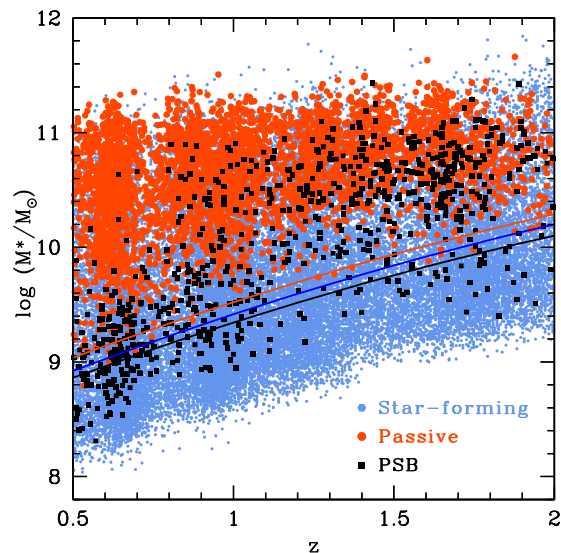


Figure 1. The distribution of stellar mass as a function of photometric redshift for the three primary galaxy populations. The curves show the corresponding 95 per cent completeness limits, determined using the method of Pozzetti et al. (2010). Details of the galaxy classification and stellar mass determination can be found in Wild et al. (2016). In this paper, we focus on the structural properties of galaxies in the redshift range $1 < z < 2$.

decline in the number of massive PSBs at $z < 1$. The majority of PSBs at $z < 1$ are close to the 95 per cent completeness limit (see Fig. 1) and typically very faint; the median K -band magnitude for PSBs at $z < 1$ is $K = 23.0$, compared to $K = 21.8$ at $z > 1$. In this work, we therefore concentrate on the structural properties of PSBs at $z > 1$, and defer an examination of the low-redshift ground-based sample to future work using deeper K -band imaging. In the redshift range $1 < z < 2$, our initial sample consists of 24 880 star-forming galaxies, 2043 passive galaxies and 502 PSBs, of which 9183, 2001 and 385, respectively, have stellar masses $M_* > 10^{10} M_\odot$.

2.4 CANDELS-UDS

Throughout this work, we compare our ground-based determinations of galaxy size and Sérsic index with measurements from the *Hubble Space Telescope* (HST) CANDELS survey (Grogin et al. 2011; Koekemoer et al. 2011), using measurements provided in van der Wel et al. (2012). The UDS is one of the three targets for the CANDELS Wide survey, with imaging in the J and H bands taken with the Wide Field Camera 3 (WFC3). The CANDELS imaging covers only ~ 7 per cent of the UDS field (~ 9 per cent of the area used in our analysis), but this is sufficient to provide an independent test and calibration for our ground-based structural parameters. Full details of the GALFIT measurement of structural parameters within CANDELS are given in van der Wel et al. (2012).

3 GROUND-BASED MEASUREMENTS OF SIZE AND SÉRSIC INDEX

We determined structural parameters for the K -band galaxy sample using the GALAPAGOS software (Barden et al. 2012). The package allows the automated use of GALFIT (Peng et al. 2002) to fit Sérsic light profiles (Sérsic 1968) to all galaxies in the UDS, parametrized with a Sérsic index, n , and effective radius, R_e , measured along the semi-major axis. We acknowledge that many high-redshift galaxies are described by more complex morphologies (see Bruce et al. 2014),

but single Sérsic fits provide a simple parametrization to allow us to compare the bulk properties of the galaxy populations.

An accurate determination of the point spread function (PSF) is critical for this process as galaxies at $z > 1$ typically have half-light radii below 0.5 arcsec. Following the work of Lani et al. (2013), we investigated PSF variations across the UDS field and found that most variations occurred between WFCAM detector boundaries within the UDS mosaic (Casali et al. 2007). Testing revealed that we could obtain consistent results by splitting the UDS field into 16 overlapping subregions, corresponding to the 4×4 WFCAM tiling pattern. Within each region, the light profiles of approximately 100 stars were stacked to provide the local PSF measurement, with variations across the field in the range 0.75–0.81 arcsec (full width at half-maximum). Considerable care was taken to mask sources in the vicinity of the stars used for PSF measurement.

From the resulting measurements of size and Sérsic index, we rejected ~ 9 percent of galaxies where `GALFIT` failed to converge on a Sérsic solution. The rejection rate was similar for the star-forming, passive and PSB populations. A further ~ 1 percent of galaxies were rejected (a priori) if the fits were formally very poor ($\chi_r^2 > 100$), which typically corresponded to highly blended objects on the K -band image. Matching the output from `GALAPAGOS` with our supercolour catalogue, we obtain a final sample of 8098 star-forming galaxies, 1829 passive galaxies and 348 PSBs in the redshift range $1 < z < 2$ with $M_* > 10^{10} M_\odot$.

In Figs 2 and 3, we display the resulting size and Sérsic measurements for the subset of UDS galaxies within the *HST* CANDELS survey. Ground-based measurements are compared with those obtained using H -band CANDELS measurements, as published in van der Wel et al. (2012).

For the size measurements, we find a tight relationship between the ground-based K -band and CANDELS H -band sizes, as previously found by Lani et al. (2013). On average, the sizes obtained from CANDELS are systematically ~ 13 percent larger, which is consistent with previous comparisons of size measurements as a function of waveband (e.g. Kelvin et al. 2012). The systematic offset is consistent among the three galaxy populations studied here; so we apply no corrections for this effect. The characteristic scatter in $\delta R/R$ given by the normalized median absolute deviation (σ_{NMAD}) is 17, 16 and 24 percent for the star-forming, passive and PSB populations, respectively.

Ground-based measurements of Sérsic index are far more uncertain for a given galaxy (Fig. 3), and we find a significant degree of scatter when comparing ground-based and CANDELS measurements. Formally, the characteristic scatter in $\delta n/n$ given by the normalized median absolute deviation (σ_{NMAD}) is 45, 39 and 35 percent for the star-forming, passive and PSB populations, respectively. Nevertheless, there is a clear correlation, and we find that ground-based determinations are sufficient to distinguish populations with ‘high’ Sérsic indices (e.g. $n > 2$) from those with ‘low’ Sérsic indices ($n < 2$). Comparing the three primary galaxy types, we find consistent results; the passive and PSB populations show consistently high Sérsic indices (from ground- or space-based measurements), while star-forming galaxies are concentrated at lower values. The binned distribution demonstrates that the correlation between ground- and space-based Sérsic indices is not perfectly 1:1, but we see no systematic differences in this relation between the three populations. We conclude that ground-based measurements can be used to broadly compare the Sérsic indices for our galaxy populations. In addition, we will use the subset of galaxies with *HST* measurements (~ 9 percent) to verify any conclusions drawn from the larger ground-based sample. The Sérsic distributions will be compared further (and as a function of stellar mass) in Section 5.

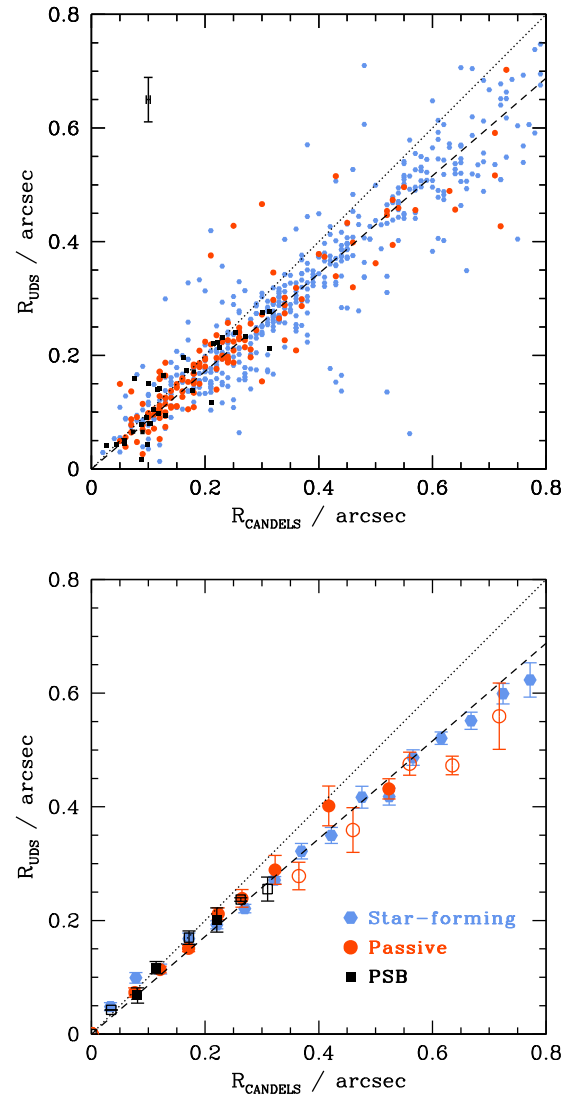


Figure 2. A comparison of size measurements for galaxies measured with ground-based K -band imaging and *HST* H -band imaging, using the subsample of ~ 9 percent of galaxies within the UDS CANDELS mosaic. The upper panel compares half-light radii for individual galaxies. We find that ground-based imaging can provide robust measurements of galaxy sizes, although the relationship is not precisely 1:1. A linear fit to all points suggests that ground-based sizes are ~ 13 percent smaller on average (dashed line). A characteristic uncertainty on individual measurements is shown, representing the median error on the PSB sizes. The lower (binned) distribution compares mean sizes for the three key populations, with unfilled symbols representing mean values determined from fewer than five galaxies. We find no evidence for a significant systematic bias in ground-based size determinations with spectral type. Galaxies shown have photometric redshifts in the range $1 < z < 2$ and stellar masses with $\log(M_*/M_\odot) > 10$ to match the samples used in this work.

4 THE SIZES OF POST-STARBURST GALAXIES

4.1 The size–mass relation

In Fig. 4, we compare the size versus stellar-mass relation for galaxies in the redshift range $1 < z < 2$. Individual galaxies are shown, along with mean values as a function of stellar mass (in bins of 0.25 dex). In the upper panels, we show the results from the ground-based

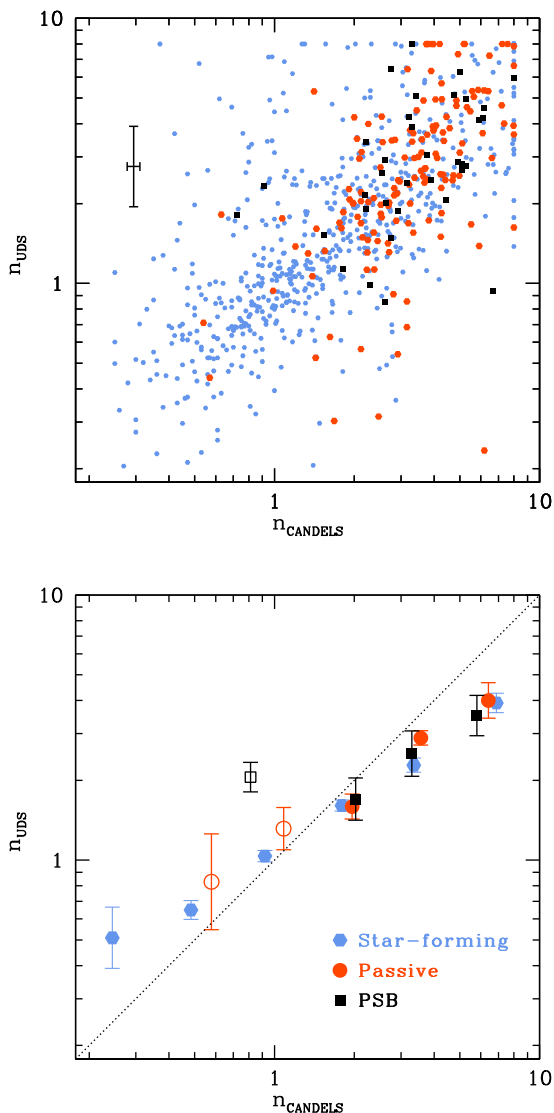


Figure 3. A comparison of Sérsic index measurements for galaxies measured with ground-based K -band imaging and HST H -band imaging, using the subsample of ~ 9 per cent of galaxies within the UDS CANDELS mosaic. The upper panel compares individual galaxies, with a characteristic error bar denoting the median uncertainty in $\log_{10}(n)$ for the PSB population. We find that ground-based determinations of Sérsic indices are sufficient to broadly distinguish populations with high average values from those with low average values. The lower (binned) distribution compares the mean Sérsic indices, binned as a function of n_{CANDELS} . Open symbols denote mean values determined from fewer than five galaxies. There are deviations from a 1:1 relation, but no evidence for a systematic bias in ground-based Sérsic determinations with spectral type. Galaxies shown have photometric redshifts in the range $1 < z < 2$ and stellar masses with $\log(M_*/M_\odot) > 10$ to match the samples used in this work.

K -band imaging, while the lower panels are based on independent sizes from CANDELS H -band imaging (covering ~ 9 per cent of the sample). The 95 per cent mass completeness limits are shown (see Section 2.3), determined at $z = 2$ to provide conservative limits. In determining mean values for the ground-based sample, we applied a 5σ clip (with one iteration) to remove extreme outliers, but removing this constraint has no significant influence.

Representative error bounds for individual galaxies are shown on the left-hand panels, based on the median errors on the PSB

sample. For the CANDELS sizes, data are taken from van der Wel et al. (2012), which include estimates for random and systematic errors from GALFIT. For the ground-based individual errors, we add in quadrature the scatter in $\delta R/R$ determined by the comparison with CANDELS (Section 3). The representative uncertainty on stellar masses is based on our Bayesian mass-fitting analysis described in Wild et al. (2016), as briefly outlined in Section 2.3.

The size–mass relations show the expected trends for star-forming and passive galaxies, consistent with previous studies (e.g. Daddi et al. 2005; Trujillo et al. 2006; van Dokkum et al. 2008; McLure et al. 2013; van der Wel et al. 2014). On average, passive galaxies appear significantly more compact than star-forming galaxies of equivalent stellar mass, but show a steeper size–mass relation, leading to convergence at the highest masses ($M_* \sim 10^{11.5} M_\odot$). Intriguingly, we find that PSB galaxies at this epoch are also extremely compact; they are comparable in size to the established passive galaxies, with evidence that they are smaller on average at high mass ($M_* > 10^{10.5} M_\odot$). These trends are apparent with the large ground-based sample and with the smaller CANDELS sample.

We performed a bootstrap analysis as a simple test of significance, randomly sampling the (ground-based) populations within each mass bin, with replacement. For the four bins above $10^{10.5} M_\odot$, the fraction of the resampled populations in which the passive galaxies show mean sizes equal to (or smaller than) the mean of the PSB population are 0.07, 5×10^{-5} , 1.2×10^{-4} and 4×10^{-5} (low-to-high mass, respectively). We note that the final bin contains 86 passive galaxies but only three PSBs, so the bootstrap comparison for this bin may be unreliable. Overall, assuming no systematic errors, we find evidence that massive PSB galaxies at $z > 1$ are significantly more compact, on average, than passive galaxies of comparable mass. Repeating the analysis using the median sizes produced very similar trends. The median analysis and further tests of robustness are presented in Appendix A. Our results are consistent with the findings of Yano et al. (2016), who also found evidence that high-redshift PSB galaxies are very compact.

As an additional comparison, in Fig. 5 we display the distribution of $\Sigma_{1.5} \equiv M_*/R_c^{1.5}$ for the three galaxy populations, measured for the redshift range $1 < z < 2$ and stellar masses $M_* > 10^{10.5} M_\odot$. Following Barro et al. (2013), we use this parameter to effectively remove the slope in the galaxy size/mass relation. Fitting a function of the form $M_* = \Sigma R_c^\alpha$ to the passive population, we find a best fit with $\alpha = 1.55$, in very good agreement with the value $\alpha = 1.5$ assumed by Barro et al. (2013). A simple Kolmogorov–Smirnov (KS) test rejects the null hypothesis that passive galaxies and PSBs are drawn from the same underlying distribution in $\Sigma_{1.5}$ with a significance > 99.99 per cent, with the same significance obtained with either value of α .

Given the strong evolution of the PSB mass function (Wild et al. 2016), a concern is that massive PSBs are more common at higher redshifts, which may bias the size–mass comparison when measured over a wide redshift range. In Fig. 6, we therefore display the size–mass relation in two narrower redshift bins, $1.0 < z < 1.5$ and $1.5 < z < 2.0$. With two independent samples, the results confirm that PSB galaxies, on average, show smaller half-light radii than the passive population at high mass ($M_* > 10^{10.5} M_\odot$). An additional test was performed using a weighted mean, with a redshift-dependent weight determined for each PSB using the ratio of the $n(z)$ distributions for passive galaxies and PSBs. The resulting size–mass relations were barely changed, with only a slight reduction in the significance of the differences reported above.

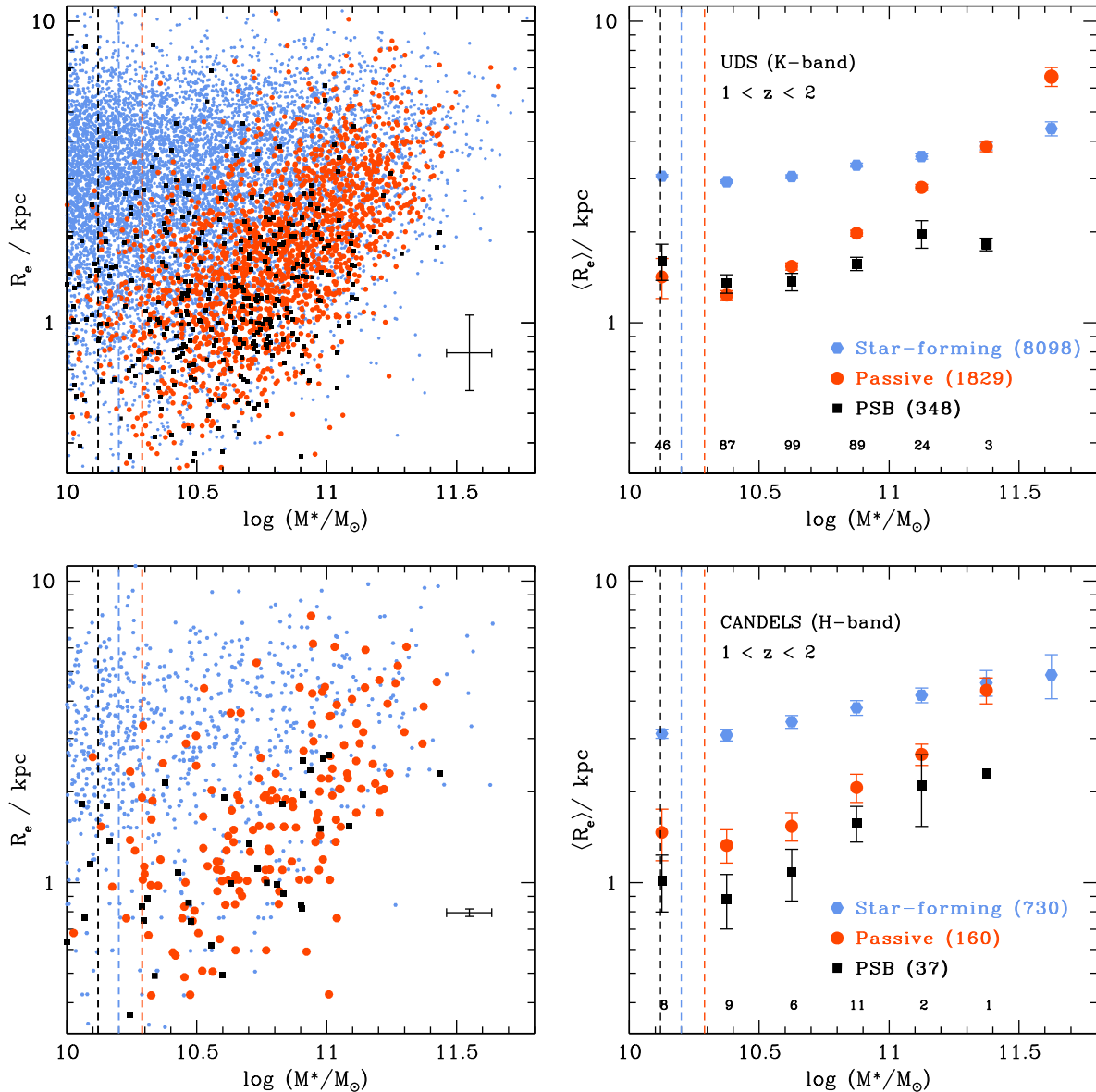


Figure 4. The stellar size–mass relation for star-forming, passive and PSB galaxies in the redshift range $1 < z < 2$. The top figures show the results from the ground-based *K*-band sample, showing individual galaxies (left) and mean sizes as a function of stellar mass (right). For the individual galaxies (left), a characteristic 1σ error bound is displayed, showing the median uncertainties in the fitted size and stellar mass for the PSB population. For the binned relation (right), the numbers in parentheses denote the number of galaxies in each sample, while the number of PSBs per mass bin is also shown. Errors on mean sizes represent the standard error on the mean (though we caution that the highest mass PSB bin contains only three galaxies). The lower figures show the equivalent for the subsample of galaxies with *HST* CANDELS *H*-band imaging, with sizes determined by van der Wel et al. (2012). Very similar trends are observed, although we note the small sample of PSBs (e.g. one galaxy in the highest mass bin). Overall, we conclude that PSB galaxies are exceptionally compact, with evidence that (on average) they are smaller than typical quiescent galaxies at the highest stellar masses ($M_* > 10^{10.5} M_\odot$). The dashed vertical lines denote the 95 per cent completeness limits, determined at the upper redshift range ($z = 2$).

A natural interpretation of our findings is that quiescent galaxies are most compact when they are newly quenched, but then grow with cosmic time. Given the short-lived nature of the PSB phase, we expect the majority of passive galaxies to have gone through a similar stage in their past (Wild et al. 2016). Our results therefore provide evidence for the genuine growth of individual galaxies, suggesting that the growth of the population as a whole is not purely caused by a progenitor bias. We discuss the implications further in Section 6.

A simple calculation allows us to compare the size differences with the observed cosmological growth. Based on population

synthesis models, we estimate that the established passive population quenched approximately 0.5–1 Gyr before the PSB population at these redshifts (Wild et al. 2016), and the characteristic difference in size (e.g. based on the shift in $\Sigma_{1.5}$) is approximately 25 per cent on average at $M_* > 10^{10.5} M_\odot$. The implied growth rate is similar to the observed cosmological growth, parametrized by van Dokkum et al. (2010) in the form $r_e \propto (1+z)^{-1.3}$ (i.e. ~ 25 per cent per Gyr at $z = 1.5$ – 2). An improvement on these tentative conclusions will require more accurate age-dating of the stellar populations, which will soon be possible with growing spectroscopic samples.

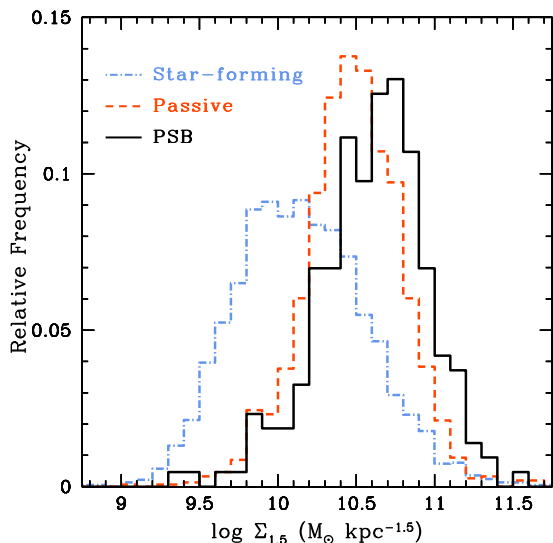


Figure 5. We compare the distribution of $\Sigma_{1.5}$ values for the three galaxy populations in the redshift range $1 < z < 2$, with stellar masses $M_* > 10^{10.5} M_\odot$. This parameter ($\Sigma_{1.5} \equiv M_*/R_e^{1.5}$), defined by Barro et al. (2013), effectively removes the slope of the galaxy mass/size relation; high values of $\Sigma_{1.5}$ correspond to galaxies that are compact for their stellar masses. A KS test rejects the null hypothesis that passive galaxies and PSBs are drawn from the same underlying distribution in $\Sigma_{1.5}$, with a significance of >99.99 per cent.

4.2 Stellar mass uncertainties

In this section, we explore the potential impact of both random and systematic errors on our stellar masses.

The typical uncertainty from our Bayesian stellar mass fitting is $\sigma \simeq 0.1$ dex for all galaxy types, allowing for the degeneracy between fitted parameters and the uncertainties on photometric redshifts. To investigate the impact on our conclusions, we performed Monte

Carlo realizations, allowing the stellar masses to shift randomly within a Gaussian probability distribution in $\log M_*$. We found no impact on any of the results presented in Section 4.1. Comparing the resulting distributions in $\Sigma_{1.5}$, the significance of the difference between the PSB and passive galaxy populations was unchanged, suggesting that the sample overall is large enough to minimize the influence of random errors.

To investigate the influence of fitting methods, we re-evaluated the size–mass relations using two independent sets of stellar masses derived by Simpson et al. (2013) and Hartley et al. (2013), the latter also using an independent set of photometric redshifts. No significant differences were found.

As a note of caution, however, we acknowledge that the observed differences between PSBs and passive galaxies could arise if our stellar masses are systematically overestimated for younger stellar populations. Our stellar masses are based on population synthesis models from BC03, which may underestimate the influence of thermally pulsing asymptotic giant branch (TP-AGB) stars (Maraston et al. 2006). Such stars may have a major contribution to the rest-frame near-infrared light for stellar populations in the age range 0.2–2 Gyr, potentially leading to overestimated stellar masses for passive galaxy populations. The influence of TP-AGB stars is discussed further in Wild et al. (2016), where it was found that the influence of TP-AGB stars is strongest for galaxies with BC03-determined ages >1 Gyr, for which the ages and mass-to-light ratios are reduced using the models of Maraston et al. (2006). The net effect would be to move our passive galaxies to lower masses relative to the younger PSB population, which would enhance the differences in the size–mass relation.

In summary, our findings appear robust to known sources of random and systematic error, but we acknowledge the possibility that unknown systematic uncertainties in the stellar mass determination may contribute to the difference in size–mass relations presented in our work. Future deep infrared spectroscopy may allow a more detailed investigation of the inherent uncertainties in determining stellar masses from photometric data.

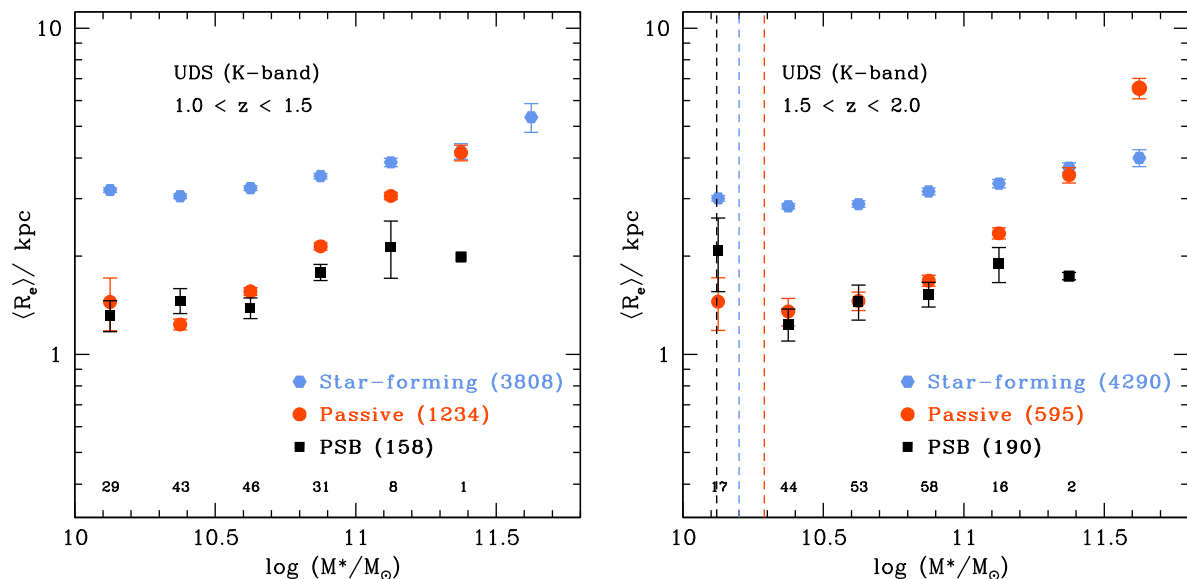


Figure 6. A comparison of the galaxy mean size–stellar mass relation for star-forming, passive and PSB galaxies in two redshift bins. The numbers in parentheses denote the number of galaxies in each sample, while the number of PSBs per mass bin is shown at the bottom of each plot. Errors on mean sizes represent the standard error on the mean (though we note the small number of PSBs in the highest mass bins). The vertical lines denote the 95 per cent completeness limits (all below $10^{10} M_\odot$ for the low-redshift bin).

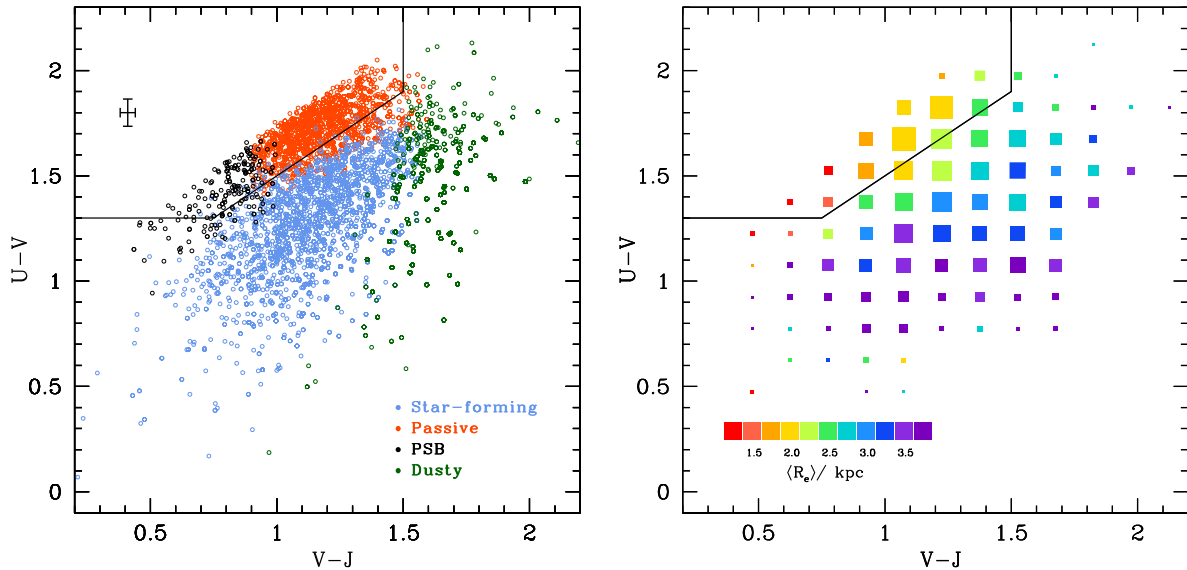


Figure 7. Rest-frame UVJ colour–colour diagrams for UDS galaxies in the redshift range $1 < z < 2$, and within the mass range $10.5 < \log(M_*/M_\odot) < 11.5$. Previous studies have separated galaxies into ‘quiescent’ and ‘star-forming’ categories using the boundary shown. The left-hand panel compares the classification of galaxies using supercolours with the UVJ method (in this diagram separating the dusty PCA class from the other star-forming galaxies). We find good agreement between the classification methods, with a very similar boundary between star-forming and passive types. PSB galaxies selected by supercolours are primarily located at the blue end of the quiescent UVJ region, in good agreement with the boundaries proposed by Whitaker et al. (2012). A representative error bar is displayed, showing the median uncertainties for the PSB population. The right-hand panel shows average sizes determined for all galaxies in colour–colour bins, without using supercolours. Symbol size is proportional to the number of galaxies per bin. The trends confirm that ‘young-quiescent’ galaxies selected by the UVJ technique show smaller average sizes than redder passive galaxies, consistent with our classification based on PCA supercolours.

4.3 A comparison with UVJ selection

To allow a comparison of our supercolour technique with previous work, in Fig. 7 (left) we present a rest-frame UVJ colour–colour diagram for UDS galaxies in the redshift range $1 < z < 2$. As previously shown in W14, the classification of galaxies using supercolours agrees very well with the more traditional UVJ colour selection (Labbé et al. 2005; Wuyts et al. 2007). PSB galaxies are generally found at the blue end of the passive UVJ region, in good agreement with the findings of Whitaker et al. (2012). The distribution in $U - V$ alone confirms that PSBs predominantly lie in the classic ‘green valley’, intermediate between passive and star-forming galaxies, but the addition of the $V - J$ colour isolates this population in the distinct region corresponding to the youngest red-sequence galaxies.

In the right-hand panel of Fig. 7, we illustrate the average effective radii in colour–colour bins. We select the subset of galaxies over the mass range $10.5 < \log(M_*/M_\odot) < 11.5$ to minimize the effects of the size–mass relation. The trends confirm that ‘young quiescent’ galaxies selected by the UVJ technique show smaller average sizes, in good agreement with our analysis based on supercolours. Our results are consistent with a similar recent analysis by Yano et al. (2016).

5 THE SÉRSIC INDICES OF POST-STARBURST GALAXIES

In Fig. 8, we compare the Sérsic indices for star-forming, passive and PSB galaxies at $z > 1$. The distributions obtained from the ground-based K -band data are consistent with those obtained for the smaller CANDELS sample. In both cases, we find that star-forming galaxies show a distribution peaking sharply at $n \simeq 1$, while passive and PSB galaxies show very different distributions, peaking

at significantly higher values. A KS test confirms these findings, rejecting the null hypothesis that either passive or PSB galaxies are drawn from the same distribution as star-forming galaxies to a high level of significance ($\gg 99.99$ per cent, using the ground-based sample). In contrast, the Sérsic distributions for passive and PSB galaxies do not appear significantly different.

The right-hand panel in Fig. 8 presents the median Sérsic indices as a function of stellar mass. We find evidence for a slight increase in the median Sérsic index with stellar mass for all populations, but in all mass bins the PSB galaxies show significantly higher Sérsic indices than star-forming galaxies, and values consistent with the passive population. Using the mean produced very similar trends, but Sérsic indices were slightly higher in all cases (by $\delta n \simeq 0.5$).

We caution that single Sérsic fits provide only a crude parametrization of the data, as it is now well established that most galaxies at this epoch have more complex morphologies (e.g. Bruce et al. 2014). A high Sérsic index does not necessarily imply a purely spheroidal system, and low Sérsic indices do not necessarily imply the presence of an established disc (Mortlock et al. 2013). Nevertheless, it is clear from our data that the PSB galaxies are structurally very different to the actively star-forming population, and more comparable to ultracompact equivalents of the passive population. We explore multiple-component fitting in future work (Maltby et al., in preparation).

6 DISCUSSION

We have presented evidence that massive ($M_* > 10^{10.5} M_\odot$) recently quenched (PSB) galaxies at high redshift ($z > 1$) are exceptionally compact. Furthermore, they show high Sérsic indices, indistinguishable from the established passive population at the same epoch. We conclude that the structural transformation must have occurred

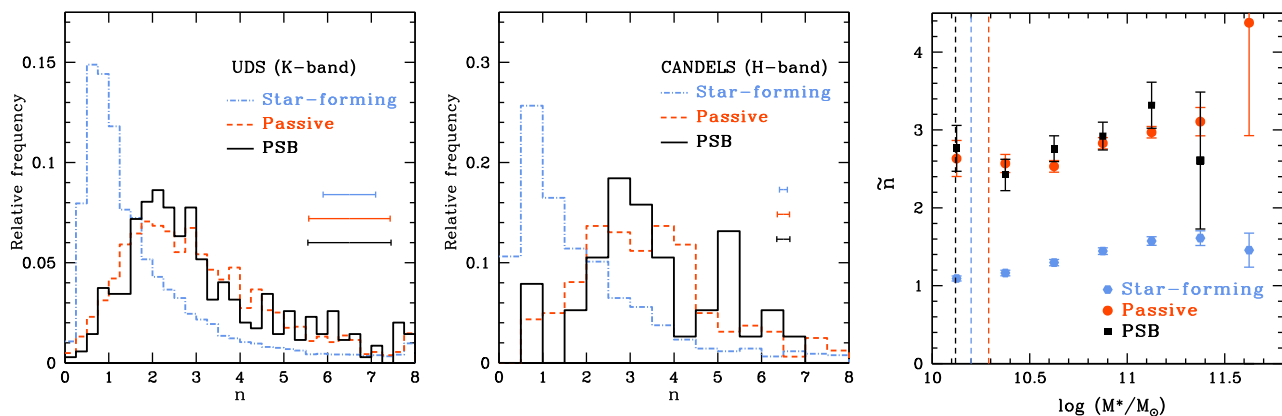


Figure 8. A comparison of the Sérsic indices for star-forming, passive and PSB galaxies in the redshift range $1 < z < 2$ with stellar masses $M_* > 10^{10} M_\odot$. The left-hand panel shows a histogram of Sérsic indices determined from ground-based UDS K -band imaging. The central panel shows a histogram of Sérsic indices determined for the smaller sample with available *HST* H -band imaging from CANDELS (from van der Wel et al. 2012). Characteristic uncertainties are displayed for each population, showing the median error on the fitted Sérsic index for individual galaxies. The right-hand panel shows median Sérsic indices as a function of stellar mass for the larger K -band sample, using identical binning to Fig. 4. We conclude that PSB galaxies show significantly higher Sérsic indices than star-forming galaxies, but with a distribution that is indistinguishable from the older passive population.

before (or during) the event that quenched their star formation. Given that the majority of massive passive galaxies at $z > 1$ are thought to have passed through a PSB phase (Wild et al. 2016), our findings suggest a strong link between quenching and the formation of a compact spheroid.

Our results confirm the findings of Whitaker et al. (2012), who found evidence that younger passive galaxies are more compact at $z > 1$, and the more recent *HST* CANDELS study by Yano et al. (2016). At intermediate redshifts ($z \sim 1$) previous studies have found conflicting results on the relationship between stellar age and the compactness of passive galaxies, with indications that progenitor bias may be playing a role at this epoch (Keating et al. 2015; Williams et al. 2017).

Our findings may be explained if high-redshift PSB galaxies are formed from the dramatic collapse of gas at high redshift, formed from either a gas-rich merger (e.g. Hopkins et al. 2009; Wellons et al. 2015), or from gas inflow feeding a massive disc, which becomes unstable and collapses by ‘compaction’ (e.g. Dekel et al. 2009; Zolotov et al. 2015; Tacchella et al. 2016). Star formation must then be rapidly quenched, either by a central AGN or feedback from highly nucleated star formation (e.g. Hopkins et al. 2005; Diamond-Stanic et al. 2012), leaving an ultracompact PSB remnant. It may be possible to test these evolutionary scenarios by comparing the properties of PSB galaxies with their likely active progenitors, i.e. star-forming galaxies caught during the merging or ‘compaction’ phase. Current candidates include submillimetre galaxies, many of which appear to be highly compact at $\sim 250 \mu\text{m}$ in the rest-frame (e.g. Simpson et al. 2015), and the high-redshift ‘blue nuggets’ (e.g. Barro et al. 2013; Mei et al. 2015; Barro et al. 2017). Whatever the true progenitors for our PSBs, the most likely explanation is that structural transformation occurred immediately prior to quenching. The fact that the PSBs and passive galaxies have indistinguishable Sérsic indices (Fig. 8) would suggest that most of the structural change is already established when the star formation is quenched, unless the structural transformation occurs on a much shorter time-scale than the ~ 500 Myr lifetime for the PSB phase.

Following the formation of the proto-spheroid, there are currently two leading explanations for the observed growth in passive galaxies with cosmic time. Minor gas-free mergers provide

a plausible physical mechanism (e.g. Bezanson et al. 2009; Naab et al. 2009), and indeed there is evidence that high-redshift passive galaxies are larger in dense environments, where such interactions are more likely (e.g. Lani et al. 2013). Alternatively, progenitor bias may mimic the observed growth, since passive galaxies formed at later times are typically larger (e.g. Carollo et al. 2013; Poggianti et al. 2013).

Our finding that PSB galaxies are more compact than older passive galaxies, on average, would suggest that we are observing an earlier phase in the lifetime of steadily growing spheroids. Thus, progenitor bias is unlikely to be the primary cause for the observed growth at early times; our observed trends show precisely the opposite behaviour (with younger galaxies being more compact). On the other hand, if massive PSB galaxies represent newly formed ‘red nuggets’, it is notable that their abundance is a strong function of redshift; massive ($M_* > 10^{10.5} M_\odot$) PSB galaxies are several times more abundant at $z \sim 2$ compared to $z \sim 0.5$ (Wild et al. 2016). Thus, while the majority of high-mass passive galaxies at $z \sim 2$ are likely to have been through the ultracompact PSB phase (Wild et al. 2016), this may become an increasingly less dominant channel towards lower redshifts, when progenitor bias may play a more significant role in explaining size evolution (e.g. see Fagioli et al. 2016; Williams et al. 2017). Even at low redshift, however, there is evidence that the most compact quiescent galaxies have evolved from post-starburst progenitors (Zahid et al. 2016).

Finally, we note that the mass function for PSBs shows a very distinctive evolution in shape (Wild et al. 2016). At high redshift ($z \sim 2$), the mass function resembles that of quiescent galaxies, dominated by high-mass systems with a sharp decline in space density above a mass of $M_* \sim 10^{10.5} M_\odot$. At low redshift ($z < 1$), the population is dominated by lower mass systems, with a shape resembling the mass function for star-forming galaxies. These features are interpreted as evidence for two distinct formation channels for PSB galaxies; high-mass systems formed from gas-rich dissipative collapse and low-mass systems formed from environmental quenching or the merging of normal disc galaxies (Wild et al. 2016). Our structural findings are in good agreement with this scenario, with the PSBs above the same characteristic mass displaying distinctive, ultracompact morphologies, consistent with a highly dissipative, gas-rich origin. We will present a detailed study of the structural

parameters for low-mass PSBs in future work (Maltby et al., in preparation).

7 CONCLUSIONS

We present a study of the structural parameters for a large sample of photometrically selected PSB galaxies in the redshift range $1 < z < 2$, recently identified in the UKIDSS UDS field. These rare transition objects provide the ideal sample for understanding the links between the quenching of star formation and the structural transformation of massive galaxies.

We demonstrate that deep ground-based near-infrared imaging can be used to obtain robust sizes and Sérsic indices for large samples of high-redshift galaxies. From the resulting size–mass relation, we find that massive ($M_* > 10^{10.5} M_\odot$) PSB galaxies are exceptionally compact at $z > 1$, with evidence that they are more compact on average than established passive galaxies at the same epoch. Since most high-mass passive galaxies at $z > 1$ are likely to have been through a PSB phase (Wild et al. 2016), the implication is that quiescent galaxies are most compact when they are newly quenched, thereafter growing with cosmic time. An important caveat, however, is to acknowledge the considerable uncertainty in stellar mass estimation, as discussed in Section 4.2. As an avenue for future research, it will be important to determine whether stellar masses are systematically overestimated for recently quenched stellar populations.

We also find that PSB galaxies show high Sérsic indices, significantly higher than star-forming galaxies on average, but statistically indistinguishable from the Sérsic indices of established passive galaxies at the same epoch. We conclude that massive PSB galaxies represent newly formed compact proto-spheroids. Furthermore, the structural transformation of these galaxies must have occurred before (or during) the event that quenched their star formation.

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APPENDIX A: ROBUSTNESS TESTS

In this section, we discuss a number of additional tests that were performed to investigate the robustness of the size–mass relations presented in this paper.

Throughout this work, we have measured average sizes when comparing galaxy populations, yielding evidence that PSB galaxies are typically smaller than passive galaxies of comparable stellar mass. The use of a mean may produce misleading results, however, if either population is skewed by a significant number of outliers (e.g. misclassified interlopers from other galaxy categories). In Fig. A1 (left-hand panel), we therefore reproduce the size–mass relation from Fig. 4, but this time using median size values. In most bins, the median sizes are slightly smaller than the mean, as the size distributions show a slight tail to high values. The significant differences between the passive and PSB galaxies remain, however. At high mass ($M_* > 10^{10.5} M_\odot$), the overall significance of the trends is essentially unchanged compared to the results outlined in Section 4.1. We conclude that the use of a mean has not biased our primary conclusions.

As a further source of error, we considered the possibility that the passive and PSB samples are contaminated by star-forming galaxies, e.g. due to uncertainties in classification. If the contaminating fraction is higher for the passive population (for reasons unknown), this could skew the size measurements upwards. We tested for this effect by applying a cut in Sérsic index. Noting the very different distributions in Sérsic index between star-forming and passive samples (see Fig. 8), we re-evaluated the size–mass relations using only passive and PSB galaxies with $n > 2$ (see Fig. A1, right-hand panel), again using the median size to further reduce the impact of

interlopers. The striking difference in sizes remains, with a negligible reduction in significance. Using a mean estimator yields the same result, with a size–mass relation that is almost identical to the upper-right panel of Fig. 4. We conclude that ‘contamination’ from galaxies with low Sérsic indices (whether passive or star forming) is not affecting our conclusions.

As an additional test, we investigated the influence of using a cleaner (though less complete) sample of PSB galaxies. As outlined in Section 1 and Maltby et al. (2016), the primary source of contamination is between PSB galaxies and ‘normal’ passive galaxies. Depending on the precise selection criteria, between 20–40 per cent galaxies in the PSB category would be classified as passive (rather than PSB) using spectroscopy, while 6–10 per cent of the passive category would be spectroscopically classified as PSBs (Maltby; private communication). Based on fig. 3 in Maltby et al. (2016), we therefore identify a ‘cleaner’ PSB sample by selecting galaxies further from the passive/PSB boundary, with superclusters $SC2 > 6$. In this regime, formally 100 per cent of PSB candidates (15/15) were confirmed with $W_{H\delta} > 5 \text{ \AA}$. Using this new subsample, the resulting size–mass relation (evaluated using the standard mean estimator) is shown in Fig. A2 (left-hand panel). We find that the difference in size compared to passive galaxies remains, and in fact is slightly enhanced; the mean PSB size is formally smaller in five out of six bins. We conclude that contamination of the PSB category by older passive galaxies can only act to dilute the differences we observe.

As another test for contamination, we combined the PCA classification with the classic UVJ criteria (e.g. see Fig. 7), to exclude PSBs and passive galaxies that are classified as ‘star-forming’ using rest-frame UVJ colours. The aim is to remove red star-forming galaxies that may have been misclassified by the PCA technique. Using these joint criteria removes 26 per cent of passive galaxies and 34 per cent of PSBs from our primary sample ($z > 1$, $M_* > 10^{10} M_\odot$). The resulting size–mass relations are shown in Fig. A2 (right-hand panel). We find that the difference between the PSBs and passive galaxies at high mass remains, and in fact is slightly enhanced.

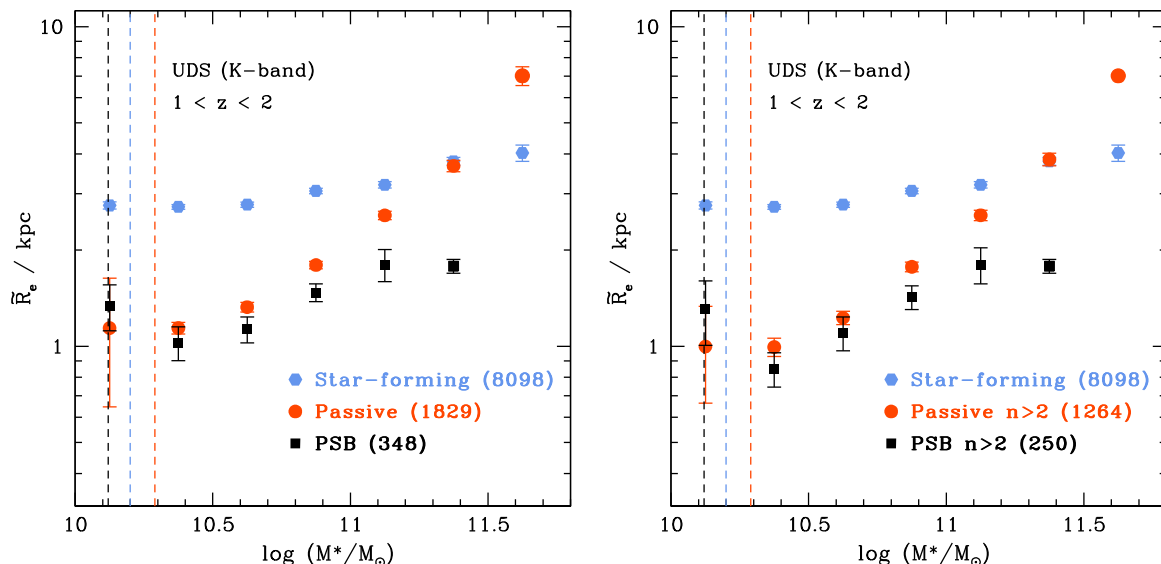


Figure A1. Two examples of tests for robustness. The left-hand panel shows the size–mass relation for comparison with Fig. 4 ($1 < z < 2$), but using the median rather than the mean effective radius per bin. The right-hand panel shows the size–mass relation (also using median values) after the removal of all passive and PSB galaxies with $n < 2$. Since star-forming galaxies have significantly lower Sérsic indices (see Fig. 8), this is a test to determine if contamination from SF galaxies is affecting the size–mass relations. In both cases, we find that our primary conclusions are unchanged, i.e. PSB galaxies at high mass ($M_* > 10^{10.5} M_\odot$) appear significantly smaller than both star-forming and passive galaxies.

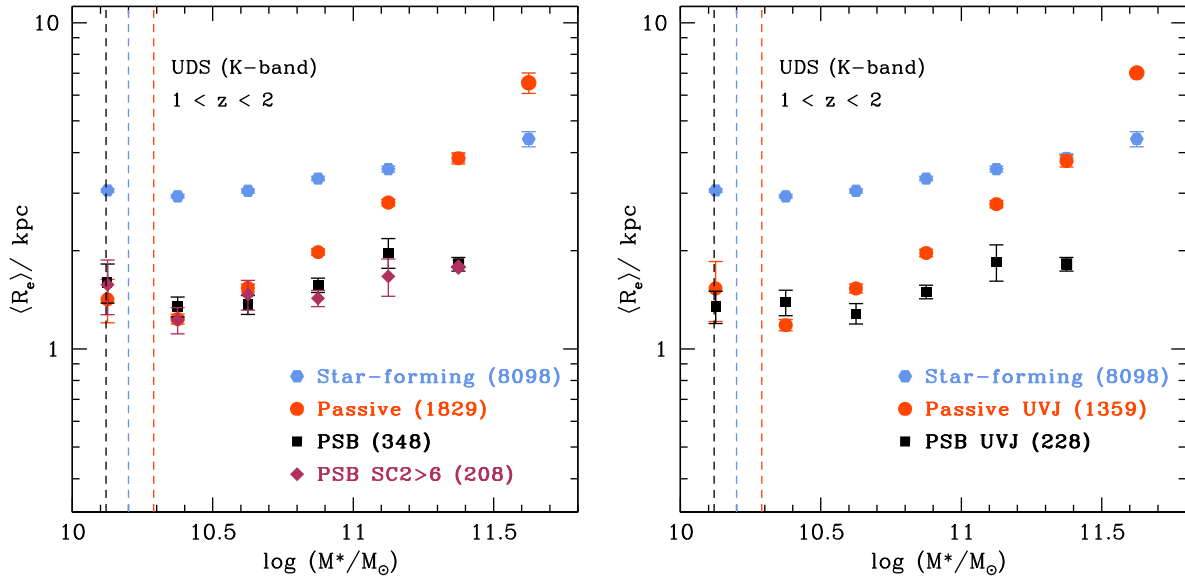


Figure A2. Two further tests for robustness. The left-hand panel shows the ground-based size–mass relation, using the mean size (as shown in Fig. 4), with the addition of a comparison sample of ‘secure’ PSBs, identified further from the passive/PSB boundary (with supercolours $SC2 > 6$). The right-hand panel shows the size–mass relation using only the subset of passive galaxies and PSBs that simultaneously lie within the quiescent region of the UVJ diagram (e.g. see Fig. 7). In both cases, we find little change in the observed trends, with evidence for a slight enhancement in the difference between high-mass PSBs and passive galaxies using the restricted samples.

Finally, we performed a variety of tests using more stringent cuts on the structural parameters derived for our ground-based galaxy sample, using the CANDELS data set as a calibrating sample. No significant differences were found. We noted, however, that ground-based size measurements become increasingly unreliable when GALFIT assigns a very low axis ratio, $q < 0.1$. Approximately 6 per cent of the galaxies in our sample are affected, mostly among the star-

forming galaxies, but also affecting 3–4 per cent of the passive and PSB sample (mostly at low mass; $M_* < 10^{10.5} M_\odot$). Removing these galaxies had no major influence on the size–mass relations; in fact, the difference in size between passive and PSB galaxies became marginally more significant.

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