Compact galaxies and the size-mass galaxy distribution from a colour-selected sample at $0.04 < z < 0.15$ supplemented by $ugrizYJHK$ photometric redshifts

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ABSTRACT

The size-mass galaxy distribution is a key diagnostic for galaxy evolution. Massive compact galaxies are of particular interest as potential surviving relics of a high-redshift phase of star formation. Some compact galaxies at low redshift could be nearly unresolved in Sloan Digital Sky Survey (SDSS) imaging and thus not included in SDSS galaxy samples. To overcome this, a sample was selected from the 9-band combination of SDSS and UKIRT Infrared Deep Sky Survey (UKIDSS) photometry to $r < 17.8$. This was done in two stages: first using colour-selection, and then by obtaining accurate photometric redshifts (photo-z) using scaled flux matching (SFM). Compared to spectroscopic redshifts (spec-z), SFM obtained a 1-sigma scatter of 0.0125 with only 0.3% outliers ($|\Delta \ln(1+z)| > 0.06$). A sample of 163 186 galaxies was obtained with $0.04 < z < 0.15$ over 2300 deg$^2$ using a combination of spec-z and photo-z. Following Barro et al., $\log \Sigma_{1.5} = \log M_\ast - 1.5 \log r_{50,\text{maj}}$ was used in order assess the completeness and number density of massive compact galaxies ($\log M_\ast > 10$, $\log \Sigma_{1.5} > 10.5$). The spectroscopic completeness was 76% for compact galaxies compared to 92% for normal-size galaxies. This difference is primarily attributed to SDSS 'fibre collisions' and not the completeness of the main galaxy sample selection. Using environmental overdensities, this confirms that compact quiescent galaxies are significantly more likely to be found in high-density environments compared to normal-size galaxies. By comparison with a high-redshift sample from 3D-HST, $\log \Sigma_{1.5}$ distribution functions show significant evolution, with this being a compelling way to compare with simulations such as EAGLE. The number density of compact quiescent galaxies drops by a factor of about 30 from $\sim 2$ to $\log(n/\text{Mpc}^{-3}) = -5.3 \pm 0.4$ in the SDSS-UKIDSS sample. The uncertainty is dominated by the steep cut off in $\log \Sigma_{1.5}$, which is demonstrated conclusively using this complete sample.

Key words: galaxies: evolution — galaxies: luminosity function, mass function — galaxies: distances and redshifts — galaxies: structure

1 INTRODUCTION

The galaxy population of the local Universe is very different to its ancestral population ten billion years ago at $z \sim 2$. One of the most striking changes is the transformation of the radially small massive galaxies seen at high redshift to the larger and more diffuse red galaxies seen today. Multiple observations indicate that a high proportion of galaxies at $z > 2$ are already ‘red and dead’ as well as unusually small for their mass relative to local red galaxies (e.g. Daddi et al. 2005; Trujillo et al. 2007). A quintessential high-redshift quiescent galaxy, or ‘red nugget’, has a stellar mass ($M_\ast)$ of $\sim 10^{11} M_\odot$ and a half-light radius of $\sim 1$ kpc (van Dokkum et al. 2008; Damianov et al. 2009).

Considering the demographics in more detail, at $z \sim 2$ almost half of the massive ($M_\ast > 10^{10} M_\odot$) galaxy population are both quiescent (e.g. Cimatti et al. 2004; Kriek et al. 2006) and radially smaller than quiescent galaxies locally (Daddi et al. 2005; Trujillo et al. 2007; Longhetti et al. 2007; Buitrago et al. 2008; Barro et al. 2013). The red nuggets at $z \sim 2$ measure $5–6$ times smaller than the median size of low-redshift samples (Shen et al. 2003; Lange et al. 2015) for the same mass (van Dokkum et al. 2008). These observations have posed a significant challenge for theories of galaxy evolution.

In a hierarchical structure formation scenario, red nuggets should evolve into the most massive ellipticals in the local Universe (e.g. Trujillo et al. 2007). An early proposed mechanism for this evolution involved an adiabatic expansion of stellar systems in response to a significant mass loss from their inner re-

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gions. This mass expulsion is thought to be driven by means of stellar winds or/and quasars and to reduce the effective radius as $R_s \propto M^{-1}$ (Fan et al. 2008; Damjanov et al. 2009; Fan et al. 2010; Ragone-Figueroa & Granato 2011). However, the amount of the stellar mass loss is too small to explain the size evolution (Damjanov et al. 2009). Compact massive galaxies are already quiescent in terms of star-formation activity at high $z$ and they do not seem to possess sufficient gas to increase their stellar component significantly (Bezanson et al. 2009).

A natural hierarchical explanation for this radial growth would involve major mergers ($\sim 1:1$ mass ratio) building the red sequence from the high-redshift compacts to the local red giant ellipticals. However, major mergers result in equal growth of both mass and radius (Damjanov et al. 2009); they shift galaxies along the high-redshift mass-radius relation rather than towards the low-redshift relation (see also Bovlan-Kolehin et al. 2006). Major mergers are effectively ruled out of consideration for this reason, and because ‘wet’ (star-forming) mergers would leave a signature in the stellar density profiles of galaxies that is not seen (Szomoru et al. 2012).

The current view for explaining the size-mass evolution is that a series of minor mergers together with accretion of a stellar envelope have combined to build either local elliptical galaxies or massive spiral/S0 galaxies (Hopkins et al. 2010; Sonnenfeld et al. 2013; van Dokkum et al. 2013; Graham et al. 2013). Progenitor bias has also been involved in explaining the apparent size evolution of the red galaxy population as a class (e.g. Szomoru et al. 2012; Carollo et al. 2013). In fact, as noted by Barro et al. (2013), both paths must operate: an early formation of massive compact galaxies that become quenched and then grow via minor mergers (Naab et al. 2009; Hilz et al. 2012), and a late-arrival path in which larger star-forming galaxies build mass and then form extended quenched galaxies (Barro et al. 2013).

It has long been recognised that local massive ellipticals generally have old stellar populations with little recent star formation. However, they could still have undergone significant evolution due to mergers unless they are compact. The stochastic nature of merging processes suggests that a non-negligible number of quiescent massive compact galaxies at each redshift between 2 and 0 should be unaltered, old and compact ‘relics’ (Trujillo et al. 2014). Quantifying the number density of these massive compact relics in the present-day universe is thus an important constraint on galaxy formation models (Quilis & Trujillo 2013; Ferré-Mateu et al. 2017), in addition to relics being local analogs of the high-redshift red nuggets (Saulder et al. 2015; Yildirim et al. 2017; Martin-Navarro et al. 2019).

Valentinuzzi et al. (2018) searched for and found a population of compact galaxies in local $0.04 < z < 0.07$ clusters using mass and surface mass density lower limits. Poggianti et al. (2013) showed that the fraction of these ‘superdense’ galaxies was 3-4 times higher in groups with high velocity dispersion ($> 500$ km/s) compared to the field. This means that it requires large volumes using blind surveys in order to sample compact galaxies in high-density environments. Saulder et al. (2015) searched the Sloan Digital Sky Survey (SDSS) for compact quiescent galaxies, using a lower limit on galaxy velocity dispersion ($> 300$ km/s) in addition to an upper limit on size ($\lesssim 2$ kpc), finding only 76 galaxies at $0.05 < z < 0.3$. Even these are not as extreme as the high-redshift red nuggets. Using deeper imaging in the Galaxy And Mass Assembly (GAMA) survey regions, Britagro et al. (2018) found 22 massive compact galaxies ($log M_* > 10.9$) with number density $\sim 10^{-6}$ cMpc$^{-3}$ at $z < 0.3$. Various authors have quantified the evolution in the number density of compact galaxies (e.g. Barro et al., 2013; Cassata et al. 2013; van Dokkum et al. 2013; Tortora et al. 2013; Charbonnier et al. 2013), for log $M_*$ > 10 or higher limits, for quiescent/star-forming galaxies, and with various definitions of compactness (e.g. Gargiulo et al. 2016; Lu et al. 2019). The number density of compact quiescent galaxies peaks around $z \sim 1-2$.

There is some concern that local galaxy surveys could be missing extremely compact galaxies due to mis-identification with stars in the input catalogue. For example, for the SDSS main galaxy sample, $r < 17.77$ mag, a profile separator is used for galaxy selection (Strauss et al. 2002). Without this, there would be about ten times as many stars as galaxies for this magnitude limit. Liske et al. (2006) spectroscopically identified all sources over $1.14$ deg$^2$ to $B < 20$ mag for the Millenium Galaxy Catalogue (MGC). They estimated that about 1% of galaxies in the MGC input catalogue were mis-identified as stars. The volume probed in the $\sim 1$ deg$^2$ region, however, was not sufficient to search for massive compact galaxies. Taylor et al. (2010) considered the selection of galaxies in SDSS, which includes cuts against saturation, spectroscopic fiber crosstalk, and the concentration of light. All of these characteristics predispose compact galaxies to exclusion by the SDSS automated data pipeline for spectroscopic selection. Taylor et al. concluded that the SDSS completeness should be $\gtrsim 75\%$ for the types of compact galaxies seen at high redshift but maybe as low as $\sim 20\%$ for the smallest galaxies.

The aim of this paper is to determine the local number densities of compact galaxies using a complete sample. This is enabled by star-galaxy separation using colours and photometric redshifts based on 9-band photometry from the combination of SDSS (York et al. 2000) and the UKIRT Infrared Deep Sky Survey (UKIDSS, Lawrence et al. 2007). The sample selection and photometric redshifts are described in §2 and §3. The results of the size-mass relations and distributions are presented and discussed in §4 and a summary is presented in §5. We assume a flat ΛCDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$ and $\Omega_{m,0} = 0.3$.

## 2 SAMPLE SELECTION

### 2.1 Data

Sources were selected from the SDSS DR14 database with $r < 17.8$ (r-band extinction-corrected Petrosian magnitude) covering five separate sky areas as shown in Table 1 from tables PHOTO-PRIMARY and, where available, SPECOBJ. This approximately matched the UKIDSS Large Area Survey (LAS) sky coverage. No restrictions were applied based on photometric flags or star-galaxy separation. This produced a catalog of 3.38 million sources covering 2664 deg$^2$.

Sources were selected from the UKIDSS database LASYJHKSOURCE table, which provides combined data for the LAS survey. The magnitude limits were $Y < 18.4$ or $J < 18.1$.

### Table 1. Sky areas. RA and DEC limits for selection of sources from catalog. The areas were chosen to approximately match UKIDSS LAS coverage.

| RA range (deg.) | DEC range (deg.) | note |
|-----------------|-----------------|------|
| 125 to 238      | −2 to 15        | LAS main region |
| 114 to 128      | 18 to 30        |      |
| 190 to 210      | 22 to 36        |      |
| 240 to 250      | 22 to 32        |      |
| > 309.2 or < 58.6 | −1.26 to 1.26   | Stripe 82 |

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with magnitude types petromag, apermag3 or apermag4. These limits were a magnitude fainter than expected for any typical type of galaxy given the SDSS r-band limit. The aim was to be inclusive at this stage. This produced a catalog of 15.28 million sources.

Sources were selected from the GAIA DR2 GAIA SOURCE table over the areas defined in Table 1. This produced a catalog of 12.02 million sources, of which, 687,471 have a GAIA G-band magnitude brighter than 15.

2.2 Masking radii around GAIA sources

The SDSS main galaxy sample (Strauss et al. 2002) excluded sources for which the saturated flag was set. This was to remove artifacts that are caused by light either diffracted or scattered from bright stars. Without resorting to this flag, it is instead possible to remove these types of artifacts by masking the sky area around selected stars. These stars are, of course, uncorrelated with the galaxy distribution and there is no bias in trimming the catalogue using this method.

The exclusion radius around GAIA stars was empirically determined using the spectroscopically-confirmed galaxy sample from SDSS. To do this, the sky density of confirmed galaxies around each star was measured in bins of separation and GAIA magnitude of the star. Two examples of this are shown in Figure 1. The radius at which the sky density (within the radius) is 25% of the expected sky density was determined. This was chosen as visually this is the radius at which the impact of the stellar stray light becomes negligible. Figure 2 shows the resulting exclusion radii versus the GAIA magnitude.

2.3 Trimming the area

The sample selection requires UKIDSS data and since the initial query did not take account of the exact coverage, significant adjustment to the area was needed. In particular, there is a requirement for $Y$, $J$ and $K$ data, and the UKIDSS coverage was defined with the criteria that valid photometry exists in all these bands. At the same time, there are genuine SDSS galaxies without a UKIDSS catalogue match and these should not be rejected. Therefore the SDSS sample was trimmed by area and not by match criteria.

The SDSS master sample was trimmed in area using the following:

- Seven polygons were defined where there was no UKIDSS coverage and sources within these polygons were removed.
- A $6' \times 6'$ grid was defined and sources in grid areas without any UKIDSS coverage were removed.
- One polygon was defined where there was no SDSS spectroscopy and sources within this polygon were removed.
- Sources in areas with $g$-band Galactic extinction greater than 0.4 were removed.
- Sources in the masked areas around $G < 13.5$ GAIA stars were removed (of course, note GAIA sources include galaxies but no spectroscopically-confirmed SDSS galaxies had a GAIA aperture magnitude brighter than 14.5 in the sample. Therefore, 13.5 is a safe limit that even compact galaxies would not be excluded.

This produced a catalog of 2.48 million sources covering 3300 deg$^2$.

2.4 Colour-colour galaxy selection

In order to avoid using a profile separator for star-galaxy separation, galaxies were selected using a combination of SDSS and UKIDSS colours. To do this, we considered two colour-colour diagrams: $J - K$ versus $g - i$ and $Y - K$ versus $g - z$. These show the clearest separation between galaxies and stars, while also not requiring matched-aperture or matched-profile photometry between UKIDSS and SDSS. For UKIDSS, we used apermag4 and for SDSS, we used PSF and PETRO magnitudes.

The basic method is to obtain a quadratic fit to the stellar locus of the UKIDSS colour as a function of the SDSS colour over a suitable range, with clipping of the function beyond that range. The galaxy selection is then defined as galaxies with UKIDSS colour greater than 0.2 above the function value.

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1 GAIA G-band flux measurements use a rectangular aperture of 0.77" × 1.057" (12 × 18 pixels) for sources brighter than 16th mag, and 0.77" × 0.77" for fainter sources (Gaia Collaboration et al. 2018).
The $J-K$ separator is given by
\[ \Delta_{sg,jk,gi} = J_{AB} - K_{AB} - f_{locus}(g - i) \]  
with the locus function as per Baldry et al. (2010). For this paper, we determined the locus function for $Y-K$ versus $g-z$ colours using spectroscopically-confirmed stars and with point-spread function (PSF) magnitudes for the SDSS colours. This additional separator is given by
\[ \Delta_{sg,yk,gz} = Y_{AB} - K_{AB} - f'_{locus}(g - z) \]  
where
\[ f'_{locus}(x) = \begin{cases} 
-0.8297 & x < 0.3 \\
-1.04 + 0.74x - 0.13x^2 & 0.3 < x < 2.8 \\
0.0128 & x > 2.8 
\end{cases} \] (3)

Figure 3 shows the two colour–colour diagrams used to distinguish stars from galaxies. Note that when determining the $\Delta$ values for the selection, the bluer of SDSS PSF and SDSS Petrosian magnitudes are used for each source. This is in order to be inclusive toward galaxy selection (where the Petrosian colours could be different from the PSF colours). The colour-only galaxy selection is then given by
\[ 0.2 < \Delta_{sg,jk,gi} < 3 \ & \ 0.2 < \Delta_{sg,yk,gz} < 3 \]  
with the high cuts used to exclude some cases of photometric measurement problems. Figure 4 shows these selection boundaries with the distributions of $\Delta_{sg,yk,gz}$ versus $\Delta_{sg,jk,gi}$ for stars and galaxies.

The colour–colour selection results in 225 634 sources. Of these, 198 123 have an associated reliable SDSS redshift, with 99.2%, 0.3% and 0.5% classified as a galaxy, star and quasar, respectively (a galaxy being defined to have $0.002 < z < 0.4$ or by
s spectral class from the SDSS pipeline). This demonstrates the high purity of this selection.

2.5 Additional selections

The above selection is not complete because of the reliance on UKIDSS-SDSS matching, and this can miss extended sources where the UKIDSS aperture position is offset or undefined. In addition, the method of trimming the area to UKIDSS Y, J and K coverage is not perfect. Additional sources with SDSS photometry but no UKIDSS match were selected using the SDSS star-galaxy profile separator,

$$\Delta_{\text{ag, prof}} = r_{\text{model}} - r_{\text{prof}},$$

satisfying the following criteria:

$$\Delta_{\text{ag, prof}} > 0.5 \; \& \; \text{not SATURATED} \; \& \; \mu_{r,50} < 24.5,$$

where $\mu_{r,50}$ is the Petrosian half-light surface brightness. These criteria selected 15 309 sources.

On top of the UKIDSS-SDSS and SDSS-only selections, 4533 sources that were galaxy targets in DR7 and 169 spectroscopically-confirmed galaxies, but not otherwise selected, were included. Including all four selections, this results in 245 645 sources, of which 86.1% have redshifts from SDSS and 0.2% from 2MRS (Huchra et al. 2012). This leaves 13.7% without spectroscopic redshifts (spec-z).

3 PHOTOMETRIC REDSHIFTS FROM SCALED FLUX MATCHING (SFM)

The above combined selection (§ 2.4) primarily selects galaxies. However, 1.0% of the sources are spectroscopically-confirmed stars (kept in for testing purposes) and a significant fraction of those without spec-z are stars. This is because there are about 10 times as many stars as galaxies at these magnitudes ($r < 17.8$), and finding any nearly unresolved galaxies is like 'looking for a needle in a haystack'. To refine the search further, we use a photometric redshift (photo-z) technique that identifies sources with galaxy-like fluxes (beyond that already considered with the colour-colour selection). In addition, redshifts are needed to estimate luminosities and physical sizes.

Photo-z methods are generally divided into two classes: template fitting (e.g. Babbedge et al. 2004; Brammer et al. 2008) and empirical. When there are many sources with reliable spec-z covering the colour and magnitude space of a sample, which is the case for this SDSS-UKIDSS sample, empirical methods should be more accurate (Koo 1999). Here, we note that empirical methods can be further divided into: (a) predictive modelling, for example, using neural networks (Firth et al. 2003) or analytical functions (Connolly et al. 1995; Sedgwick et al. 2019a); and (b) photometric-property matching, typically using colours and a magnitude (Beck et al. 2016). In the latter method, a source’s photo-z is obtained by the distribution of spec-z for galaxies with similar properties. Here, we use scaled flux matching (SFM). This is similar to colour matching except that it works in linear flux space with the advantage that it can naturally deal with missing data, low S/N measurements (Sedgwick et al. 2019b) or, more generally, different errors in each band.

3.1 General method

For each source $i$ and band $k$, the uncertainty in the flux is given by:

$$\sigma_{r,k,i}^2 = \sigma_{r,p,k,i}^2 + (a_k f_{i,k})^2$$

where $\sigma_{r,p,k,i}$ is the Poisson/counting or linear error, $a_k$ is the band-dependent fractional error, and $f_{i,k}$ is the flux. If the Poisson error is not well determined, then a band-dependent value could be used. The flux measurements and flux uncertainties are also corrected for Galactic extinction.

For each source, the fluxes are matched to the matching-set galaxy ($j$) fluxes with chi-squared defined as:

$$\chi^2_{i,j} = \sum_k \frac{(f_{i,k} - n_{i,j} f_{j,k})^2}{\sigma_{r,k}^2}$$

where $n_{i,j}$ is the usual best-fit normalization when scaling a model to fit data points with errors (obtained from solving $dx^2/dn = 0$):

$$n_{i,j} = \frac{\sum_k f_{j,k} f_{i,k}/\sigma_{r,k}^2}{\sum_k f_{j,k}^2/\sigma_{r,k}^2}.$$

Note that no uncertainty is applied to the matching-set fluxes in the calculation of chi-squared.

The reliability weight of the match is then given by:

$$w_{i,j} = \exp(-\chi^2_{i,j}/2) W_j$$

where $W_j$ is any additional weight assigned to galaxy $j$ of the matching set. This could be, for example, to downweight redshift bins that are well populated. Importantly, $w_{i,j}$ is set to zero where $i$ and $j$ refer to the same galaxy. This is so the photo-z of the matching-set galaxies are independent of their spec-z.

These weights could then be used to estimate a probability distribution function (PDF) if desired. In general, this method is accurate if the matching set is large and the galaxies for which photo-z are desired are within the covered range of spectral-energy distribution (SED) type and redshifts. A characterization of the PDF is then given by the weighted mean and standard deviation. The weighted mean of the redshift variable is given by:

$$\zeta_{\text{phot}} = \sum_{i,j} w_{i,j} \zeta_{j,\text{spec}} / \sum_{i,j} w_{i,j}$$

Noting that $\zeta$ (zeta) is the appropriate quantity to use when dealing with redshift measurements and errors (Baldry 2018).

The initial estimate of the uncertainty (nominal error) is given by:

$$\zeta_{i,\text{err}}^2 = \left( \sum_{i,j} w_{i,j} \zeta_{j,\text{spec}}^2 / \sum_{i,j} w_{i,j} \right) N_{i,\text{eff}} - 1$$

which is the weighted standard deviation multiplied by a correction factor to obtain the sample standard deviation. The effective number of measurements for reliability weights is given by

2 Note for coding purposes in languages like IDL, R and PYTHON, the calculations can be performed using inbuilt matrix multiplication where appropriate rather than loops. This is known to be significantly faster.

3 To reduce computation time and to obtain an estimate of the weighted mean even if too many matching-set galaxies have similar weight, only a set number of the matching-set galaxies with the highest weights (lowest $\chi^2$) are included in the calculation of the weighted mean and nominal error. In this paper, we used 2500. For comparison, Beck et al. 2016 used the best 100 matching-set galaxies with all these given the same weight.
\[ N_{i,\text{eff}} = \left( \sum_j w_{i,j} \right)^2. \] (13)

### 3.2 Specific implementation

SDSS ModelMag values were converted to fluxes in units of nanomaggies (log-flux zeropoint of 22.5 mag, AB system; Blanton et al. 2005) in units of nanomaggies (log-flux zeropoint of 22.5 mag, AB system; Blanton et al. 2005). UKIDSS APERMAG4 (1.4″-radius aperture) magnitudes were converted to fluxes in the same units (Vega to AB magnitude conversion was taken to be +0.63, +0.94, +1.38, +1.90 for Y, J, H, K; Hill et al. 2011), though we note this is not necessary for SFM).

Despite the fact that the SDSS and UKIDSS fluxes were not obtained using the same types of apertures, the SFM method could still be used to calculate photo-z. However, an improvement can be made by scaling the SDSS fluxes to better match the UKIDSS fluxes prior to using SFM. This allows for a greater number of potential low \( \chi^2 \) matches. For each source, the \( i \)-band flux within a 1.4″ circular aperture was estimated using both the de-Vaucouleurs and exponential profile fits (§ 4.4.5.5 of Stoughton et al. 2002) and combined with weights FRACDEV and 1–FRACDEV, respectively (analogous to CMODEL, Abazajian et al. 2004). This is effectively a (PSF-deconvolved) circular-aperture flux estimated using a galaxy profile model. The ratio between this flux and the \( i \)-band ModelMag was determined, and used to scale the SDSS fluxes, for each source.

The choice of flux errors is important as it sets the relative weights between the best fitting matching-set galaxies. By guidance from nominal limiting magnitudes and by trial and error, the linear errors, in place of Poisson errors, were taken to be (0.84, 0.54, 0.72, 1.08, 4.44, 3.0, 3.0, 3.0, 3.0) nanomaggies for \( (u, g, r, i, z, Y, J, H, K) \). The fractional errors \( (\alpha) \) were taken to be 0.05 in the \( u \)-band and 0.02 in all the other bands. The \( u \)-band was down weighted by this because of the significantly larger spread in these magnitudes compared to a median SDSS magnitude for each source. This spread primarily reflects variations in star-formation rate (SFR) with less constraint on photo-z.

For any missing measurements (mostly where no UKIDSS match was available), the error is set to a extremely large value \( 100000 \) and effectively set-\( 0 \). This is taken as having reliable photo-z.

### 3.3 Selecting reliable galaxy redshifts

In order to assess the reliability of the photo-z, the number of matches with \( \chi^2 < 30 \) is considered, hereafter \( C_{30} \), along with the nominal error (\( \zeta_{i,\text{err}} \)). As expected, the fraction of photo-z outliers generally increases with the nominal error estimate. To select sources with reliable photo-z, we additionally applied the criteria \( \zeta_{i,\text{err}} < 0.031 \). In total, 93.1% of the 245 645
sources from Section 2 have reliable photo-z; and 98.3% of spec-z confirmed galaxies. Thus most of the 6.9% of the sample without reliable photo-z are expected to be stars. Of the reliable photo-z sample, only 1 in 1000 are spec-z confirmed stars; and of those with photo-z > 0.04, only 1 in 3000. Thus without using any photometric profile information, these have a very low stellar contamination.

3.4 Redshift accuracy

Figure 7 shows a plot of spec-z versus photo-z for the reliable photo-z sample. The correlation is good with no obvious bias (considering that the contours represent logarithmically spaced number densities). The 68th percentile (σ68) of |Δ ln(1 + z)| is 0.0125, and the 95th percentile (σ95) is 0.030.

These SFM (ugrizYJHK) redshifts were compared with the empirical photo-z for SDSS from [Beck et al. 2016]. The latter were determined using ‘local linear regression’ for redshift as a function of the r-band magnitude and four colours (u - g, g - r, r - i, i - z). For the Beck et al. photo-z to spec-z difference, σ68 = 0.0144 and σ95 = 0.0357 using a comparison sample of photo-z for which the Beck et al. analysis defines as reliable (PHOTOCOUNTCLASS = 1). Thus, the SFM photo-z have a 25-30% reduction in the error variance compared to the Beck et al. photo-z. This is because of the addition of the near-IR data rather than the method, which is a similar empirical method using a χ^2 matching formalism. In any case, the Beck et al. photo-z were not determined for SDSS sources photometrically classified as stars. Therefore we only use the SFM photo-z that also do not have a magnitude prior.

3.5 Final galaxy sample selection

For the 245 645 sources from §3 redshifts are assigned with the following priority: reliable SDSS spec-z, 2MRS, and then reliable photo-z (§3), with 86.1%, 0.2%, and 9.4%, respectively. The remainder are assumed to be stars or quasars. Redshifts are converted from the heliocentric to the CMB frame, used hereafter. The galaxy sample selection for this study is then 0.04 < z < 0.15.

Compact galaxy candidates were visually inspected and 27 sources whose photometry was significantly affected by scattered light (missed by the masking procedure) or a bright neighbour were rejected. In addition, 138 sources with GAIA photometry that had S/N > 5 for their parallax measurement or S/N > 10 for their proper motion were rejected. The latter cut was set high because there were many obviously extended sources that had S/N between 5 and 10, some of which may be star-galaxy blends but in other cases it was not clear. After the redshift limits and these cuts, a sample of 163 186 sources remained. Figure 8 shows the sky positions of a subset of the sample.

4 RESULTS AND DISCUSSION

4.1 Stellar masses

Stellar masses (M*,) were determined for the spec-z and photo-z sample using the the method of [Sedgwick et al. 2019a] (updated from [Bryant et al. 2015]) such that

\[
\log M_\ast = -0.4i + 0.4D + f(z) + g(z)(g - i)_{\text{obs}}
\]

where i is the i-band CMODEL magnitude, D is the distance modulus, and (g - i)_{\text{obs}} is the observed colour using Petrosian magnitudes. This effectively folds the mass-to-light ratio and k-correction into the same formula. The functions f(z) and g(z) are calibrated to a stellar-population fitted set of stellar masses. In this case, the functions were calibrated using the GAMA survey photometry and products [Baldry et al. 2018] with the stellar masses from the MAGPHYS code [da Cunha et al. 2008] applied by [Driver et al. 2016]. These masses were used in order to be consistent with the high-z comparison sample.

The functions used in this paper are given by f(z) = 1.008 - 3.531z + 21.64z^2 - 35.28z^3 and g(z) = 0.8132 + 3.304z - 30.26z^2 + 55.60z^3. The calibration is valid over the range 0 < z < 0.35. The stellar initial mass function (IMF) assumed was the Chabrier (2003) IMF.

We note that dynamical modelling using resolved spectroscopy [Cappellari et al. 2013, Posacki et al. 2015] and de-
tailed stellar population analysis (Conroy & van Dokkum 2012; La Barbera et al. 2013) have suggested that there is a bottom-heavy IMF in early-type galaxies that have high velocity dispersion. This is relevant for massive and/or compact galaxies. However, Collier et al. (2018) showed that the mass obtained using gravitational lensing for four low-redshift (z < 0.07) massive ellipticals was consistent with a Kroupa (2001) IMF. Strong lensing of these galaxies is dominated by their stellar mass (Smith & Lucey 2013) and therefore is an accurate constraint on stellar mass-to-light ratios. Stellar masses obtained assuming a Kroupa IMF are only about 0.05 dex higher than using the Chabrier IMF.

The stellar mass approximation, above, uses observed colour. To define red galaxies, we use

\[
(u - r)_{\text{adj}} = u - r - 4.5 \ln (1 + z). \tag{15}
\]

This approximates the k-and-evolution correction for dividing the red and blue sequences of galaxies at a rest-frame u - r ∼ 2.

Specific star formation rates (SSFRs) were obtained for the sample from the SDSS table GAL_SPEC_EXTRA. These were derived from spectral emission lines (Brinchmann et al. 2004) with aperture corrections using photometry (Salim et al. 2007). For sources without a match, e.g. with photo-z only, the nearest SFM match was used for the SSFR. This provided SSFR measurements for 98.6% of galaxies with log M* > 10. Red galaxies were defined using \((u - r)_{\text{adj}} > 2.0\) while quenched galaxies were defined using \(\log (\text{SSFR}/\text{yr}^{-1}) < -11.2\) (or using the red galaxy definition for the 1.4% without SSFR measurements) for this \(z < 0.15\) sample.

### 4.2 Half-light radii

Various half-light radii (\(r_{\text{50}}\)) are provided for SDSS. The SDSS pipeline computes Petrosian \(r_{\text{50}}\) (circular), de Vaucouleurs and exponential profile fits (elliptical) (Stoughton et al. 2002). Only the profile fits take account of the PSF. In addition, Simard et al. (2011) provides bulge plus disk simultaneous fits, and Sersic fits for SDSS galaxies with spec-z, using GM2D (Simard et al. 2002). These are provided for the g- and r-bands.

Since the Simard et al. fits are not provided for sources without spec-z, or for the i-band, we used the half-light radii from SDSS with a weighted geometric average of the two models for each band:

\[
\log r_{\text{50},\text{maj}} = f_{\text{dev}} \log r_{\text{dev}} + (1 - f_{\text{dev}}) \log r_{\exp} \tag{16}
\]

where \(f_{\text{dev}}\) (FRACDEV) is the coefficient that provides the best linear combination of the two profile fits, clipped between 0 and 1 (Abazajian et al. 2004). Figure 9 shows a comparison between the half-light radii from these non-simultaneous fits with the simultaneous fits (de Vaucouleurs bulge plus exponential disk) of Simard et al. There is generally good agreement with 93% of galaxies within 0.1 dex, and 98.5% within 0.2 dex. The geometric weighted mean for SDSS agreed marginally better with the comparison sample than the linear weighted mean.

The final \(r_{\text{50, maj}}\) we used was taken as the mean between the \(r\) and \(i\)-band. This was to increase the fidelity, ensuring that compact galaxies had to have small fitted radii in two bands, while avoiding the bluer \(g\)-band that crosses the 4000 Å break at \(z > 0\) and the \(z\)-band which is of lower S/N. The mean rest-frame effective wavelength of the \(r\)- and \(i\)-bands is \(\approx 6000–6500\) Å for \(0.04 < z < 0.15\). For a few sources, half-light radii were clipped to a minimum of 0.3\(^{\prime}\). In total, there were 34 unresolved sources with mean radius < 0.35\(^{\prime}\) and that were photometrically classified as a star by the SDSS pipeline. Of the 18 that had estimated stellar masses \(\log M*/10\) > 10, all but one had \(\log \text{SSFR} > -10\). This sample is of interest as candidate compact starbursts but has no significance for the number densities of the compact quiescent population. Note Taylor et al. (2010) used a minimum of 0.75\(^{\circ}\) for the \(g\)-band sizes, however, we find that reasonable agreement between the Simard et al. (2011) and pipeline half-light radii, and between \(i\) - and \(r\)-bands, extends to lower values. This is testament to the accuracy with which the PSF is measured and accounted for in the galaxy profile fitting.

### 4.3 Size-mass distribution

Figure 10 shows the size-mass distribution of the SDSS-UKIDSS selected sample. Following Barro et al. (2013), we define a projection in the size-mass distribution that runs perpendicular to the quiescent size-mass relation at high masses. This is given by

\[
\log \Sigma_{1.5} = \log (M*/M_\odot) - 1.5 \log (r_{\text{50, maj}}/\text{kpc}) \tag{17}
\]

The orange circles in Fig. 10 represent the 26% of the compact galaxy sample that have photo-z only. For compact galaxies, there is a significantly larger fraction with photo-z compared to the full sample. This demonstrates a bias against compact galaxies in the SDSS spectroscopic sample. Figure 11 shows the spectroscopic and target completeness as a function of \(\log \Sigma_{1.5}\) (\(r < 17.75\) to minimise the issue of photometric scatter across the 17.77 selection boundary between SDSS data reduction versions). The target completeness, in this paper, is the fraction of sources that were...
selected as targets for SDSS spectroscopy regardless of whether a spectrum was obtained. The spectroscopic (target) completeness is 91.6% (99.4%) in the normal log Σ₁₅ range (8.8–10.3). This drops to 75.8% (96.7%) for log Σ₁₅ > 10.5. This means that the majority of the bias against compact galaxies is due to ‘fibre collisions’ and not the SDSS photometric selection. Fibre collisions were caused by the restriction of how close fibres could be placed on the spectroscopic plate (Stoughton et al. 2002). The bias arises because compact galaxies are more likely to be found in proximity to other SDSS galaxies (Trujillo et al. 2014) (§4.6).

Figure 10. Size-mass distribution for the galaxy sample (0.04 < z < 0.15). The contours and points represent the majority of the galaxy sample, while the circles represent galaxies with log Σ₁₅ > 10.5 (black with spec-z and orange with photo-z). The dashed line shows log Σ₁₅ = 9.85, which is the median for the quiescent population at log(M∗/M⊙) > 10. The dotted lines show the two-power-law fits from Lange et al. (2013) for the r- and i-bands r_{50,ma}(z) with the early-type division using Sersic index u − r.

The fraction of red galaxies and quenched galaxies as a function of log Σ₁₅ is also shown in Figure 11. The red fraction is higher than the quenched fraction for less compact galaxies. This is because the estimate of SSFR takes account of internal dust attenuation whereas the u − r colour does not. In other words, some dusty star forming galaxies appear as red but not as quenched. The red/quenched fraction rises from less than 0.2 at dusty star forming galaxies appear as red but not as quenched. The tenuation whereas the u is because the estimate of SSFR takes account of internal dust at

4.4 High-z comparison

In order to compare the distribution functions from the SDSS-UKIDSS sample at z ∼ 0.1 to high redshift, we used the 3D-HST survey data. These are five fields with near-IR grism spectra (Brammer et al. 2012) and photometry from HST primarily from the CANDELS treasury programme (Grogin et al. 2011). The construction of the photometric catalogues, including space and ground-based imaging, is described in (Skelton et al. 2014). The science area (USE PHOT=1) of the combined fields is 0.249 deg². The sources were assigned photo-z, ground-based spec-z or grism redshifts (Momcheva et al. 2014).

Structural parameters using Sersic models were determined for the sources by van der Wel et al. (2013) in the near-IR F160W (H) and F125W (J) bands. These included half-light radii and profile-integrated magnitudes. Stellar masses and SSFR were determined by Driver et al. (2018) using MAGPHYS. For this paper, the stellar masses were corrected for the difference between the F160W magnitude (Skelton et al. 2014) used in the MAGPHYS fitting and the Sersic F160W magnitude. F125W was used if F160W was not available (< 0.5% of sources). The same procedure was used in van der Wel et al. (2014), except here we use the MAGPHYS stellar masses. Selecting galaxies with 0.5 < z < 2.5, log M∗ > 10. USE PHOT = 1, and rejecting poor fits visually checked by van der Wel et al. (2014), produced a volume-limited sample of 9757 galaxies (over 4.8 × 10⁵ cMpc³).

The half-light radii were obtained using the F160W band (> 99.5% of sources), which has a pivot wavelength of 15400 Å. This matches the rest-frame wavelength used for the low-redshift sample at z ∼ 1.5. At higher redshifts, the rest-frame wavelength drops below 6000 Å and thus the measured radii are potentially affected more significantly by younger stellar populations. This is mitigated by the fact that the colour gradients in galaxies are close to zero at z ∼ 2–2.5 (Suess et al. 2019). Therefore, measurements in F160W in the high-z sample can be reasonably compared to the low-z measurements without significant concern regarding the dependence of radii on rest-frame wavelength.

Star-forming galaxies form a ‘main sequence’ in SSFR versus stellar mass that evolves with redshift (Noeske et al. 2007; Salim et al. 2007; Pearson et al. 2018; Popesso et al. 2019). Therefore, we define ‘quenched’ using a dividing line that evolves with redshift such that

\[
\log(\text{SSFR}_{\text{divide}}/\text{yr}^{-1}) = -11.2 + 1.2 \ln(1 + z),
\]

which corresponds to −10.4 at z = 1 and −9.7 at z = 2.5.
Figure 12. Galaxy stellar mass functions. The hatched regions represent the Poisson counting uncertainties ($\pm \sigma$).

$$[-11.2 + 2.76 \log(1 + z)].$$  This dividing line is about 1 dex below the SSFR versus redshift of the main sequence for log $M_*$ > 10 galaxies.

4.5 Distribution functions

The total volume covered by the SDSS-UKIDSS sample is $54.6 \times 10^6 \text{cMpc}^3$. This is only a volume-limited sample for log $M_* \gtrsim 10.9$. To determine distribution functions including galaxies less massive than this, 1/Vmax weighting was used (Eales 1993). Vmax was determined from the observed r-band Petrosian magnitude, redshift and limiting magnitude of 17.8 for each galaxy. At log $M_* = 10.0$, Vmax is about $5 \times 10^6 \text{cMpc}^3$ for the least luminous galaxies, which are quenched galaxies. Thus the volume covered is larger than, or comparable to, the high-z comparison sample for all types of galaxies with log $M_* > 10$.

Figure 12 shows the galaxy stellar mass functions (GSMFs) for the SDSS-UKIDSS sample and for the high-z comparison split into three redshift bins. This demonstrates the trend that most of the highest mass galaxies (log $M_* > 11$) have been in place since $z \sim 2$ with more growth in number density occurring at lower masses (Davidzon et al. 2013; Muzzin et al. 2013; Mortlock et al. 2015; Wright et al. 2018; Kawinwanichakij et al. 2020). Kawinwanichakij et al. noted that the near absence of observed evolution in the number density of log $M_* > 11$ galaxies does not mean no mass growth. This is because stellar mass loss from late-stage stellar evolution could be compensated by mass growth from dry mergers or residual star formation. They estimated an upper limit of 0.16 dex for this mass growth of supermassive quiescent galaxies from $z = 1.0$ to 0.4.

Size-mass distributions of the high-z sample are shown in figure 5 of van der Wel et al. (2014). In this paper, in order to demonstrate the evolution of the size-mass distribution in comparison to the SDSS-UKIDSS sample, we computed the distribution functions in log $\Sigma_{1.5}$. In other words, this represents the number density of galaxies running perpendicular to the high-mass quiescent relation. Such a representation is suggested by the analysis of Barro et al. (2013). Figure 13 shows the log $\Sigma_{1.5}$ distribution functions for the SDSS-UKIDSS sample and three high-z redshift bins for: (a) log($M_*/M_\odot$) > 10.0, (b) quenched galaxies with the same mass limit, and (c) quenched galaxies with log($M_*/M_\odot$) > 10.9.

The evolution in the log $\Sigma_{1.5}$ distribution functions (Fig. 13)
is far more striking than the GSMF evolution (Fig. [2]). The high log $\Sigma_{1.5}$ cutoff becomes sharper and moves to lower values as the galaxy population evolves (from high to low redshift). At the same time, there is an increase in number density of the less compact galaxies (log $\Sigma_{1.5} \lesssim 10$). The pattern is similar for all three selections with narrowing of the functions for the quenched galaxies, and the supermassive (log($M_*/M_\odot$) > 10.9) quenched galaxies.

This supports the picture of Barro et al. (2013) (their figure 6): size growth due to minor mergers Naab et al. 2009 Hilz et al. 2012 for compact quenched galaxies that primarily formed at $z > 2$, and galaxies with normal sizes quenching at all these epochs. In this way, the log $\Sigma_{1.5}$ distribution cutoff at high values becomes steeper. In this paper, we have demonstrated this by using a rigorously complete low-redshift galaxy selection for compact sources, and we also used the major axis for the half-light radii. Note that the increase of half-light radii caused by minor merger growth cannot be entirely due to addition of light at large radii. This was demonstrated by van Dokkum et al. (2014) who showed that the number density of high-mass-core galaxies, with log $M_*$ > 10.5 within the central kpc of each galaxy, decreased from high to low redshift. This could be explained by a small amount of stellar-evolution mass loss from the core leading to adiabatic expansion.

In summary, compact quiescent galaxies can grow primarily through minor mergers that increase a galaxy’s mass and size. The size growth is a combination of adding mass to the envelope Huang et al. 2013 and dynamical friction causing the core to expand Naab et al. 2009. The mass increase can be compensated by mass loss from stellar evolution, and the core can also grow marginally through adiabatic expansion van Dokkum et al. 2014. It should also be noted that compact galaxies can accrete a disk becoming early-type spirals Gao & Fan 2020, and then in some cases becoming low-redshift S0 galaxies Graham et al. 2013 Deeley et al. 2020. No doubt there is more than one path to galaxy growth given the stochastic nature of hierarchical assembly. Gao & Fan (2020) estimated, based on a spectral and structural analysis of SDSS galaxies, that about 15% of compact quiescent galaxies become spirals with a massive bulge with the remaining growing through dry minor mergers to become massive early types.

The evolution of the size-mass distribution of galaxies can be examined using cosmological-scale hydrodynamical simulations. Furlong et al. 2017 found good agreement for the size-mass evolution in the EAGLE simulation compared to the van der Wel et al. 2014 observational measurements. In all cases of $z = 2$ compact galaxies identified in the simulation, stars formed at high redshift migrated to larger radii at $z = 0$ Furlong et al. 2017. For some of these galaxies, further growth occurred by mergers and star formation. Wellons et al (2015) looked at the formation of supermassive compact galaxies at $z = 2$ in the Illustris simulation, finding that they could be formed by gas-rich mergers at $z < 4$ or by assembly at early times when the universe was much denser.

To examine the EAGLE simulation in terms of the log $\Sigma_{1.5}$ distribution functions, we obtained data for five snapshots (different redshifts), four that matched the midpoints of the low- and high-z comparison measurements plus one intermediate redshift, from the 10$^8$ cMpc$^{-3}$ reference simulation box McAlpine et al. 2016. Total stellar masses were defined in spheres of radius 30 kpc around each galaxy, with half-mass radii also defined in 3D Furlong et al. 2017. Figure 14 shows the distribution functions from the simulation using these definitions of $M_*$ and $r_{1/2}$ for massive quenched galaxies using the SSFR cut of Eq. [17]. There are clear quantitative differences compared to the observational data: a lower number density at all redshifts; and a lack of ultracompact galaxies at high redshift that is not unexpected given the gravitational softening length of 0.7 kpc Schaye et al. 2013. There is however strikingly good qualitative agreement. Crain et al. 2015 note that it is important for hydrodynamical simulations to match the observed size-mass relation otherwise simulations can end up with unrealistically compact low-z galaxies. While the EAGLE reference simulation was calibrated to the low-z relation, it was not to the high-z relations, and therefore this qualitative agreement is a success of the model.

The distribution functions in Fig. 13 clearly demonstrate the number density evolution without the need to define a compact sample. Nevertheless, there is interest in the number density of compact relics that have largely evolved passively since high redshift. Figure 15 shows the evolution in the number density of compact galaxies with log $\Sigma_{1.5} > 10.5$ (cf. Barro et al. 2014 and Gu et al. 2020 use a limit of 10.45 with circularized radii). To estimate the uncertainty, the number densities were also determined using cuts at 10.4 and 10.6. The number density of low-redshift compact galaxies depends significantly on the cut since it is on the steep part of the log $\Sigma_{1.5}$ distribution function, and this is the dominant uncertainty. The evolutionary trend is clear though with a peak at $z \sim 2$ and a steep decline in the number density towards low redshift van der Wel et al. 2014. The $z \sim 0.1$ number density of compact quenched galaxies from this study is log($n/\text{cMpc}^{-3}$) = −5.3 ± 0.4 (−6.4 ± 0.5) for log $M_*$ > 10.0 (> 10.9).

### 4.6 Environment

The spectroscopic completeness of the SDSS-UKIDSS galaxy sample drops from 92% for normal-size galaxies to 76% for compact galaxies (Fig. 11). This is primarily due to fibre collisions. To evaluate the reason for and physically quantify this effect, we computed environmental densities for a selected galaxy sample.

A density-defining population (DDP) of galaxies was selected over an expanded redshift range (0.024–0.168) to avoid a red-
shift when determining densities at the sample limits of 0.04 and 0.15. The DDP was selected: (i) with $\log M_*>10.5$ or $\log M_*>10.0$ for quenched galaxies; and (ii) with a spec-z or a photo-z that had a nominal error $\zeta_{\text{err}}<0.015$. For a calibration sample with both spec-z and good photo-z (within this error limit), 90% had $\Delta \ln(1+z)<0.015$ (difference between the spec-z and photo-z). This DDP thus supplements the spec-z with accurate photo-z enabled by the SDSS-UKIDSS data and significantly reduces biases associated with fibre collisions when measuring environmental densities.

For each galaxy, the projected distances to the three nearest DDP neighbours were determined. The neighbours had to have $d_v<1200\,\text{km/s}$ using spec-z or $d_v<4500\,\text{km/s}$ using photo-z (for either the potential neighbour and/or the target), where $d_v=c\Delta \ln(1+z)$ is the velocity difference (Baldry 2018) between the target and DDP galaxy. The surface neighbour density for each galaxy is then given by

$$\log \Sigma_{\text{ddp}} = \frac{1}{2} \log \left( \frac{2}{\pi d_2^2} \right) + \frac{1}{2} \log \left( \frac{3}{\pi d_3^2} \right)$$

(18)

where $d_2$ and $d_3$ are the projected comoving distances (cMpc) to the 2nd and 3rd nearest neighbours. This is then converted to an environmental overdensity ($\delta$) using

$$\log(1+\delta) = \log \Sigma_{\text{ddp}} - f_{\text{ddp}}(z),$$

(19)

where $f_{\text{ddp}}(z)$ is a fitted function for the global surface density of the DDP (in bins of 2400 km/s) that accounts for the observational flux limit because the DDP is not a volume-limited sample. For this DDP and $r_{\text{petro}}<17.8$, $f_{\text{ddp}}(z)$ was approximated by $f_{\text{ddp}} = -0.978$ for $z < 0.0784$ and $-0.351 - 8.30 \ln(1+z)$ otherwise ($-1.511$ at $z = 0.15$). This ensures that the median value of $\delta$ is similar across the full redshift range for a particular type of galaxy.

This was tested for both quenched and star-forming galaxies with $\log M_*>10.5$.

Figure 16 shows the environmental overdensity versus log $\Sigma_{1.5}$ for the quenched galaxies. The lower panel shows the fraction of galaxies in high density environments with $\log(1+\delta)>1.5$. From this, there is a clear difference with 69 $\pm$ 8% of the most compact galaxies ($>10.6$) found in high density environments compared to 24% for normal-size quenched galaxies. This noticeable effect is in contrast to the median log $\Sigma_{1.5}$ that is 9.875 in high-density environments compared to 9.866 at lower densities. In other words, for quenched galaxies, there are small or negligible differences between the general size-mass relations at low redshift (Malby et al. 2010, Matharu et al. 2019). Matharu et al. noted that while minor mergers in clusters are less likely than in the field, the disappearance of compact cluster galaxies that are seen at high redshift can be explained by a combination of mergers with the brightest cluster galaxy and being tidally destroyed. For the rarer compact galaxies, they are nevertheless more likely to survive in high density environments (Poggianti et al. 2013, Trujillo et al. 2014, Buitrago et al. 2018). This is demonstrated conclusively using this complete SDSS-UKIDSS sample.

5 SUMMARY

The primary aim of this analysis was to determine the number density of compact galaxies using a complete sample with photometry from SDSS and UKIDSS. After masking around GAIA stars (Figs. 1–2), rather than using a not-saturated criterion, and selecting galaxies using primarily colours ($J K_g$, $Y K_g$), Figs. 3–4), a sample of 245,645 sources was obtained covering 2300 deg$^2$ to
Compact galaxies and the size-mass galaxy distribution

The majority (92%) of the sample were selected without using a profile separator, i.e. with no bias against compact galaxies, with the additional selection being mainly extended sources that did not have catalog-matched UKIDSS photometry and which were added in for completeness.

To refine the sample further, photo-z were determined using an accurate scaled flux matching (SFM) empirical method. The matching set were galaxies with reliable spec-z and photometry. A photo-z estimate can be obtained for any source even if it is missing or has bad photometry in one or more bands. The criteria for a reliable photo-z estimate were determined using: the number of matches within a chi-squared limit (Fig. 5), and the estimate of the error (Fig. 6). For sources with reliable spec-z and photo-z, the 68th percentile of $|\Delta \ln(1+z)|$ was 0.0125 (0.010 for quenched galaxies, 0.016 for star-forming galaxies) and 99.7% were within 0.06 (Fig. 7). These photo-z were more accurate than the SDSS photo-z because of the additional near-IR photometry.

Sources were assigned reliable photo-z if reliable spec-z were not available; otherwise they were not included and assumed to be stars or quasars. The selection of sources with $0.04 < z < 0.15$ produced a sample of 163,186 galaxies (10.4% with photo-z, Fig. 8). Utilizing SDSS pipeline half-light radii that were shown to be similar to the sizes from the two-component fits of Simard et al. (2011) (Fig. 9), a size-mass distribution was produced (Fig. 10). This is complete for compact galaxies because of the colour selection and photo-z. The slope of the high-mass relation for quiescent galaxies is about $2/3$, and thus following Barro et al. (2013), we computed $\Sigma_{1.5} (M_*/r_{maj}^{1.5})$ in $M_\odot$/kpc$^{-1.5}$, Eq. (3) that runs perpendicular to this slope. The spectroscopic completeness drops from 92% for normal-size galaxies to 76% for compact galaxies with $\log \Sigma_{1.5} > 10.5$ (Fig. 11) ($\log M_* > 10$). This can be attributed primarily to fibre collisions, and thus environments, rather than incompleteness of the SDSS target selection.

A high-z comparison sample was obtained from 3D-HST data with structural measurements from van der Wel et al. (2012) and stellar masses from Driver et al. (2018). The evolution in the $\log \Sigma_{1.5}$ distribution functions (Fig. 13) from high to low redshifts shows: a gradual rise in the number density at $\log \Sigma_{1.5} \lesssim 10$; while at $\Delta > 10$, there is a sharp cutoff in the number density at lower redshifts. In the SDSS-UKIDSS sample, the number densities of compact galaxies are about a factor of 30–100 below the peak at $z \sim 2$ (Fig. 15). The consensus mechanism for the growth of compact galaxies is primarily via minor mergers.

Comparing the distribution functions with different redshift snapshots from the EAGLE hydrodynamical simulation shows good qualitative agreement (Fig. 14). In addition to the GMSF (Fig. 12) and size-mass relations, using $\log \Sigma_{1.5}$ distributions is an informative way to compare simulations with data because the number densities for both normal-size and compact galaxies are clearly conveyed. This is an avenue for future research, for example, for simulations that agree with observations, the past merger history and environments of quenched galaxies with different low- and high-redshift $\log \Sigma_{1.5}$ values could be compared.

We searched amongst the entire population of (more than two million) stars and galaxies to $\tau < 17.8$, using 9-band photometry, for compact galaxies. This confirmed the low number densities ($\lesssim 10^{-3}$ cm$^{-3}$) of local compact galaxies in agreement with the SDSS analysis of Taylor et al. (2010). The $\log \Sigma_{1.5}$ distribution of local quenched galaxies is similar in low- and high-density environments (Fig. 16 upper panel). However, the rare compact galaxies are significantly more likely to survive in high density environments (Fig. 16 lower panel).

There is substantial evolution in the size-mass distribution since $z \sim 1$. In the future, the WAVES-DEEP survey with 4MOST aims to obtain redshifts for galaxies to $z \gtrsim 0.8$ over $\sim 60$ deg$^2$ (Driver et al. 2019). Coupled with Euclid imaging (Laureijs et al. 2010), this will provide galaxy structural measurements over a cosmic volume that is sufficient to divide the sample into several epochs and different types of environments. The diversification of the compact galaxy population will be illuminated in detail.

DATA AVAILABILITY

The data underlying this article were accessed from: the Sloan Digital Sky Survey at skyserver.sdss.org/ (dr14.PhotoPrimary, dr14.SpecObj, dr14.Photoz, dr7.PhotoObjAll); the WFCAM Science Archive at wsa.roe.ac.uk/ for the UKIDSS data (lasYJHKsource); the Gaia archive at gea.esac.esa.int/archive/ (gaiadr2.gaia_source); and the 3D-HST archive at 3dhst.research.yale.edu/ [the catalog is also available via ADS 2015yCat..22140024S (Skelton et al. 2014)]. Galaxy structural measurements can be accessed via ADS 2011yCat..21960011S (Simard et al. 2011), and ADS 2012yCat..22030024V (van der Wel et al. 2012).

The derived data generated in this research will be shared on reasonable request to the corresponding author.

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REFERENCES

Abazajian K., et al., 2004, AJ, 128, 502
Babbedge T. S. R. et al., 2004, MNRAS, 353, 654
Baldry I. K., 2018, arXiv:1812.05135
Baldry I. K. et al., 2018, MNRAS, 474, 3875
Baldry I. K. et al., 2010, MNRAS, 404, 86
Barro G. et al., 2013, ApJ, 765, 104
Trujillo I., Ferré-Mateu A., Balcells M., Vazdekis A., Sánchez-Blázquez P., 2014, ApJ, 780, L20
Valentinuzzi T. et al., 2010, ApJ, 712, 226
van der Wel A. et al., 2012, ApJS, 203, 24
van der Wel A. et al., 2014, ApJ, 788, 28
van Dokkum P. G. et al., 2014, ApJ, 791, 45
van Dokkum P. G. et al., 2008, ApJ, 677, L5
van Dokkum P. G. et al., 2015, ApJ, 813, 23
Wellons S. et al., 2015, MNRAS, 449, 361
Wright A. H., Driver S. P., Robotham A. S. G., 2018, MNRAS, 480, 3491
Yıldırım A., van den Bosch R. C. E., van de Ven G., Martín-Navarro I., Walsh J. L., Husemann B., Gültekin K., Gebhardt K., 2017, MNRAS, 468, 4216
York D. G., et al., 2000, AJ, 120, 1579