No evidence for evolution in the typical rest-frame UV sizes or morphologies of L_\star galaxies at 4 < z < 8

E. Curtis-Lake\(^1\)*, R.J. McLure\(^1\), J.S. Dunlop\(^1\), A.B. Rogers\(^1\), T. Targett\(^1\), A. Dekel\(^2\), R.S. Ellis\(^3\), S.M. Faber\(^4\), H.C. Ferguson\(^4\), N.A. Grogin\(^4\), K.-H. Huang\(^5\), D.D. Kocevski\(^4\), A.M. Koekemoer\(^6\), K. Lai\(^2\), B.E. Robertson\(^7\)

\(^1\) SUPA, Institute for Astronomy, University of Edinburgh, Royal Observatory, Edinburgh EH9 3HJ
\(^2\) Center for Astrophysics and Planetary Science, Racah Institute of Physics, The Hebrew University, Jerusalem 91904 Israel
\(^3\) Department of Astrophysics, California Institute of Technology, Pasadena, CA 91125, USA
\(^4\) University of California Observatories/Lick Observatory, University of California, Santa Cruz, CA 95064, USA
\(^5\) Department of Physics, University of California, Davis, CA 95616, USA
\(^6\) Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
\(^7\) Department of Astronomy, University of Arizona, 933 North Cherry Avenue, Tucson, AZ 85721, USA

ABSTRACT
We present the results of a study investigating the sizes and morphologies of redshift 4 < z < 8 galaxies in the CANDELS GOODS-S, HUDF and HUDF parallel fields. Based on non-parametric measurements and incorporating a careful treatment of measurement biases, we quantify the typical size of galaxies at each redshift as the peak of the log-normal size distribution, rather than the arithmetic mean size. Parameterizing the evolution of galaxy half-light radius as r_{50} \propto (1 + z)^n, we find n = -0.34 \pm 0.29 at bright UV-luminosities (0.3L_\star(z=3) < L < L_\star) and n = -0.57 \pm 0.76 at faint luminosities (0.12L_\star < L < 0.3L_\star). In a given luminosity range, these measurements are consistent with no evolution in typical galaxy size with redshift. Moreover, simulations based on artificially redshifting our z \sim 4 galaxy sample also confirm that we cannot reject the null hypothesis of no size evolution. This result is fundamentally caused by the systematic under-estimation of the largest galaxy sizes, such that the build-up in the tail of the log-normal size distribution seen at z \sim 4 – 5 cannot be distinguished from a scenario where the large, low surface-brightness, galaxies at higher redshifts have their sizes systematically underestimated. To explore the evolution of galaxy morphology we first compare asymmetry measurements to those from a large sample of simulated single S\textsuperscript{é}rsic profiles, in order to robustly categorise galaxies as either ‘smooth’ or ‘disturbed’. Comparing the disturbed fraction amongst bright (M_{1500} \leq -20) galaxies at each redshift to that obtained by artificially redshifting our z \sim 4 galaxy sample, we are then able to look for any evidence that galaxy morphologies are evolving. By carefully matching the size and UV-luminosity distributions of the galaxies at each redshift to the artificially redshifted z \sim 4 sample, we find no clear evidence for evolution in galaxy morphology over the redshift interval 4 < z < 8. Therefore, based on our results, a bright (M_{1500} \leq -20) galaxy at z \sim 6 is no more likely to be measured as ‘disturbed’ than a comparable galaxy at z \sim 4.

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

1 INTRODUCTION

The best constraints currently available for discerning how the first galaxies formed are derived from ultra-violet (UV)
selected samples. These are star-forming galaxies by definition and analysing their structure in the rest frame UV can provide important information about the physical mechanisms responsible for this star-formation.

The high-redshift galaxy luminosity function (e.g. Bouwens et al. 2007; McLure et al. 2009, 2013; Schenker et al. 2013; Lorenzoni et al. 2012) and spectral energy distribution (SED) fitting (e.g. Jiang et al. 2013; Curtis-Lake et al. 2013; Stark et al. 2009, 2013) allows us to understand the evolution of the abundance and stellar populations of these high-redshift galaxies, while measuring their sizes and morphologies (e.g. Ferguson et al. 2004; Bouwens et al. 2004b; Hathi et al. 2008; Conselice & Arnold 2009; Oesch et al. 2010a; Jiang et al. 2013; Ono et al. 2012) provides us with complementary information about how they grow and evolve.

A framework was laid out for understanding how the sizes of disc galaxies can be related to the evolution of their parent halos by Mo, Mao, & White (1998), according to the disc formation model of Fall & Efstathiou (1980). The Mo et al. (1998) formalism assumes that disc sizes are a constant fraction of the virial radius of their parent dark matter halos. (1998) formalism assumes that disc sizes are a constant fraction of the virial radius of their parent dark matter halos. This in turn predicts that galaxy sizes should evolve $\propto H(z)^{-1} (1 + z)^{-3/2}$ at constant halo circular velocity, or $\propto H(z)^{-2/3} (1 + z)^{-1}$ at constant halo mass. This relies on many assumptions, including a redshift invariant dark matter halo profile.

However, at high-redshift we are observationally forced to study Lyman break galaxy (LBG) sizes from the rest-frame UV, at approximately constant UV luminosity. This selection does not necessarily follow constant halo velocity or halo mass, complicating the interpretation of the inferred evolution. The exponent of the $(1 + z)^n$ relation fitted to the data therefore only reveals whether the UV luminosity most closely traces the halo velocity or halo mass if all the other assumptions hold. Previous studies suggest an evolution closer to constant halo mass evolution (Ferguson et al. 2004; Bouwens et al. 2004a), although more recent studies suggest a slightly steeper evolution, somewhere between the two scenarios ($\propto (1 + z)^{-1.12 \pm 0.17}$ for bright galaxies and $\propto (1 + z)^{-1.32 \pm 0.52}$ for fainter galaxies in Oesch et al. 2010a) and $\propto (1 + z)^{-1.30 \pm 0.13}$ in Ono et al. 2012.

Moving beyond measurements of galaxy size evolution, the evolution of galaxy morphology is clearly of interest. Without analysing galaxy morphologies we cannot address such important questions as: Are major mergers important at high redshifts? Is the star formation evenly distributed or is it occurring in distinct clumps as shown in lower redshift clump-cluster galaxies (Elmegreen & Elmegreen 2005)? How would these factors affect the inferred size evolution when measured from the rest frame UV?

Some studies have already attempted to categorise the morphologies of LBG samples using CAS/Gini/M20 measurements as well as visual inspection (e.g. Conselice & Arnold 2009; Jiang et al. 2013). Jiang et al. 2013 found the merger rate at the bright end of a sample of $z \sim 6$ LBGs to be as high as $\sim 48\%$. Although they investigated applying Gini/CAS/M20 measurements to their sample, they found that the most reliable way to distinguish interacting galaxies was by visual inspection. They concluded that the small object sizes meant that the interacting systems were not easily differentiated using non-parametric measurements alone. Conselice & Arnold (2009) investigated the morphologies of a sample of $4 < z < 6$ LBGs finding that $\sim 30\%$ of the galaxies showed distorted and asymmetric structures, and found marginal evidence that the distorted galaxies had higher star formation rates (SFRs) than their smooth counterparts.

The aim of this study is to investigate the fraction of disturbed galaxy morphologies in the LBG population, testing any evidence of morphological evolution and examining the links with the observed size evolution. We use consistent rest-frame wavelengths for the size measurements, and measure the sizes and morphologies non-parametrically incorporating a proper treatment of the biases inherent in the measurements.

Sizes are measured with a simple, non-parametric curve of growth and a simple diagnostic (the non-parametric asymmetry measurement, Conselice, Bershady, & Jangren 2000) is used to determine whether a galaxy can be distinguished from a smooth, symmetric profile. The method we employ robustly takes account of surface brightness and resolution effects on an image-by-image basis.

This morphological diagnostic is image-dependent and so careful analysis is required when investigating any evidence for evolution. This is done by comparing measurements to those derived from an artificially redshifted $z \sim 4$ galaxy sample, allowing us to investigate any evidence for evolution in the fraction of disturbed galaxies at the way up to $z \sim 8$. This artificially redshifted sample is also used as a test of whether we can reject the null hypothesis for size evolution across the redshift range studied, given our sampling of the galaxy population. Testing against the artificially redshifted $z \sim 4$ sample provides a consistent method for quantifying the significance of any measured evolution.

The structure of the paper is as follows. In Section 2 the data and sample selection is described. The non-parametric size and asymmetry measurements are described in Section 3. In Section 4 the simulations used to distinguish galaxies that are not consistent with smooth, symmetric profiles, as well as the artificially redshifted samples are described. The results are presented in Section 5 and discussed in Section 6. Finally, the conclusions are presented in Section 7.

Throughout this paper standard cosmology is assumed, with $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.3$ and $\Omega_\Lambda = 0.7$.

2 DATA

2.1 Imaging Data

The samples were selected from regions with deep near-infrared Wide-Field Camera 3 (WFC3) and optical Advanced Camera for Surveys (ACS) imaging within three main surveys: Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey (CANDELS, Grogin et al. 2011), Koekemoer et al. 2011, Ultra-Deep Field 2012 (HUDF12, Ellis et al. 2013; Koekemoer et al. 2013) and the Hubble Ultra-Deep Field 2009 (HUDF09, Bouwens et al. 2011). From the CANDELS survey we used the data covering the Great Observatories Origins Deep Survey southern field.
(GOODS-S) to provide measurements of brighter objects. For measurements of fainter objects, samples were taken from the HUDF and its two parallel fields. A summary of the depths and filters available in each of these fields can be found in McCrann et al. (2013). All analysis was performed on 60mas pixel-scale mosaics.

2.1.1 GOODS-S

To provide coverage at the bright end of the high-redshift ($z > 4$) luminosity function, the publicly available WFC3/IR imaging of GOODS-S with the F105W, F125W and F160W filters (hereinafter referred to as $Y_{105}$, $J_{125}$ and $H_{160}$ respectively) provided by the CANDELS survey (Grogin et al. 2011; Koekemoer et al. 2011) was combined with the v2.0 reduction of the publicly available ACS data (Giavalisco et al. 2004) in the optical filters: F435W, F606W, F775W, F850LP (hereinafter referred to as $B_{435}$, $V_{606}$, $i_{775}$ and $z_{850}$ respectively). This study makes use of the deep, wide and ERS (Early Release Science) regions of GOODS-S WFC3/IR imaging. In the ERS, deep F098W ($Y_{098}$) imaging is available (Windhorst et al. 2011), rather than $Y_{105}$ which is available over the rest of the GOODS-S CANDELS imaging.

2.1.2 HUDF12

To add faint galaxies to the sample, LBGs are selected from the HUDF and parallel fields. The most recent coverage of the HUDF in the near-infrared (NIR) was provided by the HUDF12 survey (Ellis et al. 2013; Koekemoer et al. 2013) and was utilised here. This includes deeper coverage in the $Y_{105}$ and $H_{160}$ filters, as well as a new deep F140W ($J_{140}$) image. ACS imaging from the Beckwith et al. (2006) HUDF ACS programme was used to provide optical coverage in the $B_{435}$, $V_{606}$, $i_{775}$ and $z_{850}$ filters.

2.1.3 HUDF09 parallel fields

Galaxies were also selected from the two deep HUDF parallel fields. A new reduction of the near-infrared data taken as part of the HUDF09 campaign (Bouwens et al. 2011) was used for both parallel fields (Koekemoer et al. 2013). In the first parallel field (P1, field centre: $03^h 33^m 03.60^s$, $-27^\circ 51' 01.80''$), we used publicly available mosaics of the Beckwith et al. (2006) ACS data, while a new reduction of the same data was used in the second parallel field (P2, field centre: $03^h 33^m 07.75^s$, $-27^\circ 51' 47.00''$).

2.2 Selection

Photometric redshifts were used to select galaxies with $z_{\text{phot}} > 3.5$ from the fields summarised above. The catalogues used to measure these photometric redshifts were produced using SEXTRACTOR in dual image mode. For each field, at least one filter was required to sample the object SEDs blue-wards of the Lyman-break. The shortest wavelength filter in the GOODS-S (deep, wide and ERS) and HUDF fields is $B_{435}$, allowing for selection of objects with $z_{\text{phot}} > 3.5$ from the $V_{606}$ image. However, in the HUDF parallel fields the shortest-wavelength deep image is $V_{606}$, and only objects with $z_{\text{phot}} > 4.5$ were selected. Each image was used in turn as the selection image, with the exclusion of the blueest filters in each field.

Aperture photometry was performed using 0.3" (5 pixel) radius aperture measurements in the $B_{435}$, $V_{606}$ and $i_{775}$ images, a 0.42" (7 pixel) diameter aperture in the $z_{850}$ image and 0.48" (8 pixel) radius apertures in the $Y_{105}$, $J_{125}$, $J_{140}$ and $H_{160}$ images. Apertures were chosen to enclose at least 70% point source flux and all photometry was corrected to total using point source aperture corrections.

Photometric errors were estimated from local image depth measurements. The local depths were estimated from the width of the distribution of aperture fluxes from multiple apertures, with the same radius as the measurement apertures, placed in empty regions of a $60'' \times 60''$ box centered on the object of interest.

An initial, inclusive, selection was performed to select likely high redshift candidates for photometric redshift analysis. The selection was designed to select all galaxies with a likely break in their SED. The detection in the selection filter, $f_s$, was required to be $> 5\sigma$ and the flux in the filter directly blue-wards, $f_b$, to be $< 5\sigma$, and any bluer filters to have $< 3\sigma$ detections ($\sigma$ is determined from the local depth estimates). This initial selection ensures a flat redshift selection distribution to high redshifts. To ensure high completeness at the lowest selection redshifts, any objects with $f_s > 5\sigma$ in $V_{606}$ ($i_{775}$, parallels) and $f_b > 5\sigma$ in $B_{435}$ ($V_{606}$) were also kept at this stage, although only 86 objects from this category make it through to the final sample, all in the $z \sim 4$ and $z \sim 5$ bins.

Photometric redshifts were then measured for all objects satisfying the initial selection criteria using the Le Phare photometric redshift code (Ilbert et al. 2009). The Ilbert et al. (2009) template set was used, which was originally used to derive photometric redshifts in the Cosmological Evolution Survey (COMOS, Scoville et al. 2007). This template set consists of the 3 SEDs of elliptical galaxies and 6 of spiral galaxies (S0, Sa, Sb, Sc, Sd, Sdm) produced by Polletta et al. (2007) and 12 additional starburst templates produced using BC03 with ages ranging from 3 Gyr to 0.03 Gyr. Intergalactic (IGM) absorption is applied using the Madan (1995) prescription and dust attenuation is included in the fitting using the Calzetti et al. (2000) dust curve with a range of extinction values, $0 < E(B - V) < 1.5$. Any objects with a high-redshift primary solution ($z_{\text{phot, best}} > 3.5$) with $\chi^2_{\text{best}} < 20$, and $\Delta\chi^2 > 2$ between the high-redshift solution and any secondary low-redshift solution, were selected.

Stellar contaminants were identified using both the SED and half-light radius information. Each object SED was fit using a set of L, M and T dwarf star reference spectra from the Spectroscopy library. Objects were rejected if the best-fitting stellar template $\chi^2$ value is statistically acceptable and the...
size of the object is similar in size to that measured from the image PSF. To be precise, the half-light radius must be within one pixel of the measured PSF half light radius for the object to be rejected. Objects with statistically acceptable fits with sizes within 1.5 pixels of the PSF half light radius are flagged.

At this stage visual inspection was performed on the whole sample to reject artifacts, objects with photometry contaminated by near-by low-redshift galaxies, or obvious low redshift interlopers. The objects were then sorted into two categories: firm high-redshift candidates (flag 1) and possible high-redshift candidates (flag 2). Objects flagged as having good stellar fits were also given a flag value of 2 (see above). Objects entering into the latter category are either very faint or have possible low-redshift solutions with $2 < \Delta \chi^2 \lesssim 4$. Those objects with $\Delta \chi^2 \lesssim 4$ tend to be quite red and although this sample is likely to have a larger fraction of low-redshift interlopers, they are included here to avoid excluding reddened high-redshift galaxies from the sample. These objects are more prevalent in the lower-redshift samples ($z_{phat} < 6$). The sample is split in this way between firm and insecure candidates so that the effect of possible interlopers on the main results can be tested. The final sample numbers in each field are presented in Table 1.

Table 1. Number of galaxies selected in each field and redshift bin (width of each bin is $\Delta z = 1$). The first row for each field gives the number of galaxies in each redshift bin, while the second row (in bold) gives the number of objects that pass the flux cuts imposed for robust size measurements (see Section 4.3).

| Redshift bins: | 4 | 5 | 6 | 7 | 8 |
|---------------|---|---|---|---|---|
| Fields:       |   |   |   |   |   |
| GOODS-S deep  | 1255 | 421 | 164 | 43 | 30 |
| ERS           | 399 | 123 | 29 | 41 | 4 |
| wide          | 328 | 137 | 37 | 6 | 11 |
| HUDF          | 229 | 106 | 72 | 23 | 10 |
| HUDF-p1       | 13 | 54 | 28 | 11 | 8 |
| p2            | 46 | 73 | 23 | 6 | 8 |

Legend: Objects passing initial selection

Objects with size measurements

3 MORPHOLOGICAL MEASUREMENTS

3.1 Size estimates

The circularised half-light radii of the selected objects are measured from their curve of growth (CoG) within the image closest to a rest-frame wavelength of $\lambda_{rest} = 1500\AA$. First SExtractor (Bertin & Arnouts 1996a) is used to produce an object mask using the segmentation map, and the image is subsampled to 1/5th of the original image scale; i.e. 0.012′′/pix. Aperture photometry is then used to measure the increase in enclosed flux as a function of radius, centering the apertures on the brightest pixel in the sub-sampled image.

The uncertainty in half-light radii measurements is driven by two factors, the background and total flux measurements. A large total flux aperture increases the errors in the size measurements, yet a small total flux aperture will systematically underestimate the sizes of large galaxies (see sections 4.2 and 4.3). Throughout the paper, a total flux aperture with a radius of 10 pixels is used to derive the main results, but a 15 pixel radius aperture is used to test whether any of the results are strongly biased by this decision.

Although an initial modal background value is first subtracted from the images, significant background structure in the images means that a secondary background estimation is performed by requiring that the curve of growth is flat between two radii close to the source (the inner radius of the background annulus is 10 (15) pixels and the outer radius is 25 (30) pixels).

The sizes are PSF corrected and the fluxes aperture corrected to total using simulated single Sérsic profiles as described in Section 4.2.

3.2 Asymmetry measurements

Asymmetry measurements are performed according to the prescription of Conselice et al. (2000). Essentially, the object is rotated by 180° and subtracted from the original image. The asymmetry is a sum of the residuals within a given radius, scaled according to the profile flux. The centre of rotation is determined as the point at which the asymmetry is minimised and is found to 1/5th pixel precision according to the method laid out in Conselice et al. (2000).

To account for the noise in the asymmetry measurements produced by the background, the background asymmetry is calculated in blank regions of the measurement images. The background value is then subtracted from the asymmetry value. In practice, the background asymmetry is measured within a fixed-size radius across the whole image and then scaled according to the size of the object. This calculation is summarised in the following equation:

$$A = \min \left( \frac{\sum |I - I_{180}|}{\sum |I|} \right) - \min \left( \frac{\sum |B - B_{180}|}{\sum |I|} \right)$$  (1)

where $I$ denotes the original image pixels, $I_{180}$ are the pixels of the image rotated about its centre by 180°, $B$ are background pixels taken from a blank part of the image and $B_{180}$ are the rotated background pixels.

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For asymmetry measurements to be useful, they must be measured within a radius associated with the physical scale of the object (Conselice, Bershady & Jangren 2000). For the physical scale we use the radius enclosing 70% of the object’s flux ($r_{70}$) as measured within the 10 pixel radius aperture. This was chosen as opposed to the Petrosian radius (used in Conselice & Arnold 2009), because it provides a higher S/N measurement.

The choice of measuring the asymmetry within $r_{70}$ restricts the analysis to asymmetric features in the central regions of the galaxies, meaning that the measurements will not be sensitive to low surface brightness features in the galaxy outskirts. Measuring $r_{70}$ using the 10 pixel total flux aperture does not significantly affect the results as the measurement varies by less than 1 pixel in the majority of galaxies when measured from apertures with 15, 20 or 25 pixel radii. Although the asymmetry measurements themselves vary a little when determining $r_{70}$ from these different sized total flux apertures, they do not vary by enough to significantly impact the fraction of objects determined to be ‘disturbed’ (where the determination of whether an object is ‘disturbed’ is described in Section 4.5).

4 SIMULATIONS

In this section the different simulations used throughout this paper are described. There are two different types of simulations, those employing the artificial redshifting of galaxies in the $z \sim 4$ sample (summarised in Table 2).

When measuring sizes and morphologies of high redshift galaxies, which are small and faint, it is important to understand the limits of the measurement diagnosticks how they can impact the final results. The main factors affecting morphology and size measurements are resolution and surface brightness. Surface brightness depends on both the size and total flux of an object, so simulation set I is designed to investigate how well the CoG algorithm and SExtractor reproduce the sizes of large, faint objects. Additionally, this simulation set allows for calibration of the total flux measurements and PSF correction.

Simulation set II is concerned with how well the typical sizes of galaxies can be determined in the face of measurement biases. This requires a firm understanding of what we mean by the ‘typical’ size of the population.

Starting with the assumption that all the selected galaxies are well described by relaxed discs, the actual disc size is expected to depend on both the virial radius of the parent halo and its spin ($R_e \propto \lambda R_{vir}$, where $\lambda$ is the halo spin parameter, $R_e$ is the effective radius of the disc galaxy, and $R_{vir}$ is the virial radius of the parent halo). Halo spins are expected to be distributed log-normally and we can see from our sample (Fig. 7) that the galaxy sizes at $z = 4 - 5$ approximate a log-normal distribution.

As argued by Huang et al. (2013), if the halo spin parameter is only weakly dependent on redshift and halo mass (Barnes & Efstathiou 1987; Bullock et al. 2001), then to measure how the typical galaxy size evolves, we need to plot the evolution in the peak of this distribution. Previous studies have plotted the mean galaxy size as a function of redshift (e.g. Ferguson et al. 2004; Bouwens et al. 2004b; Oesch et al. 2010a; Ono et al. 2012) which can be biased to large sizes due to the tail in the distribution. Simulation set II is therefore set-up to investigate how well the peak in a log-normal distribution is recovered with different diagnostics, and is used to define firm flux limits above which the peak is accurately reproduced and unaffected by measurement biases.
The final two simulation sets are designed to address the issue of different surface-brightness limits in different images. Since we always use the image closest in wavelength to rest-frame $\lambda_{\text{rest}} = 1500\AA$, objects selected at different redshifts are subject to different image depths.

Simulation set III uses the asymmetry values of simulated single Sérsic profiles to determine the cut in asymmetry above which an object can be distinguished from a smooth, axi-symmetric profile.

Finally, simulation set IV artificially redshifts the $z \sim 4$ sample to be used as a test case for null evolution in both sizes and morphologies of galaxies, so that resolution and surface brightness effects can be estimated independently of any size or morphology evolution in the underlying sample.

## 4.1 Blank background images

Each of the simulations (except the artificially redshifted $z \sim 4$ sample) employ blank background images for all relevant filters and surveys into which the simulated galaxies are inserted. These images were made to mimic the true image background using the following prescription. First, objects were masked from the real imaging data using a segmentation map produced by SExtractor. These masked areas were then filled with blank background taken from the actual image by iteratively shifting and rotating the masked image. When replacing a previously masked area with a new section of background, the noise was scaled according to the local depth measurements of the image. New depth measurements were made from the blank images to check that no significant additional structure was added to the background from the method used and that the depths matched those of the original image to within 5%. Using blank background images ensured that the measured properties were not affected by nearby sources.

## 4.2 Simulation set I: Measurement calibration

A set of simulated single Sérsic profiles ($n = 1$) were produced with uniform distributions of parameters described in Table 2 and inserted into the blank background images described above. The half-light radii were measured with the CoG algorithm as well as with SExtractor (Bertin & Arnouts 1996).

The comparison of input to corrected output sizes is displayed in Fig. 1 (top panel). The size measurements derived with these different tools primarily differ in their estimates of the sizes of the largest profiles, although all measurements systematically under-estimate these sizes. Both SExtractor and the CoG based measurements using a total flux aperture with a radius of 10 pixels systematically underestimate the sizes of Sérsic profiles (with $n = 1$) with physical sizes $r_{50} \sim 1.5$ kpc ($z = 4$), similar to the sizes measured by SExtractor at high-redshift. A slightly larger total flux aperture (with radius of 15 pixels) produces a good reproduction of the measured sizes of galaxies up to $\sim 2.0$ kpc. Although increasing the size of the total flux aperture can improve the measurements of large galaxies further, the measurements would be subject to even greater scatter and a brighter flux cut for reliable measurements would be required. An appropriate size for this aperture is then a balance between the depth required for the analysis and the typical sizes of galaxies expected.

The bottom panel in Fig. 1 shows the difference between measured and input half-light radii as a function of redshift.

### Table 2. Summary of different simulation sets. Each of the simulations using distributions of single Sérsic profiles (simulations I, II and III) also allow a uniform range of axis ratios between 0.2 and 1, and a uniform range of total magnitudes between $m_{1500} = 23$ and $m_{1500} = 31$. See text for explanation of log-normal $r_{50}$ parameter choice.

| Simulation ID | Aim                              | Distribution of parameters: Sérsic index ($n$) | $r_{50}$ |
|---------------|----------------------------------|-----------------------------------------------|---------|
| I             | Measurement diagnostics          | 1                                             | $0.5 < r_{50}$ (/pix) < 7                 |
| II            | Typical size biases              | 1                                             | log-normal, $\sigma$ (log space) = 0.2, $\mu(r_{50}$ /pix) = 3.16 |
|               |                                  | 1                                             | log-normal, $\sigma$ (log space) = 0.2, $\mu(r_{50}$ /pix) = 1.16 |
| III           | Asymmetry measurement distributions | 0.5 < $n$ < 4.5                              | $0.5 < r_{50}$ (/pix) < 10               |
| IV            | Set up null hypothesis from $z \sim 4$ galaxies | N/A - artificially redshifted $z \sim 4$ sample |         |
input magnitude. This plot shows that the two different measurement techniques produce opposite biases at faint magnitudes. SExtractor-based measurements produce systematic under-estimates at faint magnitudes, whereas the CoG-based measurements are more likely to be over-estimated. This difference is due to the difference in total flux measurement. SExtractor uses the pixels above a certain S/N threshold to determine the radius within which to determine the total flux. Below a certain flux threshold, this estimation becomes unreliable and insufficient pixels with adequate S/N lead to under-estimated Kron radii. The CoG algorithm, however, is prone to uncertainties in the background structure. Although this structure can lead to under- or over-estimated total flux values, if the total flux is negative then the size is not measured, hence a skew to over-estimated sizes.

The magnitude at which the distribution becomes skewed depends on the size of the total flux aperture, with larger total flux apertures producing biased measurements at brighter fluxes. The measurements with the 10 pixel aperture become biased at slightly fainter magnitudes than both the SExtractor measurements and the larger total flux aperture.

### 4.3 Simulation set II: Typical galaxy size bias

As demonstrated in section 4.2 the CoG algorithm systematically over-estimates the sizes of faint galaxies. It is therefore important to determine the flux limits at which these biases prevent an accurate estimate of the typical galaxy size. This is dependent on image depth and so has to be estimated for each image in turn. As explained at the beginning of this section, the appropriate typical size that we should measure to search for size evolution is the peak of the size distribution, so the simulations employ a log-normal size distribution and investigate at what flux limit the measurement of the peak becomes biased. The simulations are also used to determine what metric best measures the peak in the size distribution.

For each measurement image, a set of single Sérsic profiles (n = 1) with a log-normal distribution of sizes is added to blank background images. Two sets of simulations were run, one with the mean size of the log-normal distribution close to that measured by previous studies at $z \sim 4$ by Oesch et al. (2010a) in the bright luminosity bin ($\sim 1.3$ kpc, 3.16 pix), and one centred at the smallest sizes measured in the faint luminosity bin ($\sim 0.4$ kpc, $z = 6$, 1.16 pix). The width of each log-normal distribution was kept constant at $\sigma(log_{10}(r_{50}/\text{pixels})) \sim 0.2$.

Fig. 2 shows the results for the profiles inserted into the GOODS-S deep $i_{775}$ blank background image with two different typical size estimators, the mean of sizes in log space (panel a) and the mode (panel b). The typical size of the distribution is measured in bins of width $\Delta M_{tot} \sim 0.2$ with bootstrap resampling in each case. When using the mean as the typical size estimate, large sizes are systematically underestimated with the 10 pixel aperture whereas the true values are well reproduced with the 15 pixel aperture. Both apertures reproduce the typical sizes of small galaxies. A modal estimate reproduces the galaxy typical size for both apertures, for large and small populations, but is noisier. It is worth noting that the mean estimator here is the mean of
the logarithm of the sizes (not the mean of the distribution as measured in previous studies). In the absence of any measurement biases, it would be expected to follow the peak in the log-normal size distribution but is under-estimated due to the under-estimation of the sizes of the largest galaxies.

These simulations provide an image-dependent magnitude limit at which sizes are recovered with acceptable reliability. A conservative magnitude cut is taken from the simulations centered on the smaller typical size (0.4 kpc) with the 15pix aperture, with a mean size estimate. The magnitude limit for reliable measurements in that image is then determined as the magnitude, fainter than which, typical sizes are consistently over-estimated by greater than the 1σ uncertainties.

The total number of objects passing these magnitude limits is presented in Table 1 (bold numbers) and the magnitude limits are recorded in Table 3.

4.4 Impact of Sérsic index $n = 1$ choice in simulations I and II

The choice of a single Sérsic index of $n = 1$ in the measurement diagnostic and typical size bias simulations was investigated by repeating the simulations with $n = 2$. All of the measurements (CoG with 10 and 15 pixel apertures and SEXTRACTOR) start to systematically underestimate the sizes of the largest profiles at smaller sizes than for profiles with $n = 1$, with the 10 pixel apertures and SEXTRACTOR underestimating sizes for an input half-light radius of 2.5 pixels ($\sim$ 1 kpc at $z \sim$ 4). This leads to the modal size estimates from a 10 pixel aperture in the size bias simulations (II) being biased to low values for the larger input sizes, the 15 pixel modal estimates remain unbiased. The flux cuts for reliable typical size estimates remain unchanged. We therefore test the main results of this analysis with the 15 pixel apertures to test whether the modal values of the true samples differ from those derived with the 10 pixel aperture (see Section 5.2.2).

4.5 Simulation set III: Asymmetries of smooth profiles

To determine whether the measured asymmetry values for the selected objects are consistent with the objects being smooth and symmetric, they are compared to the measurements derived from a large set of single Sérsic profiles inserted into realistic background images (see Section 4.1). Asymmetry values for smooth profiles inserted into true images deviate from zero primarily due to pixelation, centering and image noise. For objects selected at the redshifts studied in this paper these effects are large as the galaxies are small and faint.

Single Sérsic profiles were added to the blank background images with a wide range of fluxes, half light radii and Sérsic indices (see Table 2). The distribution of measured asymmetries is then used to determine the probability that a galaxy with measured asymmetry, $A$, is disturbed. This is simply determined from the fraction of simulated objects, matched in size and flux, that have an asymmetry value smaller than $A$. For the following analysis the asymmetry value used to define a disturbed profile is chosen for a probability of $A(1 - P(\text{Symm}|f_{\text{tot}},r_{50}) = 0.98)$. In other words, 98% of the simulated, smooth profiles with matching flux and size have measured asymmetry values lower than the chosen value (see Fig. 3). These simulations allow us to determine whether the asymmetry measurement derived from a real object can be distinguished from that of a smooth profile and to what confidence. The actual value of 98% is chosen to be conservative but checks have been made to make sure that any conclusions do not depend on the precise value of $A(1 - P(\text{Symm}))$ chosen.

Fig. 3 displays how the range of measured asymmetries for smooth profiles depends on their total flux and size (and hence their surface brightness). The plot shows objects measured within the HUDF $i_{775}$ filter compared to the surface below which 98% of the simulated single Sérsic profiles lie. Objects with asymmetry values higher than the surface are labelled as ‘disturbed’. As the surface brightness of the simulated smooth profiles decreases (by decreasing their flux or increasing their size), the noise in the asymmetry values increases and higher asymmetry values are measured (hence the surface rises at large sizes, faint magnitudes). At small sizes the objects become partially unresolved, the asymmetries values are mainly determined by the shape of the image PSF and the measured asymmetries are unlikely to lie above the surface.

Postage stamps of a sub-sample of 16 $M_{1500} < -20$ galaxies are displayed in Fig. 4 sorted by the probability that they are disturbed, and separated into objects falling above and below the 0.98 probability cut. The objects were chosen to demonstrate what types of features contribute to labelling a galaxy as ‘disturbed’, as well as
Figure 4. Postage stamps of a selection of $M_{1500} < -20$ objects in the $z \sim 4$ redshift bin separated using the $P(A) > 0.98$ cut, where we require 98% of the simulated single Sérsic profiles have asymmetry values lower than the measured Asymmetry value to be able to label that object as ‘disturbed’. 

4.6 Simulation set IV: Artificially redshifted galaxies

An artificially redshifted $z \sim 4$ galaxy sample is used as a null evolution test case for both sizes and morphologies. The sample is subjected to the same measurement algorithms and brightness cuts as the true sample in each redshift bin, thereby providing a test for the significance of any measured evolution.

The sample of galaxies at $3.5 < z < 4.5$ is artificially redshifted into the different redshift bins at $z \sim 5, 6, 7 & 8$, in a similar fashion to the method employed in Bouwens et al. (2004a). For each higher redshift bin, the original sample is randomly assigned a new redshift within the $\Delta z \pm 0.5$ interval. The measurement images chosen for the artificially redshifted galaxies are those providing wavelength coverage closest to $\lambda_{\text{rest}} = 1500\AA$ at the new redshift.

The objects are scaled in flux to account for cosmological dimming, and resampled to account for the change in angular diameter distance between the actual redshift and
the new assigned redshift. If the original, re-scaled PSF is expected to be < 90% of the FWHM of the PSF of the new measurement image then the low redshift image is gaussian broadened to match the FWHM of the destination image. This situation is infrequent as the angular diameter sizes actually increase at these redshifts, and it is only when the destination image FWHM is significantly wider than the original image that any broadening is required. The re-sampled, scaled object is then inserted into a blank region of the destination measurement image. It is assumed that the background noise is dominant and so no attempts are made to scale the source poisson noise counts.

These artificially redshifted galaxies then have their half-light radii and asymmetries measured using the same methods as used on the actual sample. Any apparent evolution in any of the derived parameters can then be tested against this sample to ensure that it is not introduced by differences in resolution, sensitivity or selection limits.

4.7 Summary

The simulations show that:

- Large galaxy sizes are systematically under-estimated by the CoG algorithm used here and by SExtractor.
- Although a larger total flux aperture for the CoG algorithm is slightly less biased at large sizes, the measurements are noisier and typical size estimates become biased at brighter magnitudes.
- The typical sizes of galaxies are well reproduced at $z \sim 4$ using a modal estimate of the peak in the distribution and the 10 pixel total flux aperture. The mean, however, is biased to small sizes when using the 10 pixel total flux aperture.
- The typical sizes of galaxies will be over-estimated at faint fluxes, so strict flux limits are imposed on an image-by-image basis using simulation set II.
- If the typical sizes of galaxies are as small as previously measured, the CoG algorithm can reproduce these sizes, and does not bias the measurements to large sizes with the flux limits imposed.

Based on the simulations performed we base the following work on size measurements using the 10 pixel radius total flux aperture. This aperture gives less noisy estimates than the 15 pixel total flux aperture and will still recover the sizes of $z \sim 4$ galaxies. When measuring the typical sizes of galaxies we use a modal estimate, rather than the mean of the distribution to avoid being biased due to the systematic under-estimation of the sizes of the largest galaxies. We do not use any objects with total fluxes fainter than the limits given in Table 3 as the typical sizes are over-estimated for objects fainter than these limits.

5 RESULTS

5.1 Size-Luminosity relation

The logarithm of the galaxy size is plotted against absolute magnitude in Fig. 5 separated into separate redshift bins with $z \sim 4, 5, 6, 7$ and 8. The sizes were measured within the 10 pixel radius aperture and are colour coded according to whether they are measured as disturbed or not (see Section 4.5). The typical sizes of galaxies are measured in bins of width $\Delta M_{1500} = 0.5$ for the three lowest redshift bins and bins of width $\Delta M_{1500} = 1$ in the two highest redshift bins, since they have such low number counts. Bootstrap resampling is used to estimate the modal size and the associated uncertainties. Linear regression is then used to measure the gradient and intercept of the relation in each bin.

The evolution of the size luminosity relation is plotted in Fig. 6. We plot both the evolution in the exponent and normalisation of the relation, where these values are related

| Field   | Filter | Size measurement magnitude limit |
|---------|--------|----------------------------------|
| GOODS-S | V$_{606}$ | 27.0 |
|        | i$_{775}$ | 26.2 |
|        | z$_{850}$ | 26.2 |
|        | Y$_{105}$ | 26.6 |
|        | J$_{125}$ | 26.6 |
|        | H$_{160}$ | 26.4 |
| GOODS-S | V$_{606}$ | 27.2 |
|        | i$_{775}$ | 26.2 |
|        | z$_{850}$ | 26.2 |
|        | Y$_{998}$ | 26.2 |
|        | J$_{125}$ | 26.2 |
|        | H$_{160}$ | 26.2 |
| GOODS-S | V$_{606}$ | 27.6 |
|        | i$_{775}$ | 27.2 |
|        | z$_{850}$ | 26.4 |
|        | Y$_{105}$ | 25.6 |
|        | J$_{125}$ | 26.0 |
|        | H$_{160}$ | 26.0 |
| HUDF    | V$_{606}$ | 28.2 |
|        | i$_{775}$ | 28.0 |
|        | z$_{850}$ | 27.4 |
|        | Y$_{105}$ | 28.4 |
|        | J$_{125}$ | 28.0 |
|        | H$_{160}$ | 28.0 |
| HUDF-p1 | i$_{775}$ | 26.8 |
|        | z$_{850}$ | 26.6 |
|        | Y$_{105}$ | 27.2 |
|        | J$_{125}$ | 27.6 |
|        | H$_{160}$ | 27.0 |
| HUDF-p2 | i$_{775}$ | 27.2 |
|        | z$_{850}$ | 26.8 |
|        | Y$_{105}$ | 27.2 |
|        | J$_{125}$ | 27.2 |
|        | H$_{160}$ | 27.2 |
Figure 5. Log$_{10}(r_{50})$ vs. absolute magnitude in each redshift bin. The purple points show galaxies with asymmetry values that indicate disturbed profiles and the yellow points have asymmetry values that cannot be distinguished from those derived from axi-symmetric single Sérsic profile fits, matched in UV luminosity and size (see text for details). The chosen probability cut to distinguish disturbed profiles in this plot is 0.98, i.e. only 2% of the distribution of simulated axi-symmetric profiles have asymmetry values higher than the chosen cut. The black points show the modal sizes in bins of luminosity with $\Delta M_{1500} = 0.5$ in the $z \sim 4, 5$ and 6 redshift bins, and $\Delta M_{1500} = 1$ in the $z \sim 7$ and 8 redshift bins. The solid black line shows the best-fit size luminosity relation in each redshift bin and the dashed black line shows the $z \sim 4$ relation for comparison.

We see no evidence of any evolution in the size-luminosity relation across this redshift range. The size-luminosity relation is quite shallow in each redshift bin, other than at $z \sim 8$ which suffers from very low number statistics. The variation in the derived size-luminosity relation reflects the uncertainty in the measurement due to insufficient sampling of the population across the entire absolute magnitude range. The sampling of the $z \sim 5, 6$ populations at $M_{1500} \gtrsim -20$ is poor, and the number counts in the two highest-redshift bins are insufficient to measure the size-luminosity relation accurately.
Figure 6. Size-Luminosity relation plotted as a function of redshift. The top panel shows the evolution in the exponent of the size-luminosity relation whereas the bottom panel shows the evolution in the normalisation (see text for details). Previous measurements of the exponent are also plotted in the top panel as indicated in the legend. H13 refers to the measurements presented at $z \sim 4 - 5$ in Huang et al. (2013), J13 refers to the $z \sim 6$ size-luminosity relation measured for $M_{1500} < -20$ galaxies in Jiang et al. (2013) and G12 refers to the $z \sim 7$ size-luminosity relation presented in Grazian et al. (2012).

Given these uncertainties, we find good agreement with the size-luminosity relation measured by Huang et al. (2013). The steep measured size-luminosity relation reported by Grazian et al. (2012) at $z \sim 7$ is not reproduced by these data. Although the numbers of objects that are used to measure the relation at $z \sim 7$ in this work is much smaller than in the Grazian et al. (2012) analysis, this is due to the imposed flux cuts chosen to ensure the accurate reproduction of galaxy sizes. Without these cuts, and with SExtractor based sizes, our measured size luminosity relation would steepen significantly.

5.2 Size evolution

5.2.1 Log-normal size distribution

The size distribution of galaxies is plotted in separate redshift bins for all bright objects ($0.3-1 L_* (z=3)$) in Fig. 7. We see that the size distribution approximates a log-normal size distribution in the lowest redshift bins. Oesch et al. (2010b) suggest that the size evolution they measure is dominated by the build up of the tail to large sizes at low redshifts. Overplotted on the histogram for each redshift bin is the physical scale at which the sizes of galaxies are systematically under-estimated with the CoG algorithm, using the 10 pixel total flux aperture (at $r_{50} \sim 4$ pixels). It is not clear from this plot alone to what extent these biases affect the measured size distribution, and this is tested further in Section 5.2.3.

As argued at the beginning of Section 4, to be able to compare to the theoretical size evolution predictions, however, we need to be tracing the evolution in the peak of the size distribution function. The peak shows little evolution from this plot and this is investigated further using a modal estimator in the following sections.
5.2.2 Measured evolution in bright (0.3 – 1L\textsubscript{\textit{\textlambda}\textsubscript{\textit{z}=3}}) and faint (0.12 – 0.3L\textsubscript{\textit{\textlambda}\textsubscript{\textit{z}=3}}) luminosity bins

Galaxy size as a function of redshift is plotted in two different luminosity bins, presented in Fig. 8 (the bright luminosity bin, with 0.3 – 1L\textsubscript{\textit{\textlambda}\textsubscript{\textit{z}=3}}) and Fig. 9 (the faint luminosity bin, with 0.12 – 0.3L\textsubscript{\textit{\textlambda}\textsubscript{\textit{z}=3}}). The logarithm of the typical galaxy size, and associated uncertainties, for each redshift bin is estimated from the modal value with bootstrap resampling of the population. The best-fit evolution from these typical sizes is measured using linear regression, incorporating the measurement uncertainties into the fitting. The gradient from this fit gives the exponent, \( n \), in the \( r_{50} \propto (1+z)^{n} \) relationship. In the bright luminosity bin we measure a gradient of \( n = -0.34 \pm 0.29 \) whereas in the faint luminosity bin we measure a gradient of \( n = -0.57 \pm 0.76 \). Both of these measurements are shallower than that expected for a constant halo circular velocity selection, although not significantly so in the faint bin.

The figures show size measurements derived from 10-pixel radius apertures. The 15-pixel radius apertures were used to check that the typical size measurements aren’t significantly biased to smaller values. The simulations show that, for galaxies with a typical size similar to that measured by Oesch et al. (2010b), both sized apertures should reproduce the typical size estimate well, and the bins with the best sampling of the underlying population have good agreement between the typical sizes measured with the 10-pixel and 15-pixel aperture. The 15-pixel aperture does give larger typical sizes in the two highest-redshift bins (\( z \approx 8 \)), giving a shallower measured evolution (gradient of \( n = -0.05 \pm 0.35 \)), although it is consistent within the errors.

The sampling of the distribution is poor at all redshifts in the faint luminosity bin. The number of galaxies is too small in the \( z \approx 8 \) bin to allow for bootstrap resampling, so it is not included in the linear regression. In fact, the typical galaxy sizes are poorly constrained for all redshifts \( z > 4.5 \) in the faint luminosity bin and the associated evolution in sizes is also extremely uncertain.

We test the possibility that the derived size evolution is affected by low-redshift interlopers by measuring the size evolution for firm high-redshift candidates only in the bright bin (see section 2.2 for description of firm candidate). Uncertainties in the derived estimates increase significantly due to poorer sampling of the underlying population, and the derived evolution is shallower, hence low-redshift interlopers are unlikely to be diluting the observed size evolution.

5.2.3 Comparing to the null hypothesis

5.3 Comparison to previous work

There are two effects that make the measurement of the derived evolution uncertain; under-sampling of the underlying population by the data and under-estimation of the sizes of the largest galaxies. These effects are not sufficiently taken...
Figure 10. The results from testing against the null hypothesis. The $z \sim 4$ sample is artificially redshifted into each of the redshift bins, sub-sampled to match the sampling of the distribution by the actual sample (in number), and the gradient measured (see text for more details). The top panel (a) shows one example of deriving the evolution from the AR sample, and panel (b) shows the distribution of derived gradients for 500 realisations. The histogram of derived gradients is not centered on zero because the two highest redshift bins tend to have their typical sizes underestimated. This is due to two factors, the sampling of the underlying population and the under-estimation of the sizes of the largest galaxies. With such small sample sizes in these two bins, the estimation of the mode is dominated by small number statistics. The galaxies with sizes larger than the true typical size will have systematically under-estimated sizes, however, hence biasing the typical size measurements to lower values. The lack of bias from the simulations (Section 2) relies on good enough sampling of the underlying population that the mode is well-defined. The gradient and errors derived from the bright luminosity bin are over-plotted, showing that the derived size evolution in the bright bin is consistent with no size evolution in the underlying population.

It is possible that taking the derived size evolution from the mode estimator could mask any evolution in the spread of the distribution, which the median or the mean might be sensitive to. Although it would not be suitable for comparing to predictions from theory we repeat the above analysis using the median and the mean of the size distribution. We find in each case that we cannot reject the null hypothesis of no size evolution. This test doesn’t reject the possibility that there is evolution in the build up in the tail to large sizes (see Fig. 7), or in the width of the log-normal size distribution, only that there is no firm evidence to support that scenario.

5.4 The population of disturbed galaxies

5.4.1 Disturbed galaxies in the tail of the log-normal size distribution

Although tracking the typical sizes of high-redshift galaxies requires us to plot the peak of the log-normal distribution (see Fig. 7), rather than the mean size in real space, it is still instructive to investigate the nature of the galaxies contributing to the tail of the distribution at large sizes. The log-normal size distribution is caused by the range of halo spin parameters then we would still expect the objects with the large sizes to be well described by smooth profiles.

In this study the asymmetry measurement is used to characterise the morphology of galaxies. More accurately it provides an indication of whether there are any features associated with the galaxy lying above the background noise that are inconsistent with the profile being described as smooth and relaxed (as discussed in Section 3.2 the measurements are sensitive to features in the central regions of these number of galaxies within each redshift bin. The gradient of the AR sample (including the original $z \sim 4$ population) is then measured employing the same method as applied to the original sample. This is repeated many times to characterise the uncertainties in the derived evolution given the sampling of the distribution provided by the data.

The results from this analysis are shown in Fig. 10 where panel (a) shows one example of deriving the evolution from the AR sample, and panel (b) shows the distribution of derived gradients for 500 realisations. The histogram of derived gradients is not centered on zero because the two highest redshift bins tend to have their typical sizes underestimated. This is due to two factors, the sampling of the underlying population and the under-estimation of the sizes of the largest galaxies. With such small sample sizes in these two bins, the estimation of the mode is dominated by small number statistics. The galaxies with sizes larger than the true typical size will have systematically under-estimated sizes, however, hence biasing the typical size measurements to lower values. The lack of bias from the simulations (Section 2) relies on good enough sampling of the underlying population that the mode is well-defined. The gradient and errors derived from the bright luminosity bin are over-plotted, showing that the derived size evolution in the bright bin is consistent with no size evolution in the underlying population.

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objects). Considering that measurements taken from the rest-frame UV trace the star-forming regions in the galaxy, a large asymmetry value does not necessarily indicate a disturbed mass profile.

In Fig. 11 the object size distributions are plotted in three different redshift bins, $z \sim 4, 5$ and 6. The distribution is plotted for a constant luminosity range, $-21 < M_{1500} < -20$ within which each object has reliable asymmetry measurements. The size distributions are plotted for the whole redshift bin, as well as for the disturbed and smooth profiles separately.

This figure shows that the objects with disturbed morphologies are not all large, they have a fairly uniform distribution of sizes.

5.4.2 Fraction of disturbed galaxies in the population

To look for any evidence of evolution in the morphologies of galaxies with redshift, the fraction of disturbed profiles with $M_{1500} < -20$ is plotted as a function of redshift in Fig. 12.

The measured asymmetry is extremely sensitive to resolution and surface brightness limits in the following ways:

- First, the distribution of asymmetry values measured for symmetric, smooth profiles broadens significantly with decreasing flux, due to increased noise in lower S/N pixels.
- The pixel scale and PSF broadening provide a resolution limit. Features of disturbed profiles on small scales cannot be distinguished. The size distribution of galaxies can then affect the measured fraction of disturbed profiles.

We therefore do not hope to provide an absolute fraction of disturbed profiles among the high-redshift galaxy population but instead look for trends with redshift.

Objects at different redshifts have their asymmetries measured in images of differing depths and resolutions. These effects will potentially dominate any observed trend in disturbed fraction with redshift. Therefore the measured fraction of disturbed profiles measured from the artificially redshifted $z \sim 4$ sample are plotted (star symbols).

The results of this analysis are presented in Fig. 12 with the two panels displaying different sub-samples from the artificially redshifted galaxy population. In panel (a), the disturbed fraction for all $M_{1500} < -20$ artificially redshifted sample is plotted. This shows a slightly higher fraction of disturbed galaxies in the actual sample compared to what would be measured from the $z \sim 4$ sample in the absence of any evolution.

The asymmetry measurements are highly sensitive to size and surface brightness, however. To test whether these differences are due to the higher redshift galaxies showing more disturbances, the distributions of size and UV luminosity are matched between the true galaxy sample and the artificially redshifted galaxies. Each galaxy in the true sample is assigned matches within the artificially redshifted samples within $r_{50} \pm 0.25$ kpc, $M_{1500} \pm 0.25$. A sample is then randomly drawn from these matches, with repeats. The mean and standard deviation for the measured fraction is then plotted on panel (b).

These results suggest that galaxies are self-similar with increasing redshift. Thus a galaxy at $z \sim 6$ is just as likely to show a disturbed profile as one at $z \sim 4$ with the same physical size and UV luminosity.
6 DISCUSSION

The size evolution for galaxies from \(z \sim 4\) to \(z \sim 8\) presented in section 5.2.2 is shallower than that reported in many previous studies. There are two main reasons for this discrepancy, the measurement of typical galaxy size at each redshift and the redshift baseline over which the measurements are made. The bright flux limits imposed by the simulations (Table 3) are also more strict than employed in previous studies. Although the inclusion of fainter objects may bias typical \textsc{sextractor}-based size estimates to smaller sizes (\textsc{sextractor} systematically under-estimates sizes of the faintest galaxies, see Section 4.2), mean estimates of typical sizes from our sample agree well with previous works, suggesting that this particular effect is likely to be small.

The studies by Ferguson et al. (2004) and Bouwens et al. (2004a) find size evolution consistent with that expected for objects selected at constant halo mass \((r_{50} \propto (1+z)^{-1})\). These studies fit to sizes over a wide range of redshifts, from \(1 \lesssim z \lesssim 5\) in the case of Ferguson et al. (2004) and from \(2 \lesssim z \lesssim 6\) in the case of Bouwens et al. (2004a). Subsequent studies have extended the coverage out to higher redshifts; Oesch et al. (2010a) add \(z \sim 8\) selected galaxies; Ono et al. (2012) add \(z \sim 9\) galaxies plus robust size estimates from deeper imaging of \(z \sim 7–8\) galaxies. Although Oesch et al. (2010a) quote slightly steeper evolution than the earlier studies (gradients of \(n = -1.32 \pm 0.52\) and \(n = -1.12 \pm 0.17\) in the faint and bright luminosity bins respectively) their results are still formally consistent with constant halo velocity evolution. Ono et al. (2012) find slightly tighter constraints with a measured gradient of \(n = -1.30 \pm 0.13\) suggesting that the evolution lies somewhere between the two scenarios of constant halo circular velocity or halo mass.

All of the studies mentioned above use a mean estimator to describe the typical sizes of galaxies at each redshift. The build up of the tail to large sizes in the size-distribution to low redshift would naturally steepen the fit to the size evolution compared to a modal estimate (see Fig. 7). There is also a large difference in the redshift baseline used to constrain the measured evolution. This study addresses only the evolution of sizes in galaxies at \(z \gtrsim 3.5\), below which U-band imaging would be required to provide consistent rest-frame size measurements. For all redshifts studied here, the Universe was less than \(\sim 1.5\) Gyrs old. It is possible that including consistent measurements at lower redshifts could steepen the derived evolution.

Huang et al. (2013) study galaxies at \(z \sim 4–5\) and find a \(\sim 13\%\) evolution in size between these two redshifts from the peak of the size distribution in each bin. This corresponds to a gradient of \(\sim -0.67\). This is slightly steeper than that measured in the high luminosity bin \((n = -0.34 \pm 0.29)\), although it is in agreement to within \(\sim 1\sigma\).

A complementary study of disk growth, Fathi et al. (2012), claims a factor of \(\sim 8\) size increase from \(z \sim 5.8\) to \(z \sim 0\) for the brightest disc galaxies in their sample \((-24 < M_{1500} < -22)\), with most of the evolution occurring between \(z \sim 2–5.8\). This would suggest much faster evolution than constant halo mass. Fathi et al. (2012) do not claim such fast evolution for fainter galaxies more comparable to the sample presented here, primarily due to spectroscopic incompleteness at the highest redshifts. The sizes reported in their Table 1 suggest shallower evolution for \(-20 < M_{1500} < -22\) galaxies. It is worth noting that this study also measures disc scale lengths from the same observed filter and is prone
to uncertainties in the morphological k-correction applied to the highest-redshift galaxies.

Another factor that possibly contributes to the different measured size evolution is the treatment of multiple component systems. In this study, multiple component systems are treated as a single object. It is possible that they are multiple star forming clumps in an underlying system, but it is also possible that some, or all of them are instead separate systems that are close to each other and hence should be treated separately. However, using the morphology measure to remove any objects with ‘disturbed’ morphologies from the analysis does not significantly affect the results.

6.1 The hazards of measuring sizes from the rest-frame UV

When we compare the observed size evolution to that expected for the underlying halo properties, we effectively end up asking whether this constant UV selection is closest to a constant halo mass or halo circular velocity selection. Our current measurement of size evolution would lead us to state that the size evolution is shallower than that expected for either of these selections. In fact, we cannot reject the null hypothesis of no evolution at bright luminosities at $>2.5\sigma$ (see section 5.2.3), but the uncertainties in the faint luminosity bin do however, formally allow for constant circular velocity evolution. It is not clear whether the shallow measured evolution is due to disc galaxies not following the growth of their parent halos at these redshifts, whether a constant UV selection is not suitable for studying disc growth as a function of underlying halo properties, or whether galaxies at these epochs are not, in fact, steadily growing, relaxed discs.

If we want to compare the measured size evolution to halo properties in order to provide constraints for galaxy formation models, we first need to consider whether the size measured from the rest-frame UV would sufficiently trace the size of an underlying disc. The star formation tends to trace gas density rather than stellar mass, so for relaxed systems with a gas density profile that does trace stellar mass profile, it would be reasonable to expect that the measured size evolution is representative of that of an underlying disc. If, however, there are modes of star formation that distribute the gas throughout the disc (such as mergers or disk instabilities induced by accretion of cold gas, e.g. those expected to produce the clump-cluster galaxies presented by Elmegreen & Elmegreen 2005), then the UV luminosity and inferred size will differ significantly to that of a relaxed system of the same size.

Clearly, to resolve whether the lack of size evolution observed in this study is indicative of a lack of evolution in the physical sizes of high-redshift galaxies we need measurements of galaxy mass profiles. For this we require high resolution, rest-frame optical/near-IR imaging and to obtain this over the redshift range studied here we require imaging from James Webb Space Telescope (JWST).

6.2 The validity of the relaxed disc assumption

The second important question to address is whether these objects can provide constraints on disc growth i.e. are they all relaxed discs and are discs growing steadily with time?

The current framework used to link observed galaxy size evolution to halo properties relies on a number of assumptions, including that the total angular momentum of the baryons is equal to the total angular momentum of the dark matter halo. It does not take into account accretion of material that is not aligned with the initial angular momentum of the halo.

The recent studies of Danovich et al. 2012, 2014 investigate in more detail the angular momentum transfer onto disk galaxies gas transport via streams, rather than wide angle cylindrical infall. These results are based on halos selected at $z \sim 2.5$ that later evolve into massive elliptical galaxies. They find that the direction of angular momentum of the disc is most closely correlated to the dominant stream (Danovich et al. 2012), but that the overall spin of the disk is likely to be only moderately smaller than that of the dark matter halo (Danovich et al. 2014).

However, other studies suggest that while a galaxy is initially forming, the relaxed disc state may be transitory (Sales et al. 2012; Padilla et al. 2013). Sales et al. (2012) even investigated the correspondence between morphological parameters and underlying halo parameters from a sample of 100 parent halos with halo mass similar to that of the Milky Way in the GIMIC gasdynamic simulation. They report that the most important factor driving galaxy morphologies is not the underlying halo properties, but the “coherent alignment of the angular momentum of baryons that accrete over time to form a galaxy”.

Dynamical measurements of the galaxies selected here are not available to us at this time. However, observations of a small sample of lower redshift (13 galaxies at $z \sim 2.5$) star forming galaxies indicate that lower-mass objects with higher gas fractions seem to be dispersion dominated while larger, more massive systems have higher velocity shear (Law et al. 2009).

It is beyond the scope of this paper to determine whether all the selected galaxies are rotationally supported discs, or even whether the disturbed morphologies indicate merger activity or disc instabilities. We do show, however, that there is a range of different types of galaxies selected, and not all of them display evidence of smooth, axi-symmetric profiles. Although it is possible that warping of discs could produce high asymmetry measurements, the presence of distinct clumps in many of these systems indicates the likelihood that the star formation is not tracing the underlying mass distribution in the same way as for smooth profiles. The other assumptions inherent in trying to compare galaxy properties to halo properties need to be tested, however, as the studies mentioned in this discussion suggest that the sample may also contain dispersion dominated systems that are not appropriate for comparing to a scenario for disc growth.
7 CONCLUSIONS

We have measured the size and morphology evolution for a sample of galaxies in the redshift range $4 < z < 9$. They have been selected using photometric redshifts from the CANDELS GOODS-S, HUDF and parallel fields.

The size measurements reported are half-light radii taken from images closest in wavelength to $\lambda_{\text{rest}} = 1500\text{Å}$ using a non-parametric curve-of-growth. We find that this measurement technique and SExtractor both systematically underestimate the sizes of the largest galaxies. Additionally, at faint magnitudes the typical galaxy size (the peak in the a log-normal size distribution) becomes systematically over-estimated when using the curve-of-growth measurement.

Image-dependent flux limits are set from simulations of single Sérsic profiles to ensure that typical galaxy sizes are not over-estimated. Simulations with galaxy sizes distributed log-normally show that typical size measurement should not be significantly biased due to this effect when a modal size estimate is used and the size distribution is well sampled.

Measuring the size evolution of $4 < z < 9$ galaxies from the peak in the log-normal size distribution of the form $r_{50} \propto (1+z)^n$ we find $n = -0.34 \pm 0.29$ in the $(0.3-1)L_\text{r}$ luminosity bin and $n = -0.57 \pm 0.76$ in the $(0.12-0.3)L_\text{r}$ luminosity bin. Although we cannot reject the case of evolution consistent with that expected for disc galaxies selected at constant halo mass, we note that these results are consistent with no evolution in galaxy sizes. We set up a test for whether we can reject the null hypothesis of no size evolution in the bright luminosity by artificially redshifting the $z \sim 4$ sample into each successive redshift bin and mimicking the sampling of the underlying population. This test shows that we cannot reject the null hypothesis of no size evolution and furthermore, the weak measured evolution can be explained by under-sampling of the population in the highest redshift bins, making measurement of the mode too uncertain.

Measurement of the typical galaxy sizes from the peak in the log-normal size distribution as a function of luminosity gives a shallow measurement of the size-luminosity relation ($r_{50} \propto L^{0.06 \pm 0.03}$ at $z \sim 4$) that shows no evidence of evolution across the redshift range probed.

To investigate any evidence for evolution in galaxy morphologies, we use an image-dependent specifier for whether or not the galaxy can be measured as ‘disturbed’. A single non-parametric measure for galaxy morphology (the asymmetry) is compared to measurements from populations of simulated single Sérsic profiles to see whether the galaxy measurements are significantly different to those measured from smooth axi-symmetric profiles matched in size and flux. The fraction of ‘disturbed’ profiles is compared to that measured from galaxies drawn from the artificially redshifted $z \sim 4$ sample, with matched distributions of size and UV luminosity. We find no evidence for evolution in the ‘disturbed’ fraction of galaxies, with a galaxy at $z \sim 6$ having the same probability of being labelled ‘disturbed’ as a galaxy at $z \sim 4$ matched in luminosity and size.

Acknowledgments

ECL would first like to thank Esther Marmol-Queralto for all the support and helpful advice. ECL would also like to acknowledge financial support from the UK Science and Technology Facilities Council (STFC). RJM acknowledges the support of the European Research Council via the award of a Consolidator Grant (PI McLure). JSD acknowledges the support of the European Research Council via the award of an Advanced Grant, and the contribution of EC FP7 SPACE project ASTRODEEP (Ref. No.: 312725). ABR acknowledges the award of STFC PhD studentships. AD acknowledges support from ISF grant 24/12, NSF grant AST-1010033, and I-CORE Program of the PBC and ISF grant 1829/12. This work is based on observations taken by the CANDELS Multi-Cycle Treasury Program with the NASA/ESA HST, which is operated by the Association of Universities for Research in Astronomy, Inc., under NASA contract NAS5-26555. This research has benefitted from the SpeX Prism Spectral Libraries, maintained by Adam Burgasser at http://pono.ucsd.edu/~adam/browndwarfs/spexprism.

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