ACTIVE AND PASSIVE GALAXIES AT $z \sim 2$: REST-FRAME OPTICAL MORPHOLOGIES WITH WFC3

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ABSTRACT

We use the high angular resolution in the near-infrared of the Wide Field Camera 3 (WFC3) on the Hubble Space Telescope to determine $YHVz$ color–color-selection criteria to identify and characterize $1.5 < z < 3.5$ galaxies in the Hubble Ultra Deep Field 2009 (HUDF09) and Early Release Science (GOODS-South) fields. The WFC3 NIR images reveal galaxies at these redshifts that were undetected in the rest-frame UV HUDF/GOODS images, as well as true centers and regular disks in galaxies classified as highly irregular in rest-frame UV light. Across the $1.5 < z < 2.15$ redshift range, regular disks are unveiled in the WFC3 images of $\sim 25\%$ of both intermediate and high mass galaxies, i.e., above $10^{10}$ $M_\odot$. Meanwhile, galaxies maintaining diffuse and/or irregular morphologies in the rest-frame optical light—i.e., not yet dynamically settled—at these epochs are almost entirely restricted to masses below $10^{11}$ $M_\odot$. In contrast at $2.25 < z < 3.5$ these diffuse and/or irregular structures overwhelmingly dominate the morphological mix in both the intermediate and high mass regimes, while no regular disks, and only a small fraction ($\sim 25\%$) of smooth spheroids, are evident above $10^{11}$ $M_\odot$. Strikingly, by $1.5 < z < 2.25$ roughly two out of every three galaxies at the highest masses are spheroids. In our small sample, the fraction of star-forming galaxies at these mass scales decreases concurrently from $\sim 60\%$ to $\sim 5\%$. If confirmed, this indicates that $z \sim 2$ is the epoch of both the morphological transformation and quenching of star formation which assemble the first substantial population of massive ellipticals.

Key words: galaxies: evolution – galaxies: formation – galaxies: high-redshift

Online-only material: color figures

1. INTRODUCTION

The redshift interval $1.5 < z < 3.5$ represents an important epoch for the study of galaxy formation and evolution, encompassing both the peak of cosmic star formation (Lilly et al. 1996; Madau et al. 1996, 1998; Hopkins & Beacom 2006; Bouwens et al. 2007; Tresse et al. 2007) and the peak of active galactic nucleus (AGN) activity (Warren et al. 1994; Fan et al. 2001; Croom et al. 2004; Barger & Cowie 2005). One efficient method for identifying large samples of galaxies at these redshifts is via application of color-based selection criteria to optical-to-near-infrared (NIR) imaging surveys. Established selection criteria now exist for the identification of $z \sim 3$ systems via the Lyman break in observed UV-to-optical colors (cf. Lyman break galaxies, LBGs; Steidel et al. 1996, 2003) and $1 < z < 3.5$ systems via the Balmer break or 4000 Å break in observed optical-to-NIR colors (cf. extremely red objects (EROs); Thompson et al. 1999; Franx et al. 2003; McCarthy et al. 2004; Van Dokkum et al. 2006; BX/BMs: Steidel et al. 2004; Adelberger et al. 2004; and BzKs: Daddi et al. 2004, 2005). Importantly, with optical-to-NIR color-selection criteria it is possible to sample uniformly both actively star-forming and passively evolving systems at high redshift (e.g., Daddi et al. 2004).

The new Wide Field Camera 3 (WFC3) on the Hubble Space Telescope (HST) has greatly enhanced the UV and NIR imaging capabilities of this observatory, offering sharper imaging and greater throughput with a new complement of narrowband and broadband filters. In particular, the unprecedented depth and sharpness of the NIR WFC3 images further enhances our capacity to detect LBGs at the era of peak star formation in the universe—as well as at much higher redshifts; see, e.g., the WFC3 detections of numerous galaxy candidates at $z \sim 7–8$ (Bouwens et al. 2010a, 2010b; Oesch et al. 2010; Wilkins et al. 2010; McLure et al. 2010; Bunker et al. 2010; Finkelstein et al. 2010) and even $z \sim 10$ (Bouwens et al. 2011).

In this paper, we use the WFC3 data acquired so far in the context of the Hubble Ultra Deep Field 2009 (HUDF09) and Early Release Science (ERS) programs to (1) extract $H_{160}$-band-based galaxy catalogs down to, respectively, $AB = 27$ and 25 mag; (2) derive optimal color-selection criteria ($YHVz$) for the identification and characterization of galaxies at $1.5 < z < 3.5$, based on the WFC3 NIR filter set (complemented by optical Advanced Camera for Surveys (ACS) data); and (3) use the constructed WFC3 $H_{160}$-band source catalogs to investigate, through qualitative comparisons with archival ACS optical data in the HUDF09 and ERS fields, differences and similarities in the rest-frame UV and optical morphologies of $1.5 < z < 3.5$ galaxies. The efficiencies of the $YHVz$ selection criteria presented here are established via comparisons with archival ACS optical data in the HUDF09 and ERS fields, differences and similarities in the rest-frame UV and optical morphologies of $1.5 < z < 3.5$ galaxies. The efficiencies of the $YHVz$ selection criteria presented here are established via comparisons with archival ACS optical data in the HUDF09 and ERS fields, differences and similarities in the rest-frame UV and optical morphologies of $1.5 < z < 3.5$ galaxies. The efficiencies of the $YHVz$ selection criteria presented here are established via comparisons with archival ACS optical data in the HUDF09 and ERS fields, differences and similarities in the rest-frame UV and optical morphologies of $1.5 < z < 3.5$ galaxies.
Section 4, we describe the estimation of photometric redshifts, specific star formation rates (SSFRs), and stellar masses via spectral energy distribution (SED) fitting. In Section 5, we present $YHV_z$ color-selection criteria for the identification of galaxies at $1.5 < z < 3.5$ using the WFC3 and ACS filters. In addition, we carefully quantify selection efficiencies and contamination rates for these criteria according to the spectroscopic, and (up to) 15 band photometric, redshifts of galaxies in our master source catalogs. Furthermore, the characterization of passively evolving galaxies at $1.5 < z < 3.5$ via a simple extension of our selection criteria (passive $YHV_z$) is explored in Section 5.4, and the alternative color selections $JHVI$ and $VIH$, using filters from the CANDELS/Wide program (excluding $Y_{098}$ which is available only within the GOODS-N field; Koekemoer et al. 2011), are presented in Section 5.5. In Section 6, we publish our master source catalogs containing positions, photometric apertures, and photometric redshifts for all robust detections to $H_{160} < 27$ mag in the HUDF09 and $H_{160} < 25$ mag in the ERS. In Section 7, we compare the rest-frame UV and optical morphologies of galaxies in the HUDF09 and ERS fields at $1.5 < z < 3.5$, and examine the mass scales over which key structural sub-types are revealed by the WFC3. We summarize in Section 8. Note that we adopt a cosmological model with $\Omega_M = 0.75$, $\Omega_{\Lambda} = 0.25$, and $h = 0.7$, and that all magnitudes are quoted in the AB system throughout.

2. DATA

2.1. HUDF09

The HUDF09 program (Bouwens et al. 2010a) now in progress will observe a $\sim 4.7$ arcmin$^2$ central region of the HUDF (Beckwith et al. 2006) with the new WFC3 on the HST for a total of 96 orbits. The exposure time is divided between three NIR filters: $Y_{098}$ (F098M), $J_{125}$ (F125W), and $H_{160}$ (F160W). The first epoch data used here total 60 orbits (16 in $Y_{098}$, 16 in $J_{125}$, and 28 in $H_{160}$) and reach a uniform depth in all filters of $\sim 28.8$ mag in a $0^\prime\prime.2$ radius aperture (despite the necessary rejection of two orbits of $Y_{098}$ imaging due to severe persistence issues). Our reduction of the WFC3 imaging data using the multidrizzle package (Koekemoer et al. 2002) produces final science grade images with point-spread function (PSF) FWHM of $\sim 0.15$ and a pixel size of $0.06$ (see Bouwens et al. 2010a). Rebinning of the HUDF ACS $B_{435}$ (F435W), $V_{606}$ (F606W), $i_{775}$ (F775W), and $z_{850}$ (F850LP) images to the scale of our WFC3 frames was also performed to facilitate aperture-matched photometry.

2.2. ERS

The ERS program has observed a northern section of the GOODS-South field (Giavalisco et al. 2004) in the WFC3/IR channel in 10 pointings for a total of 60 orbits (see Windhorst et al. 2010). The exposure time was divided evenly between three NIR filters: $Y_{098}$ (F098M), $J_{125}$ (F125W), and $H_{160}$ (F160W), reaching a depth of $\sim 27.5$ mag in a $0^\prime\prime.2$ radius aperture) over an area of $\sim 40$ arcmin$^2$. Our reduction of this data (Bouwens et al. 2010a) was performed using the same procedures as for the HUDF09 WFC3 imaging, resulting in final science grade images with PSF FWHM $\sim 0.15$ and a pixel size of $0.06$. The GOODS ACS $B_{435}$ (F435W), $V_{606}$ (F606W), $i_{775}$ (F775W), and $z_{850}$ (F850LP) images were again rebin to the same scale as the reduced WFC3 frames.

2.3. Ancillary Data sets

A wealth of complementary data including photometry at wavelengths beyond the range of the HUDF/HUDF09 and GOODS/ERS HST imaging has been gathered for objects in the HUDF and GOODS-South fields by a number of different teams. Much of these data where publicly available have been compiled in the GOODS-MUSIC catalog (Grazian et al. 2006; Santini et al. 2009), which we employ in this study for objects with unambiguous matches in our primary source catalogs (see Section 3.1 below). The GOODS-MUSIC catalog contains PSF- and aperture-matched photometry (derived via the ConvPhot package; De Santis et al. 2007) in the following additional filters: ESO 2.2-WFI and VLT-VIMOS U, ESO VLT/ISAAC J, H, and $K_s$, Spitzer IRAC 3.6, 4.5, 5.8, and 8.0 $\mu$m, and MIPS 24 $\mu$m. A compilation of spectroscopic redshifts is also included in the GOODS-MUSIC catalog, mainly sourced from the GOODS (Vanzella et al. 2005, 2006, 2008), K20 (Mignoli et al. 2005), and VVDS (Le Fevre et al. 2004) projects.

In addition to the GOODS-MUSIC catalog, we also employ the published spectroscopic redshifts and spectral classifications for passive galaxies at $z \sim 2$ in the HUDF and GOODS-South fields from Daddi et al. (2005) and CIMATT et al. (2008; hereafter pBzK). The former sample consists of seven high-redshift sources in the HUDF with passive BzK colors, confirmed via analysis of low-resolution GRAPES spectra, of which three lie in the region of WFC3/IR imaging from the HUDF09 program. The latter sample consists of 13 galaxies from the GMASS catalog of Spitzer 4.5 $\mu$m detected sources in the GOODS-South field with a prominent Mg$_{b}$Fe feature in their ESO VLT/ FORS2 spectra, of which 10 lie in the region of WFC3/IR imaging from the ERS program. In total, two and eight of these pBzK galaxies in the Daddi et al. and CIMATT et al. samples, respectively, lie within the target range of our $YHV_z$ color-selection criteria ($1.5 < z < 3.5$). A further three and six GMOS spectroscopic redshifts from the $1 < z < 2$ Roche et al. (2006) ERO sample were employed for objects in the HUDF09 and ERS, respectively. Although only one of the corresponding objects was missing a “confident” spectroscopic redshift in the GOODS-MUSIC catalog, the Roche et al. redshifts were preferred due to the higher confidence and precision of these measurements. Importantly, for one object (ERS0325) assigned $z_{\text{spec}} = 0.481$ in the GOODS-MUSIC catalog, the value of $z_{\text{spec}} = 2.017$ reported by the Roche et al. team is much more consistent with its observed UV-to-IR SED. Finally, for the purposes of star–galaxy separation we also refer to the PEARs-S star catalog of Pirzkal et al. (2009).

3. EXTRATION OF THE $H_{160}$ HUDF09 AND ERS SOURCE CATALOGS

3.1. Details

Master source catalogs based on all robust $H_{160}$ detections to $H_{160} < 27$ mag and $H_{160} < 25$ mag in the HUDF09 and ERS imaging, respectively, were constructed as follows. First, SExtractor (Bertin & Arnouts 1996) was run on each of the reduced $H_{160}$ science images with four different choices of deblend parameters representing hot ($\text{nthresh} = 64$), medium ($\text{nthresh} = 16$), cold ($\text{nthresh} = 8$), and very cold ($\text{nthresh} = 2$) extractions. In each case, the RMS frames output from multidrizzle were scaled to reflect the true signal-to-noise (S/N) of the reduced science images before their application as weight maps, and the following key control parameters were adopted: $\text{detect} _{\text{thresh}} = 1.5 \sigma$, $\text{detect} _{\text{minarea}} =$, $\text{detect} _{\text{minarea}} =$.
12, and min_cont = 0.0001. Based on these $H_{160}$ extractions we then re-ran SExtractor in dual image mode to recover aperture-matched fluxes and Kron magnitudes from the remaining optical-to-NIR HST images ($B_{435}$ to $J_{125}$). Careful visual inspection of the output Kron ellipses of sources identified in each extraction was then performed to remove spurious detections and to identify the most appropriate aperture for flux measurement of each real source. When choosing the best aperture we considered both the positions of possible matches in the GOODS-MUSIC catalog and the appearance of each source in all seven ACS plus WFC3 ($B_{435}$ through $H_{160}$) filters. In ambiguous cases we favored the deblending of objects into distinct concentrations of $H_{160}$ flux (the filter expected to best trace the underlying stellar mass distribution, modulo some uncertainty regarding the role of thermally pulsing asymptotic giant branch (TP-AGB) stars). For calibration of the NIR magnitudes we employed the latest (AB system) WFC3/IR zero points available from the STScI Web site, and for the optical magnitudes we adopted the ACS zero points determined by the GOODS team. A total of 1052 and 3078 sources were thereby recovered to $H_{160} < 27$ mag and $H_{160} < 25$ mag in the HUDF09 and ERS imaging, respectively. To define the master source catalogs employed in this analysis we limit our samples to those systems with high S/N coverage in all seven available ACS plus WFC3 filters and lying within the region of sky covered by the GOODS-MUSIC catalog, a total of 993 and 2630 objects in the HUDF09 and ERS, respectively.

For all objects in our master source catalogs we searched for counterparts in the GOODS-MUSIC catalog (Santini et al. 2009) with matching positions and photometric apertures. All object pairs with centroid differences of $\sim 0\prime.24$ (i.e., 4 pixels in our drizzled WFC3 images) and $B_{435}$, $V_{606}$, $I_{775}$, and $z_{850}$ magnitudes differing by less than 0.5 mag between the two catalogs were classified automatically as successfully matched—426 sources in the HUDF09 and 1954 in the ERS fields. The remaining object pairs not satisfying these criteria were visually inspected, and a further 44 and 294 matches were thereby recovered for the HUDF09 and ERS fields, respectively.

For most galaxies at $H_{160} > 24.5$ mag no counterpart could be identified due to the brighter GOODS-MUSIC selection limits ($z_{850} < 26$ mag or $K < 23.5$ mag). In total, 523 and 382 objects in our master source catalogs from the HUDF09 and ERS, respectively, were ultimately deemed to be missing valid counterparts in the GOODS-MUSIC catalog.

### 3.2. Star–galaxy Separation

Star–galaxy separation in our HUDF09 and ERS samples was performed as follows. First, all sources matched to counterparts in the GOODS-MUSIC catalog with spectroscopic redshift quality flag $< 2$ and $z_{\text{spec}} = 0$ (2 objects in the HUDF09 and 29 in the ERS) and all objects with centroids matched within $0\prime.36$ to members of the PEARS-S star catalog of Pirzkal et al. (2009; an additional 3 and 16 sources in the HUDF09 and ERS, respectively) were identified as spectroscopically confirmed stars. In addition, all ultra-compact outliers from the observed $H_{160}$ apparent magnitude–Kron radius distributions at $\log_{10}(R_{\text{Kron}}/''') < -0.125 \times (H_{160} - 20) + y$ (with $y = 0.2$ for the HUDF09 and 0.075 for the ERS) not already identified as spectroscopically confirmed stars were visually inspected and classified as candidate stars (2 in the HUDF09 and 35 in the ERS) unless resolved structure was clearly evident. Figure 1 shows these candidate stars on the $H_{160}$ apparent magnitude–Kron radius diagnostic diagram. We exclude these sources from our analysis of galaxy color-selection efficiencies in Section 5.

### 4. ESTIMATES FOR REDSHIFTS, SPECIFIC STAR FORMATION RATES, AND STELLAR MASSES

#### 4.1. Photometric Redshift Estimates

We have computed photometric redshifts for all objects in our HUDF09 and ERS source catalogs via template fitting to the observed SEDs in the HST ACS and WFC3 filters ($B_{435}$ to $H_{160}$), supplemented by the additional photometry in the GOODS-MUSIC catalog (for a total of 15 passbands) where a valid counterpart could be identified. The actual template fitting was performed using the Zurich Extragalactic Bayesian Redshift Analyzer (ZEBRA; Feldmann et al. 2006). To recover optimal photometric redshifts ZEBRA modifies an empirical template library (Polletta et al. 2007; plus model SEDs for very blue objects from Bruzual & Charlot 2003) to account for systematic mismatches against the observed SEDs.

We quantify empirically our mean photometric redshift uncertainties by comparison against matched objects with confident (quality flag $< 2$) spectroscopic redshifts in the GOODS-MUSIC, Daddi et al., Cimatti et al., and Roche et al. catalogs (86 in the HUDF09 and 446 in the ERS), as illustrated in the panels in the leftmost columns of Figure 2. We thereby estimate typical uncertainties ($\Delta z = z_{\text{spec}} - z_{\text{phot}}$) of $\Delta z \sim 0.063(1+z)$ and $\Delta z \sim 0.039(1+z)$ for the HUDF09 and ERS master source catalogs, respectively. The larger uncertainties in the HUDF09 photometric redshifts reflect the relatively small number of confident SED template libraries available in this field for calibration of our SED template library. We also note low rates of catastrophic failures for the ZEBRA photometric redshift pipeline, namely that $<5\%$ of galaxies in the HUDF09, and $<9\%$ of galaxies in the ERS, are in disagreement with their spectroscopic redshifts by $\Delta z > 0.2(1+z)$.

At $z < 1.5$, where the greatest numbers of spectroscopic redshifts are available (78 in the HUDF09 and 355 in the ERS), the mean uncertainties are reduced to $\Delta z \sim 0.058(1+z)$ and $\Delta z \sim 0.035(1+z)$, respectively. Nevertheless, at $z > 1.5$ our photometric redshift accuracy remains satisfactory with uncertainties of only $\Delta z \sim 0.069(1+z)$ and $\Delta z \sim 0.056(1+z)$, respectively—although we note that in the case of the HUDF09 the reliability of this comparison is limited by the small number (8) of spectroscopic redshifts in this interval. Hence, as a further stage of quality control on our ZEBRA photometric redshifts we also evaluate here the performance of the output confidence intervals derived from the posterior probability distribution in redshift space for each galaxy. Specifically, we examine the ratio between $\Delta z$ (i.e., the absolute difference between the maximum likelihood photometric redshift and the true spectroscopic redshift) and the width of the 1$\sigma$ confidence interval for each galaxy (see Ilbert et al. 2009). If our posterior probability distributions are well estimated then we would expect the value of this quotient to be less than one for roughly 68% of each sample. In fact, our investigation reveals a slight underestimation of uncertainties by ZEBRA such that a rescaling of these confidence interval widths by 1.25 and 1.35 for the HUDF09 and ERS samples, respectively, is required in order to achieve the 68% target. Having calibrated our

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2 http://www.stsci.edu/hst/wfc3/phot_zp_lbn
8 http://archive.stsci.edu/pub/hlsp/goods/2/12
9 Identified as those objects occupying areas of the reduced science images with local background RMS less than twice the global background RMS.
Figure 1. Distributions of galaxies, spectroscopically confirmed stars, and candidate stars in the $H_{160}$ apparent magnitude–Kron size plane in our master source catalogs to $H_{160} < 27$ mag in the HUDF09 (top row) and $H_{160} < 25$ mag in the ERS (bottom row). The red hashed area in each case denotes the region within which small size outliers were classified as candidate stars unless resolved structure was clearly evident upon visual inspection (as described in Section 3.2). The black, dark blue, and light blue (smoothed) contours, respectively, enclose 68%, 95%, and 99% of the detected objects in each survey. (A color version of this figure is available in the online journal.)

Figure 2. Evaluation of the accuracy of our ZEBRA photometric redshifts for galaxies in the HUDF09 (top row) and ERS (bottom row). The panels in the leftmost columns present the one-to-one comparison between our photometric redshifts and available spectroscopic redshifts, while those in the columns second from the left evaluate our estimates of the photometric redshift uncertainties for these galaxies against the same spectroscopic benchmarks. (The green, yellow, and red shaded regions here mark deviations of $<5\%$, $<20\%$, and $>20\%$ in $\Delta z/(1 + z)$, respectively.) The panels in the two rightmost columns illustrate the redshift distributions of galaxies in each field both as an ensemble, and after subdivision into those systems with spectroscopic redshifts, photometric redshifts with matched GOODS-MUSIC photometry, and $HST$-based photometric redshifts only. See Section 4.1 for further details. (A color version of this figure is available in the online journal.)
photometric redshift uncertainties we fold these via Monte Carlo simulation into our subsequent error calculations for the selection efficiencies of the color–color criteria presented in Section 5.

In Figure 2, we summarize graphically the key properties of our HUDF09 and ERS galaxy redshift catalogs. In order from the left-hand side of the page the four columns of this figure each contain two panels demonstrating for the HUDF09 and ERS (top and bottom rows, respectively): (1) the close agreement between our photometric redshift estimates and the benchmark spectroscopic values where available in each sample; (2) the necessity of our (slight) rescaling of the (ZEBRA) estimated uncertainties to ensure consistency in the cumulative distribution functions for (absolute) empirical redshift error divided by 1σ confidence interval width, i.e., \(|\Delta z|/1\sigma\) error; (3) relative frequency histograms contrasting the redshift distributions of galaxies with spectroscopic redshifts against those for galaxies without (further subdivided according to presence/absence of additional GOODS–MUSIC photometry)—the latter distinction thereby highlighting the unique power of WFC3/IR imaging for exploring the \(z \sim 1.5\) discovery space; and (4) the overall redshift distributions for all galaxies in our magnitude limited samples—both of which peak around \(z \sim 1\), as is typical for untargeted, deep imaging surveys with optical/near-IR selection (e.g., Rudnick et al. 2001; Ilbert et al. 2009).

Finally, we note that our HUDF09 \(H_{160} < 27\) mag master source catalog contains both \(z \sim 7\) candidates at this brightness from Oesch et al. (2010); UDFz-42566566 and UDFz-38807073 plus the probable supernova (UDFz-34537360), all of which were assigned photometric redshifts \(z \sim 6.9\) by ZEBRA. However, the remainder of the recently reported \(z \sim 7\) and \(z \sim 8\) candidates in the HUDF09 and ERS fields (Bouwens et al. 2010a, 2010b; Oesch et al. 2010; Wilkins et al. 2010) are fainter than the apparent magnitude limits employed in this study.

4.2. Specific Star Formation Rate and Stellar Mass Estimates

SSFRs and stellar masses for all galaxies in our HUDF09 and ERS samples were estimated using an updated version of ZEBRA, ZEBRA+ (P. A. Oesch et al. 2011, in preparation). ZEBRA+ computes various galaxy physical properties based on template fitting to model SEDs with the (previously computed) photometric redshift, or measured spectroscopic redshift, held fixed. For this analysis we employed a library of SED templates based on the Bruzual & Charlot (2003) stellar population synthesis code with a Chabrier initial mass function (Chabrier 2003), drawn from a grid of exponential decay star formation rate models well sampled over a wide range of ages (0.01–12 Gyr), decay rates \((\tau = 0.05–9\) Gyr), and metallicities (0.05–2 \(Z_\odot\)). The impact of dust reddening is accounted for during template fitting via a Calzetti extinction law (Calzetti 2001) with the \(E(B-V)\) value a free parameter (see Sargent et al. 2010 for a demonstration of the impact of dust reddening on galaxies at intermediate redshift). Of course, there is a substantial degree of degeneracy in the choice of stellar population template and dust extinction model inherent in the fitting of broadband SEDs, which is expected from previous studies to dominate the error budget (contributing \(\Delta \log M \approx 0.20\) dex) in samples for which broadband flux measurements are available in a significant number of filters adequately sampling each galaxy SED (e.g., Bolzonella et al. 2010; Taylor et al. 2010). Thus, for galaxies in our sample matched to counterparts in the GOODS–MUSIC survey we expect to achieve roughly this level of accuracy, although for galaxies with \(HST\)-only photometry our uncertainties will be necessarily higher. Details for ZEBRA+, including a further investigation into the relevant uncertainties, are given in P. A. Oesch et al. (2011, in preparation; see also Oesch et al. 2009).

We note that of the 3 and 10 spectroscopically confirmed passive galaxies of Daddi et al. and Cimatti et al., respectively, which enter our HUDF09 and ERS samples, all but one have ZEBRA+ estimated SSFRs representative of passively evolving stellar populations (i.e., SSFR \(< 10^{-10} \text{ yr}^{-1}\)). The one discrepant object (ERS2953) was assigned an intermediate SSFR of \(1.2 \times 10^{-9} \text{ yr}^{-1}\) with an extreme \(E(B-V)\) fit of 0.6 mag.

In Figure 3, we present the distributions of galaxies in our HUDF09 and ERS master source catalogs in both absolute (rest-frame \(B\)-band) magnitude and stellar mass as function of redshift. Two selection limits are indicated on each plot: (1) the SED-dependent completeness limit corresponding to the lower bound on luminosity/mass of the faintest/least massive systems detectable at a given redshift above our \(H_{160}\) magnitude threshold—all members of our HUDF09 and ERS samples thus lie above, or on, this line and (2) the SED-independent completeness limit corresponding to the respective lower bound under the constraint of full detectability for galaxies of all spectral types. Note that the observed distributions of galaxies are not tightly bound by the former until \(z \sim 2.5\) as the largest \(K\)-correction from observed \(H_{160}\) to rest-frame \(B\) below this redshift occurs for the reddest spectral type (which is not matched to any of the faintest/least massive systems in these surveys; see, for comparison, Cameron & Driver 2007, 2009). The SED-independent limits presented here set the thresholds \((M > 10^{10.5} \text{M}_\odot\) for the HUDF09 and \(M > 10^{11}\) \(\text{M}_\odot\) for the ERS) for selection of the mass-limited galaxy samples used to investigate the morphological mix at \(z \sim 2\) in Section 7.

5. OPTIMIZATION OF \(HST\)-BASED COLOR-SELECTION CRITERIA FOR \(1.5 < z < 3.5\) GALAXIES

5.1. YHVz Color Selection

Through visual inspection of synthetic evolutionary tracks for model stellar populations in our ZEBRA+ template library we have identified \(Y_{105/098} - H_{160}\) versus \(V_{606} - z_{850}\) as the most favorable parameter space for selection and characterization of \(1.5 < z < 3.5\) galaxies given the set of WFC3 and ACS filters employed in the HUDF09/HUDF and ERS/GOODS imaging programs. Example tracks for instantaneous burst and constant star formation rate models (with metallicities of \(Z = 0.35 \text{Z}_\odot\) and formation redshifts of both \(z_{\text{form}} = 4\) and \(z_{\text{form}} = 6\) are presented in Figure 4 to illustrate the expected evolution of active and passive systems in this plane. These tracks indicate that galaxies at \(1.5 < z < 3.5\) should be significantly redder in \(Y_{105/098} - H_{160}\) at fixed \(V_{606} - z_{850}\), than galaxies at lower or higher redshifts. Moreover, according to the Calzetti (2001) reddening law, the effect of dust extinction on the observed galaxy colors in this diagram is simply a diagonal shift (as indicated in Figure 4) with the potential to move lower redshift objects into the region of high-redshift color–color space only for passively evolving systems at \(z > 1\). When the corresponding color–color distributions of real galaxies at \(1.5 < z < 3.5\) in the HUDF09 and ERS are contrasted against those at lower and higher redshifts (see Figure 4 again) it is clear that galaxies at these epochs are indeed well separated, occupying distinct color–color sequences with minimal overlap.
Figure 3. Distributions of galaxies in absolute (rest-frame $B$) magnitude and stellar mass derived via the ZEBRA+ code for galaxies in our master source catalogs to $H_{160} < 27$ mag in the HUDF09 (top row) and $H_{160} < 25$ mag in the ERS (bottom row). The (conservative) SED-independent selection limits for each sample are indicated via the green-shaded regions on each plot, while the boundaries of SED-dependent incompleteness (set by the difference between the reddest and bluest spectral templates matched in our fits) are marked in yellow (with red hashes indicating 100% detection incompleteness). Galaxies in our samples for which reliable spectroscopic redshift measurements are available are highlighted in blue. (A color version of this figure is available in the online journal.)

Guided by this qualitative analysis we define a $1.5 < z < 3.5$ selection function, $YHVz$, via the combination of a diagonal and a vertical limit as follows:

$$Y_{105/098} - H_{160} > m \times (V_{606} - z_{850}) + b$$

or

$$Y_{105/098} - H_{160} > c.$$  

(1)

Maximization of the selection rate ($S$) over this parameter space with the constraint that the $z < 1$ low-redshift interloper contamination rate ($C_{z<1}$) not exceed 5% returned the selection parameters $m = 1.1$, $b = -0.25$, and $c = 1.0$ for the HUDF09, and $m = 1.0$, $b = -0.1$, and $c = 1.5$ for the ERS. Specifically, for the HUDF09

$$Y_{105} - H_{160} > 1.1 \times (V_{606} - z_{850}) - 0.25$$

or

$$Y_{105} - H_{160} > 1.$$  

(2)

and for the ERS

$$Y_{098} - H_{160} > V_{606} - z_{850} - 0.1$$

or

$$Y_{098} - H_{160} > 1.5.$$  

(3)

These optimal $YHVz$ selection criteria identify $96\% \pm 1\%$ and $92\% \pm 1\%$ of galaxies in our target redshift interval of $1.5 < z < 3.5$ to $H_{160} < 27$ mag in the HUDF09 and $H_{160} < 25$ mag in the ERS, respectively. The corresponding strict contamination rates ($C$) from interlopers at lower and higher redshifts ($z < 1.5$ or $z > 3.5$) are only $15\% \pm 2\%$ in each case, with contamination from $z < 1$ low-redshift interlopers ($C_{z<1}$) of only $5\% \pm 1\%$ (as constrained during the optimization process). The quoted uncertainties were computed according to the widths of the (median-centered) intervals containing 68% of output $S$, $C$, and $C_{z<1}$ values recovered from a series of 1000 Monte Carlo simulations (with replacement) in which the colors and redshifts of galaxies were randomly shifted according to their estimated errors—the errors in galaxy colors defined according to the Poissonian errors in the underlying broadband fluxes, and the redshift errors set to the (scaled) values from ZEBRA+ (see Section 4.1) for galaxies with photometric redshifts only (and zero for those with spectroscopic redshifts). This resampling process also accounts naturally for the binomial errors (Cameron 2010) in the measured selection and contamination rates.

5.2. Tradeoffs between Sample Completeness and Sample Purity

The efficiency of $YHVz$ selection is ultimately limited by intrinsic variations in the stellar population ages, star formation rates, and metallicities of galaxies, which preclude a perfect division by redshift on a single color–color diagram. Comparison
Figure 4. YHVz color selection of galaxies at 1.5 < z < 3.5 in the Hubble Space Telescope ACS plus WFC3 imaging of the HUDF and GOODS-South fields from the HUDF09 (top row) and ERS (bottom row) programs. The observed distributions in Y(105.098) − H(160) vs. V(606) − z(850) color–color space of all objects in our HUDF09 (H160 < 27 mag) and ERS (H160 < 25 mag) master source catalogs are shown in the left-hand panels. Galaxies with redshifts in the range 1.5 < z < 3.5 are marked with circles, while those outside this redshift interval are marked with triangles, and these symbols are highlighted blue and purple, respectively, if the redshift is spectroscopic, rather than photometric. The optimal YHVz selection criteria we derive for the high-redshift population in each survey are indicated by the union of the green- and yellow-shaded regions—the particular significance of the yellow-shaded corner for passive galaxy selection is discussed in Section 5.4. Synthetic color–color tracks revealing the redshift evolution of archetypal active and passive stellar population models (with Z = 0.35 Z⊙, and both zform = 4 and zform = 6) in the relevant filters are shown for comparison in the right-hand panels. Example reddening vectors corresponding to Calzetti (2001) extinction for galaxies observed at z = 2 are marked by black arrows.

(A color version of this figure is available in the online journal.)

of our optimal selection criteria against the model evolutionary tracks presented in Figure 4 demonstrates a necessary “tradeoff” between high completeness for both active and passive systems at z \gtrsim 3, and exclusion of active systems at z < 1.5. Photometric errors in the measured colors of galaxies contribute only modestly to the recovered selection and contamination rates due to the unprecedented depth of the HUDF09/HUDF and ERS/GOODS imaging. Specifically, photometric errors can be excluded (above a 90% confidence level) as the cause of YHVz misclassifications for over 75% of all galaxies with conflicting spectroscopic redshifts in our master source catalogs, and for over 55% of galaxies with conflicting photometric redshifts. We explicitly note the existence of one object in the HUDF09, and three objects in the ERS, with confident YHVz classifications “strongly” in conflict with their measured spectroscopic redshifts (i.e., offset by more than 0.5 mag to the wrong side of our selection limits). The one strongly conflicting object in the HUDF09 (UDF0045) is a compact system at z_{spec} = 1.216 with a spectral classification of “broad-line AGN” (Grazian et al. 2006). Of the three strongly conflicting objects in the ERS, one has an “AGN” spectral class (ERS2179, z_{spec} = 1.617) and two are flat spectrum sources with noisy spectra for which we disagree with the confidence levels assigned to the redshifts (ERS2585, z_{spec} = 1.883; ERS0463, z_{spec} = 0.117).

The dependence of selection efficiency on apparent magnitude is an important consideration for the application of
any color-selection criteria (e.g., for identifying specific high-redshift galaxy types for spectroscopic follow-up). For subsamples of our HUDF09 and ERS sources at brighter magnitude limits the \( YHVz \) selection efficiencies remain stable but the contamination rates increase marginally. For instance, at \( H_{160} < 25 \) mag in the HUDF09 and \( H_{160} < 23 \) mag in the ERS we recover contamination rates of \( C = 17\% \pm 4\% \) and \( 21\% \pm 4\% \), and \( C_{<1} = 8\% \pm 2\% \) and \( 10\% \pm 3\% \), respectively. This is an expected consequence of the higher ratio of low-redshift sources to high-redshift sources in the brighter subsamples, given the intrinsic limitations of redshift determination in a single-color–color diagram. The dependence of \( YHVz \) selection efficiency on apparent magnitude in our HUDF09 and ERS source catalogs is further quantified in Table 1.

### 5.3. A Comparison of Performance

We have compared the efficiency of \( YHVz \) \( 1.5 < z < 3.5 \) selection against the \( BzK \) \( 1.4 < z < 2.5 \) selection of Daddi et al. (2004). To this purpose, we have computed the corresponding \( BzK \) selection and contamination rates for all galaxies in our master source catalogs well matched to GOODS-MUSIC objects with measured \( K_s \) magnitudes. For \( BzK \) we obtain \( S = 84\% \pm 1\% \) and \( 86\% \pm 1\% \), \( C = 30\% \pm 2\% \) and \( 30\% \pm 2\% \), and \( C_{<1} = 3\% \pm 1\% \) and \( 4\% \pm 1\% \) to \( H_{160} < 27 \) mag in the HUDF09 and \( H_{160} < 25 \) mag in the ERS, respectively (as summarized in Table 1). Comparatively, \( YHVz \) selection offers a more efficient mechanism for high-redshift galaxy selection with a significantly more precise sampling of the target redshift interval than \( BzK \) (i.e., lower strict contamination rates).

A further distinction between \( YHVz \) and \( BzK \) is that the former fully exploits the very high angular resolution and uniformly high sensitivity of both the WFC3 and ACS, whereas the latter requires \( K_s \) imaging, not available, for large galaxy samples, at a similarly high resolution. As a result, only \( YHVz \) selection allows the confident photometric identification of high-redshift galaxies with neighbors at angular separations below the confusion limit of ground-based \( K_s \)-band imaging. This enables more detailed studies of the structural assembly and star formation properties of galaxies at these crucial epochs.

### 5.4. Passive \( YHVz \)

According to the stellar population evolution models presented in Figure 5, galaxies at \( 1.5 < z < 3.5 \) with actively star-forming and passively evolving stellar populations occupy distinct regions of the \( Y_{105/98} - H_{160} \) versus \( V_{606} - z_{850} \) color–color plane. In particular, high-redshift passively evolving systems are expected to exhibit much redder \( V_{606} - z_{850} \) and \( Y_{105/98} - H_{160} \) colors than star-forming systems at the same epochs. This is consistent with the observed colors of spectroscopically confirmed passive galaxies at \( 1.5 < z < 3.5 \) from the Daddi et al. and Cimatti et al. samples, as shown in Figure 5. Interestingly, all but one of these confirmed passive galaxies can be identified simply via an extension of our optimal \( YHVz \) selection criteria to define a passive \( YHVz \) selection analogous to the \( pBzK \) object class. Specifically, for the HUDF09

\[
Y_{105} - H_{160} < 1.1 \times (V_{606} - z_{850}) - 0.25 \quad \text{and} \quad Y_{105} - H_{160} > 1
\]

(4)

and for the ERS

\[
Y_{998} - H_{160} < V_{606} - z_{850} - 0.1 \quad \text{and} \quad Y_{998} - H_{160} > 1.5.
\]

(5)

In addition to the well-studied \( pBzK \) objects, our passive \( YHVz \) selection criteria identify an additional 4 and 10 galaxies with photometric, and/or spectroscopic, redshifts of \( 1.5 < z < 3.5 \) in the HUDF09 and ERS, respectively. (The one passive \( YHVz \) galaxy with a spectroscopic redshift not from either the considered \( pBzK \) catalogs, ERS2182, exhibits only a tentative \( OIII \) emission line detection at the upper wavelength limit of its VLTI/FORS2 optical spectrum from the GOODS program; Vanzella et al. 2005, 2006, 2008.) Photometric errors in the colors of these additional passive candidates enable us to robustly assign 8 (4 from the HUDF09 and 4 from the ERS) to the passive \( YHVz \) class above a 90\% confidence level.

According to the Calzetti (2001) model, dust reddening should move galaxies at \( z \approx 2 \) near parallel to our passive \( YHVz \) boundary, implying minimal contamination of our passive sample from dust reddened, star-forming objects at \( 1.5 < z < 3.5 \). Indeed, the best-fit model templates to the observed SEDs of all confident passive \( YHVz \) galaxies at \( 1.5 < z < 3.5 \) in our catalogs were representative of very low SSFRs.
GOODS-South fields from the HUDF09 (left column) and ERS (right column) programs. The YHVz color selection of passively evolving galaxies at 1.5 < z < 3.5 in the Hubble Space Telescope ACS plus WFC3 imaging of the HUDF and GOODS-South fields from the HUDF09 (left column) and ERS (right column) programs. The YHVz color–color space defined by our passive YHVz selection criteria. The photometric errors in the measured colors of 1.5 < z < 3.5 galaxies within this region are illustrated by the corresponding error bars, and the positions of spectroscopically confirmed passive galaxies at z > 1.5 from the pBzK catalogs are highlighted with red circles.

(A color version of this figure is available in the online journal.)

Figure 5. Passive YHVz color selection of passively evolving galaxies at 1.5 < z < 3.5 from the HUDF and GOODS-South fields from the HUDF09 (left column) and ERS (right column) programs. The YHVz color–color space defined by our passive YHVz selection criteria. The photometric errors in the measured colors of 1.5 < z < 3.5 galaxies within this region are illustrated by the corresponding error bars, and the positions of spectroscopically confirmed passive galaxies at z > 1.5 from the pBzK catalogs are highlighted with red circles.

(SSFR < 10⁻¹⁰ yr⁻¹), with only one galaxy requiring a high dust extinction value (E(B - V) > 0.3 mag) for an optimum fit. Only 3 of the 10 additional passive YHVz candidates in the ERS not in either pBzK sample have ZEBRA+ SED favoring models with intermediate SSFRs (10⁻¹⁰ < SSFR < 10⁻⁹ yr⁻¹) and high dust reddening values; all three enter our selection below the 90% confidence level. Similarly, 4 of the 17 total (pBzK plus new) passive YHVz systems in the ERS were identified as strong MIPS 24 µm sources (F₂₄µm > 20 µJy) in the GOODS-MUSIC catalog (see Figure 5). The detection of strong 24 µm emission from galaxies at these epochs provides an alternative indicator of the presence of dust-obscured star formation (see Yan et al. 2004), modulo any contribution from AGN activity: again, of the four 24 µm sources contaminating our passive YHVz catalog, three make our selection only at low confidence levels.

In Figure 6, we present WFC3 H₁₆₀ postage stamp images of all passive YHVz galaxies at 1.5 < z < 3.5 from our HUDF09 and ERS master source catalogs. Visual inspection confirms that these are typically compact systems with highly centrally concentrated light profiles and smooth morphologies, in agreement with previous studies of this galaxy class (see Van Dokkum et al. 2004, 2010; Daddi et al. 2005; Trujillo et al. 2006; Cimatti et al. 2008; Franx et al. 2008; Toft et al. 2009; Damjanov et al. 2009; Szomoru et al. 2010). However, at least six of these passive YHVz galaxies exhibit morphologies suggestive of the presence of either a stellar disk with or without clumpy sub-structure (UDF0681, ERS0177, ERS1000, UDF0993, ERS0354). The presence of disk-like morphologies within a subset of passive z ~ 2 galaxies has previously been reported by Stockton et al. (2008), McGrath et al. (2008), and Cassata et al. (2010).

We stress that the passive YHVz selection criteria (similarly to, for example, the pBzK criterion) may not return the complete sample of passively evolving galaxies at the targetred redshifts. At face value, there are galaxies with very low SSFRs computed with ZEBRA+ SED fits, in both the HUDF09 and ERS samples at 1.5 < z < 3.5, which reside outside our passive YHVz limits, occupying a region of intermediate color–color space shared with dusty, star-forming sources. Given that this “green valley” region is consistent with the impact of moderate-to-high dust reddening on star-forming systems at 1.5 < z < 3.5, however, we suspect that the inherent degeneracy between the choice of reddening value and stellar population template during SED fitting is responsible for the underestimation of SSFRs in many of these additional passive candidates.

5.5. Other HST-based Criteria for Selecting z > 1.5 Galaxies: the JHV1 Criterion

Motivated by the desire to capitalize on other HST high-z surveys employing similar but not identical passbands, we have explored the performance of other color-selection criteria in isolating galaxies in the z > 1.5 redshift regime. In particular, the CANDELS team is currently in the process of surveying a total area of ~800 arcmin² on the sky with WFC3/IR and ACS with a two-tier observing strategy featuring a “wide, but shallow” component (CANDELS/Wide) and a “deep, but narrow” component (CANDELS/Deep; as described in Grogin et al. 2011 and Koekemoer et al. 2011). CANDELS/Deep features observations of regions in the two GOODS fields in each of the Y₁₀₅, J₁₂₅, and H₁₆₀ filters, supplementing the existing GOODS B₁₃₅, V₆₀₆, I₇₇₅, and z₈₅₀ ACS images. Hence, our YHVz selection can be readily applied for the study of 1.5 < z < 3.5 galaxies in this deep data set. CANDELS/Wide, however, will feature shallower imaging of regions from the GOODS-N & S, COSMOS, EGS, and UKIDSS/UDS fields in only the V₆₀₆, I₈₁₄, J₁₂₅, and H₁₆₀ filters, precluding application of our YHVz selection criteria (except in the GOODS-N region for which
Y_{105} data are available from the ERS and CANDELS/Deep programs.

To estimate the efficiency of other potential color–color-selection strategies for CANDELS/Wide, we first estimate $I_{814}$ magnitudes for all objects in our ERS $H_{160} < 25$ mag source catalog by interpolating the best-fit SED template for each galaxy against the $I_{814}$ transmission function. The wavelength coverage of the $I_{814}$ filter is significantly longer and redder than that of the $I_{775}$ filter employed in the GOODS ACS program, providing deeper imaging in this part of the spectrum for a given exposure time. Using these interpolated $I_{814}$ magnitudes we contrast the distributions of galaxies at $z > 1.5$ and $z < 1.5$ in our ERS $H_{160} < 25$ mag sample in $J_{125} - H_{160}$ versus $V_{606} - I_{814}$ color–color space in Figure 7.

By repeating the optimization procedure employed in Section 5.1 we recover the following $JHVI$ selection criteria:

$$J_{125} - H_{160} > 1.5 \times (V_{606} - I_{814}) - 0.1 \quad \text{or} \quad J_{125} - H_{160} > 0.5.$$  

(6)

It is clear from visual inspection that the distinction between galaxies above and below $z \sim 1.5$ in this $JHVI$ parameter space is less efficient than that demonstrated earlier for our $YHVz$ selection. Nonetheless, these criteria do identify 77% ± 2% of ERS $H_{160} < 25$ mag galaxies at $z > 1.5$ with a strict ($z < 1.5$) contamination rate of 26% ± 1% and a $z < 1$ interloper rate of only 5% ± 1% (as constrained in the optimization). Thus, despite the lower performance relative to our main $YHVz$ selection criteria, this alternative $JHVI$ selection still provides a useful tool for the identification of $z > 1.5$ galaxies.

5.6. Lowering the Low-$z$ Limit: VIH Galaxies Above and Below $z = 1$

As a final remark, we note that by modifying the goals of the selection to $z > 1$ galaxies one can identify more efficient color–color criteria using only the $V_{606}, I_{814}$, and $H_{160}$ filters, as shown in Figure 7. The optimum VIH criteria we recover for the ERS source catalog are

$$I_{814} - H_{160} > 1.75 \times (V_{606} - I_{814}) - 0.25 \quad \text{or} \quad I_{814} - H_{160} > 2.1.$$  

(7)

These criteria detect 85% ± 1% of ERS $H_{160} < 25$ mag galaxies at $z > 1$ (with only 5% ± 1% contamination from $z < 1$ interlopers).
normal ellipticals coexisting with massive interacting structures: with smooth disk/bulge-disk galaxies, and rather uncovered a galaxy population at these epochs rich in diversity systems, as well as ultra-compact, elliptical-like galaxies, large, V vs. H.

In recent years, ground-based or IR, the new HUDF09 and ERS $H_{160}$ images offer the most detailed view to date of the high-redshift galaxy population at rest-frame optical wavelengths. Through visual classification of the galaxies in our $1 < z < 3.5$ color-selected HUDF09 and ERS samples, we thus investigate here, qualitatively, the diversity of galaxy structure as revealed by the WFC3/IR $H_{160}$ (rest-frame optical) images relative to the ACS $z_{850}$ (rest-frame UV) images.

The first indication of the paramount importance of the rest-frame WFC3 images in understanding the $1 < z < 3.5$ galaxy population comes from the comparison with the GOODS-MUSIC catalog discussed in Section 3.1. In most cases where no counterpart to one of our $H_{160}$ sources was found in the GOODS-MUSIC catalog, the centroid offset that prevented automatic catalog matching was due to morphological differences between the rest-frame UV $z_{850}$ image (used as a basis for most GOODS-MUSIC detections) and the new rest-frame optical $H_{160}$ image provided by the WFC3. In a number of instances, the greater sensitivity of the WFC3 $H_{160}$ image to the smoother, underlying stellar mass distribution provided a confident aperture definition and centroid conflicting significantly with that adopted in the GOODS-MUSIC analysis, and no match was possible. It is evident that the rest-frame UV images on which the GOODS-MUSIC catalog was based often identify, as the galaxy center, a knot of star formation.
sive YHVz and rest-frame optical morphologies (see Section 5.4) reveals that passive galaxies at such early epochs are in-
substantially displaced from the true galaxy center. This is, on the other hand, well identified in the rest-frame optical WFC3 images.

Also, the combination of passive-SED color-selection (passive YHVz) and rest-frame optical morphologies (see Section 5.4) reveals that passive galaxies at such early epochs are indeed mostly spheroids, as shown in previous studies (e.g., Van Dokkum et al. 2004, 2010; Daddi et al. 2005; Trujillo et al. 2006). The remaining three classes do separate galaxies with very different morphologies, but, strikingly, these morphologies are unchanged in rest-frame UV and rest-frame optical light. These classes are, respectively: galaxies which, both in the rest-frame UV and rest-frame optical NIR WFC3 images, maintain a regular, spheroid-like morphology (class 2); galaxies which retain, in the NIR WFC3 images, a highly irregular/disturbed morphology, similar to that observed in the ACS rest-frame UV images (class 3); and, finally, the population of small-sized, smooth, and rather symmetric “blobs” of light in both the H$_{160}$ and z$_{850}$ images for which it is unclear whether these systems are proto-disks or spheroids (class 4). Examples of each class are given in Figures 8, 9, 10, and 11.

In class 1 objects, the rest-frame optical morphology is substantially smoother, i.e., less clumpy, and also more centrally concentrated, than in the rest-frame UV. Indeed, in such systems, the WFC3 H$_{160}$ images expose a well-defined center—in contrast with the irregular rest-frame UV morphologies. These class 1 galaxies are the only ones which show a morphological difference between their rest-frame UV and rest-frame optical images. The three remaining classes do separate galaxies with very different morphologies, but, strikingly, these morphologies are unchanged in rest-frame UV and rest-frame optical light. These classes are, respectively: galaxies which, both in the rest-frame UV and rest-frame optical NIR WFC3 images, maintain a regular, spheroid-like morphology (class 2); galaxies which retain, in the NIR WFC3 images, a highly irregular/disturbed morphology, similar to that observed in the ACS rest-frame UV images (class 3); and, finally, the population of small-sized, smooth, and rather symmetric “blobs” of light in both the H$_{160}$ and z$_{850}$ images for which it is unclear whether these systems are proto-disks or spheroids (class 4). Examples of each class are given in Figures 8, 9, 10, and 11.

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Figure 8. Rest-frame UV (ACS $z_{850}$) and optical (WFC3 $H_{160}$) postage stamp images of example 1.5 $< z < 3.5$ galaxies revealed as disk, or bulge/disk, systems by WFC3 (class 1). In each case the elliptical Kron aperture identified for that galaxy is overlaid on the image. The corresponding $z_{850}$ or $H_{160}$ apparent magnitude and best available redshift for each source are noted in the top and bottom right-side corners of each postage stamp image, respectively, with spectroscopic redshifts highlighted in yellow.

(A color version of this figure is available in the online journal.)

Figure 9. Same as for Figure 5, but this time for class 2, 1.5 $< z < 3.5$ example galaxies that show a diskless, spheroid-only morphology both in the rest-frame optical WFC3 images and in the rest-frame UV ACS images.

(A color version of this figure is available in the online journal.)

Figure 10. Same as for Figure 5, but this time for class 3, 1.5 $< z < 3.5$ example galaxies that keep a similar, highly irregular/disturbed morphology in the rest-frame optical as in the rest-frame UV.

(A color version of this figure is available in the online journal.)
small(er) bulges, consistent with counterparts identified by Papovich et al. (2005) and Stockton et al. (2008).

Class 2 objects show the smooth and compact appearance indicated by previous studies to be typical for many spheroids at these epochs (e.g., Daddi et al. 2004, 2005; Cimatti et al. 2008; Franx et al. 2008; Damjanov et al. 2009). Already Szomoru et al. (2010) have used the HUDF09 WFC3/IR images to establish, on firm grounds, the compactness of one “quenched” spheroid at $z = 1.98$ (UDF0884), extracted from the Daddi et al. sample. While many galaxies in this morphological class are identified as passive $YH_{\nu}z$ systems in our color–color-selection criteria (Section 5.4), we stress that a non-negligible fraction of them might exhibit a large-scale bar. While $z > 1$ bars, while not as frequent as at redshift $z \sim 1$, given that disks at such early times appear to be, on average, substantially hotter and more turbulent than at later times (e.g., Genzel et al. 2006, 2008, 2010).

Class 4 objects are relatively small-sized systems exhibiting smooth, symmetric morphologies, but with less centrally concentrated light distributions than the class 2 objects. As such, these class 4 objects could either be diffuse counterparts of the class 2 spheroids, or else small proto-disks in the earliest stages of growth. Future studies of the quantitative structural parameters and, ideally, kinematical properties of this object class are required to establish the place of these systems within the cosmic history of galaxy structural assembly.

In Figure 12, we present the morphological mix of these galaxy types in each of the $\sim 1.2$ Gyr intervals, $1.5 < z < 2.15$ and $2.15 < z < 3.5$, based upon counts in mass-limited samples of 30 galaxies at $M > 10^{10} M_\odot$ in the HUDF09 and 30 galaxies$^{10}$ at $M > 10^{11} M_\odot$ in the ERS (see Figure 3 for the relationship between our mass completeness limits and the distribution of galaxies in our HUDF09 and ERS source catalogs as a function of redshift). Interestingly, as we confirm via artificial noise degradation analysis of the HUDF09 images in the Appendix to this paper, despite a $\sim 14x$ shorter exposure time the depth of the ERS imaging is sufficient to perform morphological classification of the (relatively crude) nature described here at comparable accuracy to that in the HUDF09. The combined (i.e., $> 10^{10} M_\odot$) fractions of objects in the four different classes are, respectively, $29_{-7}^{+9}\%$, $45_{-4}^{+9}\%$, $13_{-3}^{+3}\%$, and $13_{-3}^{+3}\%$ at $1.5 < z < 2.15$, and $0_{-0}^{+6}\%$, $18_{-5}^{+3}\%$, $41_{-3}^{+3}\%$, and $41_{-3}^{+3}\%$ at $2.15 < z < 3.5$ (with $1\sigma$ binomial uncertainties estimated using a Bayesian approach; cf. Cameron 2010). Note that the evolution of these fractions likely implies substantial morphological transformations across the redshift $z \sim 2$ epoch of peak star formation activity. We highlight, in particular, the emergence of a substantial population of regular

\footnote{Note that it is entirely by coincidence, not design, that there exist exactly 30 galaxies in each of these mass-limited samples.}
disk morphologies and a substantial increase in the fraction of spheroidal morphologies at epochs $z \lesssim 2$.

Importantly, the four morphological classes show different redshift and stellar mass distributions. At $2.15 < z < 3.5$ class 3 objects (with highly irregular morphologies also in rest-frame optical light) and class 4 objects (with small-sized, “blob”-like morphologies) are overwhelmingly dominant at both intermediate and high mass scales, while class 2 spheroids are largely restricted to above $10^{11} M_\odot$. At $1.5 < z < 2.15$ class 3 and class 4 objects are now largely restricted to intermediate masses, while the class 2 spheroid population now dominates at high masses. At $1.5 < z < 2.15$ the class 1 systems emerge and contribute $\sim 25\%$ of the morphological mix at both mass scales. At and around the epoch of peak cosmic star formation rate in the universe, therefore, the statistical census of the brightest galaxies indicates that the most massive of them are assembled in regular, Hubble-type elliptical and disk (plus bulge) rest-frame optical morphologies, while less massive systems often reveal, in their rest-frame optical images, clear signs of dynamical youth.

Perhaps the most striking morphological difference between these two redshift intervals is the transition across the $z \sim 2$ epoch for galaxies at the highest stellar masses, $>10^{11} M_\odot$, from a diversity of structural types to a dominant population of spheroids. Although SED-fit-based SSFRs suffer from large uncertainties, and our samples of galaxies with masses above $10^{11} M_\odot$ at these redshifts are only small (16 at $2.25 < z < 3.5$ and 15 at $1.5 < z < 2.25$), we note that the assembly of the massive spheroids appears to be accompanied by a rapid “quenching” of star formation. Adopting a redshift-dependent division between star-forming and passively evolving systems based on the SSFR necessary for a galaxy to double its stellar mass between its observed redshift and the present day, and employing our SED-fit SSFRs computed with ZEBRA+ (see Section 4.2), we find that the fraction of star-forming galaxies at $>10^{11} M_\odot$ falls from $63\pm10\%$ at $2.25 < z < 3.5$ to $5\pm13\%$ at $1.5 < z < 2.25$. Using our own color-based criteria for identification of a “passively evolving” SED, i.e., passive YHVz, the fraction of quenched galaxies above $10^{10} M_\odot$ increases from $6\pm12\%$ at $2.25 < z < 3.5$ to $60\pm11\%$ at $1.5 < z < 2.25$. This is consistent with the observed decline in the star-forming fraction estimated by Feulner et al. (2005) for a selection of galaxies in the FORS-Deep and GOODS-South fields. If confirmed by larger samples, these results would indicate that $z \sim 2$ is the epoch when both morphological transformations first produce a significant population of massive spheroids and physical processes quench their star formation activity and move them to the red sequence, as expected in recent models (Peng et al. 2010).

8. SUMMARY

The wealth of WFC3 imaging of the high-redshift universe achieved or planned, coupled with archival ACS optical imaging, is self-sufficient, without additional ground-based photometry, to robustly identify galaxies in the $1.5 < z < 3.5$ redshift window. In this paper we have presented, with this aim, new,
robust, and efficient color-selection criteria established primarily on the $Y_{105/98} - H_{160}$ versus $V_{606} - z_{850}$ color–color diagram (and similar ones, slightly less efficient but still valuable, which use combinations of the HST $J_{125}$, $H_{160}$, $V_{606}$, and $I_{814}$ filters, or simply the $V_{606}$, $I_{814}$, and $H_{160}$ filters). We have also shown that an additional color selection on the $Y_{105/98} - H_{160}$ versus $V_{606} - z_{850}$ color–color diagram further enables the disentanglement of passively evolving, “quenched” galaxies from actively star-forming galaxies at these redshifts.

As a first use of the new galaxy catalog that we have produced, starting from the $H_{160}$ WFC3 images, we have performed a qualitative comparison of $1.5 < z < 3.5$ galaxy morphologies between rest-frame UV and rest-frame optical light. Regular disk galaxies—with or without a bulge—are present at these epochs—the disk components being unseen or irregular in rest-frame UV images and being clearly revealed in the rest-frame optical images. Together with the population of smooth spheroids, these regular disk galaxies have substantial stellar masses, $>10^{10} M_\odot$ (or, for the spheroids, even above this threshold). At masses $>10^{11} M_\odot$, the WFC3 NIR images reveal a transition of morphologies from a variety of structures at $z \gtrsim 2$ to a marked dominance of elliptical-like stellar distributions at $z \lesssim 2$. Across the $z \sim 2$ boundary the fraction of star-forming galaxies at $>10^{11} M_\odot$ decreases from $\sim 60\%$ to $\sim 5\%$. Consistent with analysis of the $z \lesssim 1$ population (Peng et al. 2010), and observed here in rest-frame optical morphologies and colors, $z \sim 2$ appears therefore to be the epoch at which assembly and quenching of the massive spheroid population begins in earnest. The WFC3 NIR images also reveal, however, that less massive galaxies at the same epochs often keep a highly irregular morphology, also in the rest-frame optical light, as they had in the rest-frame UV light. This indicates that their previously reported irregular morphologies in rest-frame UV are not driven by detection of star-forming populations on top of settled, underlying older stellar populations, but rather an indication of a genuine juvenile dynamical state for much of the $10^{10} < M < 10^{11} M_\odot$ galaxy population at these redshifts.

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APPENDIX

In this brief appendix we confirm through statistical image degradation that the limited depth of the ERS imaging with WFC3/IR is indeed sufficient to allow for confident morphological classification of $z \sim 2$ galaxies in the rest-frame optical, at least to the relatively crude level of detail employed in the analysis of Section 7. Adopting the ultra-deep HUDF09 $H_{160}$ images of our $1.5 < z < 3.5$ master sample as the benchmark for morphological classification at these redshifts we thus aim to demonstrate a consistency of visual appearance following artificial degradation to the noise level of the ERS. In particular, the net exposure time of the master UDF $H_{160}$ image is a factor of $\sim 14$ times greater than that of the ERS $H_{160}$ image; indeed such an extraordinary depth at these wavelengths was crucial to the principal aim of the HUDF09 program—namely, the search for $z \sim 8–10$ candidates appearing as $Y_{105}/J_{125}$ dropouts (Bouwens et al. 2010a, 2011). Consequently, the contributions of both background sky noise and shot noise in the ERS are $\sim \sqrt{4}$ times higher than in the UDF/HUDF09. The final image noise in our master frames is, moreover, weakly correlated between adjacent pixels as a result of the reduction process. Hence, rather than simply adding an independent noise component to each pixel to simulate the degradation in sky noise we attempt to at least partially approximate the impact of pixel-to-pixel correlation by degrading our UDF images instead through the stacking of blank regions of real background sky. For the addition of shot noise, however, we simply suppose that all flux detected above the $3\sigma$ sky noise level in the original UDF images corresponds to real object flux, and we directly resample this flux (with Poisson uncertainty) in the R statistical package at the ERS rate.

In Figure 13, we compare the original ($H_{160}$) HUDF09 postage stamp images of three archetypal class 1 (disk, or bulge/disk) systems from Figure 8, and three archetypal class 3 (irregular) systems from Figure 10, against our new versions of

![Figure 13](image-url)
of these images degraded to the noise level of the ERS. It is clear from inspection of this figure that the impact of the additional noise is to reduce the relative prominence of certain faint and/or fine-structure features in these $z \sim 2$ galaxies, but that the broad morphological properties of each system (e.g., the presence/absence of multiple nuclei, a central bulge, an outer disk, or a warped disk) remain readily discernible, and thus each galaxy remains clearly recognizable as a member of its assigned class. Of course, studies attempting to achieve finer morphological classifications than those conducted here, or else attempting to perform quantitative “clump science” (e.g., Förster-Schreiber et al. 2011), may well prove more sensitive to the imaging depth than our relatively crude analysis of Section 7. Further, one should not attempt to infer from the results of this Appendix that certain quantitative morphological analysis procedures (e.g., bulge-disk decomposition) will also prove insensitive to the difference in the HUDF09 and ERS imaging depths—such a statement clearly requires a more detailed investigation tailored to each morphological analysis tool under study.

As a further robustness test of the morphological evolution described in Section 7 we have investigated the possibility that the decreasing fraction of massive spheroids with increasing redshift (past $z \sim 2$) is an artifact of the impact of cosmological surface brightness dimming (and bandpass shifting) on our observations. In particular, we have verified that our visual classifications of all massive elliptical galaxies in our $1.5 < z < 2.15$ sub-sample remain consistent after artificial redshifting of their $H_{160}$ images to $z = 3$. The results of this redshifting for six archetypal $z \sim 1.5$ ellipticals from our sample are displayed in Figure 14. The extremely centrally concentrated light profiles of these systems ensure that even under substantial cosmological surface brightness dimming they remain morphologically recognizable and quite distinct from the remaining three classes. Note that in the cases of ERS2182 and ERS1238 we artificially redshift also their nearby companions, which our photometric (and/or spectroscopic) redshifts indicate to be at very nearly identical epochs.

(A color version of this figure is available in the online journal.)

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