REST-FRAME UV VERSUS OPTICAL MORPHOLOGIES OF GALAXIES USING SÉRSIC PROFILE FITTING: THE IMPORTANCE OF MORPHOLOGICAL K-CORRECTION

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ABSTRACT

We show a comparison of the rest-frame UV morphologies of a sample of 162 intermediate-redshift ($z_{\text{median}} = 1.02$) galaxies with their rest-frame optical morphologies. We select our sample from the deepest near-UV image obtained with the Hubble Space Telescope (HST) using the Wide Field Planetary Camera 2 (WFPC2; F300W) as part of the parallel observations of the Hubble Ultra Deep Field campaign overlapping with the HST/ACS Great Observatories Origins Deep Survey data set. We perform single-component Sérsic fits in both WFPC2/F300W (rest-frame UV) and ACS/F850LP (rest-frame optical) bands and deduce that the Sérsic index $n$ is estimated to be smaller in the rest-frame UV compared to the rest-frame optical, leading to an overestimation of the number of merger candidates by $\sim40\%–100\%$ compared to the rest-frame optical depending upon the cutoff in $n$ employed for identifying merger candidates. This effect seems to be dominated by galaxies with low values of $n(F300W) \leq 0.5$ that have a value of $n(F850LP) \sim 1.0$. We argue that these objects are probably clumpy star-forming galaxies or minor mergers, both of which are essentially contaminants, if one is interested in identifying major mergers. In addition, we also find evidence that the axis ratio $b/a$ is lower, i.e., ellipticity $(1 - b/a)$ is higher in rest-frame UV compared to the rest-frame optical. Moreover, we find that in the rest-frame UV, the number of high ellipticity ($e \geq 0.8$) objects are higher by a factor of $\sim2.8$ compared to the rest-frame optical. This indicates that the reported dominance of elongated morphologies among high-$z$ Lyman Break Galaxies might just be a bias related to the use of rest-frame UV data sets in high-$z$ studies.

Key words: galaxies: evolution – galaxies: formation – galaxies: statistics

Online-only material: color figure

1. INTRODUCTION

Most of our knowledge about the properties of high-redshift galaxies has been acquired by studying Lyman Break Galaxies (LBGs) at redshift $\sim2.0–5.0$ (e.g., Giavalisco 2002; Steidel et al. 2003; Ravindranath et al. 2006; Wadadekar et al. 2006a). Since most of these studies are in the optical, they probe the rest-frame UV light of LBGs at these redshifts. Deriving morphological information about a galaxy from its rest-frame UV light can be misleading as the UV light is mainly dominated by patchy star-forming regions that are not representative of the underlying galaxy mass distribution (e.g., Teplitz et al. 2006). Even so, people have used a variety of techniques to derive the morphologies of such high-$z$ objects, including the nonparametric CAS (Conselice 2003) and Gini/M20 coefficients (Lotz et al. 2004) and the parametric light profile fitting such as Galfit (Peng et al. 2002). While each of these methods have their pros and cons, all of them have been used in the past (and continue to be used) by the community for studying quantitative morphologies of high redshift galaxies. In light of this fact, it becomes imperative to be aware of the biases that are expected, as one probes progressively bluer rest-frame wavelengths at higher redshifts using each of these techniques.

Papovich et al. (2005) and Conselice et al. (2005) have carefully examined the extent of this morphological K-correction using Wide Field Planetary Camera 2 (WFPC2) and Near-Infrared Camera and Multi-Object Spectrometer (NICMOS) observations of the Hubble Deep Field North (HDF-N). More recently, Conselice et al. (2008) have examined the effects of morphological K-correction on the estimation of nonparametric CAS (Conselice 2003) and Gini/M20 coefficients (Lotz et al. 2004), using ACS and NICMOS imaging of the Hubble Ultra Deep Field. They find that CAS and Gini/M20 parameters give similar results, except that the latter tends to find larger number of mergers than the former. Despite the fact that Galfit has been used extensively for quantifying galaxy morphologies at high redshifts (e.g., Ravindranath et al. 2006), there has been no systematic study evaluating the effects of morphological K-correction on the structural parameters derived using Galfit. It is this problem that we are trying to address in the current paper. In this work, we quantify the biases that are encountered in estimating the morphological parameters of galaxies in the rest-frame UV as compared to rest-frame optical light using Galfit, a structural decomposition code that fits two-dimensional parameterized, axisymmetric, functions directly to galaxy images.

2. THE DATA AND SAMPLE SELECTION

We have utilized the HST/WFPC2 F300W band observations (orients 310 and 314) obtained in parallel with the HST/ACS HUDF that fall within the GOODS-S area and constitute the deepest image of the near UV sky ever obtained with the HST (total exposure $\sim323.1$ ks). The data set consists of a total of 409 WFPC2 F300W parallel images, with exposure times ranging from 700 s to 900 s each. A cosmic-ray-rejected, drizzled image with a pixel scale of 0.06 arcsec pixel$^{-1}$ was
constructed by combining the 409 individual exposures (de Mello et al. 2006; Wadadekar et al. 2006a), using a drizzle-based technique developed for data processing by the WFPC2 Archival Parallels Project (Wadadekar et al. 2006b). This drizzled image, which was accurately registered with respect to the Great Observatories Origins Deep Survey (GOODS) images, was then used for performing the morphological analysis presented in this paper.

For the optical imaging, we have used the publicly available version v1.0 of the reduced, calibrated images of the Chandra paper. The overlap between the Deep Field South (CDFS) acquired with version v1.0 of the reduced, calibrated images of the Chandra paper.

Mello et al.2006; Wadadekar et al.2006a), using a drizzle-based constructed by combining the 409 individual exposures (de Mello et al. 2006; Wadadekar et al. 2006a), using a drizzle-based technique developed for data processing by the WFPC2 Archival Parallels Project (Wadadekar et al. 2006b). This drizzled image, which was accurately registered with respect to the Great Observatories Origins Deep Survey (GOODS) images, was then used for performing the morphological analysis presented in this paper.

3. THE METHODOLOGY

Our aim is to quantify any biases in the derived Galfit parameters, on account of using rest-frame UV light of program objects, as opposed to their rest-frame optical light. In order to do this, we performed single-component Sérsic fits to our sample of 162 objects in both UV as well as optical. The goal is to look for systematic differences in the derived galaxy parameters as a function of their rest-frame wavelength.

3.1. The F300W Band Fits

We used the software Galfit to carry out two-dimensional modeling for our sample of galaxies. We performed single-component Sérsic fits, where the intensity profile of the galaxy is modeled with the Sérsic law (Sérsic 1968),

$$\Sigma(r) = \Sigma_e \exp \left[ -2.303 b_n \left( \frac{r}{r_e} \right)^{1/n} - 1 \right]$$

with $r_e$ being the half-light radius, $\Sigma_e$ the surface brightness at $r_e$, and $n$ being the Sérsic index and $b_n$ is related to $n$ such that $P(2n, 2.303b_n) = 0.5$, where $P(a,b)$ is the incomplete gamma function.

The model galaxy is constructed as a combination of a Sérsic component and the sky background value. Other free parameters in the model are the ellipticity of the Sérsic component and its position angle. The SExtractor-based photometric catalog of our sources provided us with valuable starting values for most of the above-mentioned parameters. This analytic model of the galaxy light distribution is then convolved with the point-spread function (PSF) of the observation and compared with the observed galaxy image. The values of the free parameters are determined iteratively by minimizing the reduced $\chi^2$. In Figure 2, we show an example fit for one of the targets in the F300W band.

In the above scheme, an accurate estimation of the PSF is crucial to the robust determination of the structural parameters of a galaxy. However, there are only four identifiable stars in the F300W image which can be used to characterize the PSF. One of these was saturated and another was too close to the edge of the frame. We used the other two stars (say X and Y) in turn, to establish that the values of the derived parameters are not severely dependent on the choice of the PSF star.

Here, we use the methodology of Rawat et al. (2007) to show that the derived parameters are invariant under the change of the PSF star. For our sample of 162 objects in the F300W band, we used Galfit in batch mode to derive the structural parameters twice for each object. In the first run, we used one of the stars (X) as the PSF. In the second run, we used the second star (Y) as the PSF, everything else remaining the same as in the first run. In Figure 3, we show the difference between the structural parameters ($n$ and $b/a$) obtained in the two cases as a function of the F300W band magnitude of the objects. As is evident, our estimation of the structural parameters is quite robust irrespective of which star is used as the PSF. The derived structural parameters in the two runs agree quite well for most of the objects, with a symmetrical scatter around the zero line, pointing toward random errors as the cause for any dispersion in the structural parameters obtained in the two runs rather than any systematic effect. For fainter objects, the random photon noise is higher and may overwhelm any systematic effect caused by the use of two different PSF stars. Also, the Sérsic index $n$, which is well known to be difficult to constrain, exhibits a greater amount of scatter than the axis ratio $b/a$. The dashed lines in the two panels encompass $\sim 80\%$ of all the objects.

3.2. The F850LP Band Fits

Single-component Sérsic fits were performed on the HST/ACS F850LP image of the 162 objects. The fits were performed in a manner consistent with the F300W-band fitting procedure. Since in the $z$-band we have a large number of identifiable stars which can be used for characterizing the PSF, we have used the star closest to a given galaxy as the model.
NO. 2, 2009

REST-FRAME UV VERSUS OPTICAL MORPHOLOGIES OF GALAXIES 1317

Figure 2. Example of the single-component Sérsic fit in the F300W band. From left to right are shown the F300W band image, the Galfit Sérsic best-fit model, and the residual after subtracting the model from the image. The IAU name of the object is indicated at top left, the photometric redshift of the object is given at top right, the fitted Sérsic index $n$ is given at bottom left, and the magnitude of the object is given at bottom right of the object frame. Each image is 6 arcsec $\times$ 6 arcsec.

Figure 3. Difference between the structural parameters $n$ and $b/a$ obtained in two separate Galfit runs, using two different stars as the PSF in the F300W band as a function of the F300W magnitude of the objects. As expected, the difference `flares' out at fainter magnitudes. The dashed lines in the two plots encompass $\sim$80% of all the objects.

A PSF. This choice is not critical; as demonstrated by Rawat et al. (2007) the derived Galfit parameters are stable to within 10% irrespective of which star is used as the PSF. One of the fits that we obtained in the F850LP band is shown in Figure 4 for an object at photo-$z = 0.98$.

4. COMPARISON BETWEEN F300W AND F850LP FITS

Figure 5 shows some examples of the morphological differences in the appearance of a galaxy observed in the UV in comparison to its appearance in the optical. In each case, the left panel is a F300W $HST$/WFPC2 image while the right panel is an F850LP $HST$/ACS image. The first object is a red, edge-on disk galaxy. The second and third objects are classified as mergers ($n \lesssim 0.8$) in the UV (see below) but not in the optical. The last object is classified as merger in the UV, but shows clear spiral structure in the optical.

Before we compare the derived quantitative parameters for our 162 objects in the F300W and F850LP bands, it is important to check for possible biases due to the varying signal-to-noiseratio (S/N) in the two filter data sets. The F300W band observation suffers from the poor UV sensitivity of the WFPC2 detector ($\sim$1.9% for WFPC2/F300W filter), while the F850LP band observations gain from the exquisite red sensitivity of the ACS/WFC detector ($\sim$25% for ACS/WFC F850LP filter; see Footnote 6). This vast difference in the UV versus optical sensitivities is compensated to a large extent by the exceptionally deep exposure in the WFPC2/F300W ($\sim$323 ks), compared to $\sim$10 ks in the ACS/F850LP. In order to quantify the expected S/N of a typical object in the UV versus optical, we made use of the exposure time calculators for the two detectors. The median surface brightness for our 162 sample objects in the F300W band is 24.03 mag arcsec$^{-2}$ compared to 22.95 mag arcsec$^{-2}$ in the F850LP band. We used the known exposure times in each of the two filters to estimate the expected S/N for the above median surface brightness objects using the $HST$/ACS and WFPC2 exposure time calculators, yielding an average S/N of $\sim$21 pixel$^{-1}$ in the F300W band and $\sim$73 pixel$^{-1}$ in the F850LP band.

Ravindranath et al. (2006) have performed extensive Monte Carlo simulations to estimate the reliability of the morphological parameters derived from the two-dimensional galaxy fitting algorithm Galfit, as a function of the S/N of the galaxy images. Their simulations suggest that the morphological parameters can be well recovered for objects with S/N $\geq 10-15$. Since we have used the methodology similar to that of Ravindranath et al. (2006) for deriving morphological parameters and the same code (Galfit) for our sample galaxies, we believe that even though the S/N in the F300W band images for our sample objects is significantly lower compared to the F850LP band, it is still sufficient (S/N $\geq 10-15$) to allow an accurate estimation of their structural parameters. Therefore, we do not expect any bias in the derived structural parameters in the F300W band compared to the F850LP band due to the difference in their S/N.

Figure 6 (left) shows the distribution of the derived Sérsic index $n$ for the 162 sources in the F300W band (45$^\circ$ hashing) as well as the F850LP band (135$^\circ$ hashing). As is apparent, the two distributions are quite different, with the distribution in F300W band peaking at much smaller values of $n$, compared to the F850LP band. A two-sample Kolmogorov–Smirnov (K–S) test confirms that there is $>99\%$ probability of the two samples being drawn from a different parent population. Figure 6 (right) shows a scatter plot of Sérsic index $n(F300W)$ versus $n(F850LP)$. Note the clumping at the bottom left, showing objects with $n(F300W) < 0.5$ and $n(F850LP) \sim 1.0$, corresponding to the peaks in the Sérsic index distribution at $n \leq 0.5$ in the F300W band and $n \sim 1.0$ in the F850LP band. The average error bars have been derived using the differences in the computed Sérsic index $n$ using two different PSFs in the F300W band as shown in Figure 3.

\footnote{Efficiency near filter pivot wavelength, including $HST$/instrument+filter as quoted from Table 1 of Comparison of WFPC2 and ACS Filters of WFPC2 Instrument Handbook v9.0.}

\footnote{WFPC2 ETC for Extended Sources—version 4.0 http://www.stsci.edu/hst/wfpc2/software/wfpc2-etc-extended-source-v40.html.}

\footnote{ACS Imaging ETC http://etc.stsci.edu/webetc/acsImagingETC.jsp.}
Figure 4. Example of the single-component Sérsic fit in the F850LP band. From left to right are shown the F850LP band image, the Galfit Sérsic best-fit model, and the residual after subtracting the model from the image. Labels are the same as in Figure 2. Each image is 6 arcsec × 6 arcsec.

Figure 5. Some examples of the difference in the appearance of a galaxy observed in the UV (left) in comparison with its appearance in the optical (right). The left cutout is a F300W filter HST/WFPC2 image from the Hubble-UDF parallels, while the right cutout is the F850LP HST/ACS image of the same object from the GOODS survey. Labels are the same as in Figure 2. Each image is 6 arcsec × 6 arcsec.

We note that in the F300W band, the Sérsic index $n$ is lower in a large number of cases compared with the F850LP band. This effect is mainly caused by galaxies with low values of $n(F300W) \leqslant 0.5$ that have a corresponding $n(F850LP) \sim 1.0$, while this effect does not seem to be important in galaxies with high values of $n$, as can be clearly seen in Figure 6 (right). This has serious consequences, as $n$ is widely used in the literature for identifying the morphological class of a galaxy. Especially, $n$ flatter than exponential is usually used for isolating galaxies with multiple cores or disturbed morphologies, possibly indicative of mergers (e.g., Ravindranath et al. 2006). However, it is imperative to note here that it is impossible to isolate a clean sample of merger candidates using this criterion, as the objects that exhibit $n$ shallower than the exponential profile include galaxies with patchy star-forming H II regions and low surface brightness galaxies, etc., in addition to true merging galaxies (see, e.g., the discussion in Ravindranath et al. 2006). Keeping the above-mentioned caveat in mind, we find from Figure 6 (left) that $n_{\text{F300W}} \leqslant 0.5$ for 57 objects, whereas $n_{\text{F850LP}} \leqslant 0.5$ for only 28 cases. This means that the use of the F300W band, which probes the rest-frame UV light of the objects at these redshifts, increases the number of merger candidates by a factor of $\sim 2$ compared with the F850LP band (rest-frame optical). This factor is less severe (but no less significant) $\sim 1.4$, if we employ an $n \leqslant 0.8$ as the cutoff for identifying merger candidates.

We checked whether the objects with $n \leqslant 0.5$ in either of the two filters are systematically fainter than the whole sample, i.e., whether poorer S/N might be responsible for these objects having anomalously low $n$. We found that in the F300W band, the median surface brightness for the subset of 57 objects with $n_{\text{F300W}} \leqslant 0.5$ is 24.08 mag arcsec$^{-2}$ (compared to 24.03 mag arcsec$^{-2}$ for the whole sample). This yields an S/N of $\sim 20$ pixel$^{-1}$ (compared to $\sim 21$ for the whole sample). Similarly, in the F850LP band, the median surface brightness for the subset of 28 objects with $n_{\text{F850LP}} \leqslant 0.5$ is 23.05 mag arcsec$^{-2}$ (compared to 22.95 mag arcsec$^{-2}$ for the whole sample). This yields an S/N of $\sim 67$ pixel$^{-1}$ (compared to $\sim 73$ pixel$^{-1}$ for the whole sample). Hence we see that the S/N
Figure 6. Left: comparison between the Sérsic index $n$ derived using Galfit, single-component Sérsic fits in the WFPC2/F300W-band (45° hashing), and the ACS/F850LP band (135° hashing) for our 162 galaxies. A two-sample K–S test shows that there is > 99% probability of the two samples being drawn from a different parent population. Right: a scatter plot of the Sérsic index $n$(F300W) vs. $n$(F850LP). Note the clumping at the bottom left (enclosed by the black rectangle), showing objects with $n$(F300W) $\leq$ 0.5 and $n$(F850LP) $\sim$ 1.0, corresponding to the peaks at $n$ = 0.5 in the F300W band and $n$ $\sim$ 1.0 in the F850LP seen in the Sérsic index distribution (left). The morphology of these objects is discussed in Section 5. The average error bars are derived using the differences in the computed Sérsic index $n$ using two different PSFs in the F300W band as shown in Figure 3.

Figure 7. Left: a comparison between the axis-ratio $(b/a)$ derived using Galfit, single-component Sérsic fits in the WFPC2/F300W-band (45° hashing), and the ACS/F850LP band (135° hashing) for our 162 galaxies. The mean values of the axis ratio are $(b/a)_{F300W} = 0.42 \pm 0.23$ and $(b/a)_{F850LP} = 0.49 \pm 0.22$. A two-sample K–S test shows that there is >99% probability of the two samples being drawn from a different parent population. Right: a scatter plot of the axis ratio $b/a$(F300W) vs. $b/a$(F850LP). Note the paucity of sources with $b/a$(F850LP) $\leq$ 0.2. The average error bars are derived using the differences in the computed axis ratio $b/a$ using two different PSFs in the F300W band as shown in Figure 3.

for the subset of objects with extremely low values of $n$ in both the filters is very similar to that for the entire sample indicating that the parameters derived for these objects are likely to be just as robust as for the entire sample.

The fact that the differences in the derived value of $n$ in the two filters are dominated by galaxies with low values of $n$(F300W) $\leq$ 0.5 that have a value of $n$(F850LP) $\sim$ 1.0 leads us to believe that we might be probing clumpy star-forming H II regions in these objects in the F300W band. The tacit assumption that we are making here is that clumpy star formation in galaxies will lead to a lower $n$ value in the rest-frame UV but not in the rest-frame optical (because the star-forming H II regions are blue). This would mean that objects with $n$(F300W) $\leq$ 0.5 and $n$(F850LP) $\sim$ 1.0 are probably clumpy star-forming galaxies which are intrinsically disky ($n$ $\sim$ 1.0). While it is true that blue neighbors will tend to mimic H II regions in the rest-frame UV by producing a shallow Sérsic profile, however, the very fact that they contribute little or no flux in the optical (parameterized by a steeper $n$(F850LP) $\sim$ 1.0) means that they cannot be massive systems (as $z$-band flux is a better tracer of stellar mass than UV flux) and will constitute minor mergers at best (see Rawat et al. 2008 for further discussion on how flux in redder wavebands is better suited for identifying massive major merger candidates). So objects with $n$(F300W) $\leq$ 0.5 and $n$(F850LP) $\sim$ 1.0
are likely to be either clumpy star-forming galaxies or minor mergers, both of which are essentially contaminants, if one is interested in identifying major mergers. In Section 5, we include comments on the morphology of individual objects with $n(F300W) \leq 0.5$ and $0.7 \leq n(F850LP) \leq 1.3$ (the working definition of $n(F850LP) \sim 1.0$) in detail to show that our assertion above is indeed correct.

Similarly, Figure 7 (left) shows the distribution of the axis ratio $(b/a)$ in the $F300W$ band (45° hashing) as well as in the $F850LP$ band (135° hashing). From the figure, we find that $(b/a)_{F300W} \leq 0.2$ for 34 objects, while $(b/a)_{F850LP} \leq 0.2$ for only 12 objects. This means that in the rest-frame UV, the number of high ellipticity ($e \geq 0.8$) objects is higher by a factor of $\sim 2.8$ compared to the rest-frame optical. This might explain the reported claim in the literature that high-$z$ LBGs tend to show a significant skew toward higher ellipticities (e.g., Ravindranath et al. 2006). Also, the mean values of the axis ratio are $(b/a)_{F300W} = 0.42 \pm 0.23$ and $(b/a)_{F850LP} = 0.49 \pm 0.22$. Again, a two-sample K–S test shows that there is > 99% probability of the two samples being drawn from a different parent population. Figure 7 (right) shows a scatter plot of the axis ratio $(b/a)_{F300W}$ versus $(b/a)_{F850LP}$. Here, we see that in the $F300W$ band, the axis ratio $(b/a)$ is lower (i.e., ellipticity $e = (1 - b/a)$ is higher) in a large number of cases compared to the $F850LP$ band. The average error bars are derived using the differences in the computed axis ratio $b/a$ using two different PSFs in the $F300W$ band as shown in Figure 3.

Another way to visualize the difference in the derived quantities $n$ and $b/a$ in UV versus optical is presented in Figure 8. Figure 8 (left) shows a histogram of the difference between the derived values of Sérsic index $n(F300W)$ and $n(F850LP)$ for our sample objects. The smooth curve is the normal distribution, centered on the origin and having the same variance as the distribution of the sample galaxies. The peak close to zero corresponds to objects having same value of $n$ in both the filters. However, the dispersion about the peak is not symmetrical. Note the sharp departure from pure Gaussianity around $-1.0 \leq n(F300W) - n(F850LP) \leq 0.0$. These objects correspond to the clump of objects around $n(F300W) \leq 0.5$ and $n(F850LP) \sim 1.0$ shown in Figure 6(b). Right: a histogram of the difference between $b/a(F300W)$ and $b/a(F850LP)$ for the same sample. Again, the smooth curve is the normal distribution, centered on the origin and having the same variance as the distribution of the sample galaxies. Both the distributions are found to have negative skew (left skewed), with the distribution having more area under the left tail than expected from a normal distribution.

Similarly, Figure 8 (right) shows a histogram of the difference between $b/a(F300W)$ and $b/a(F850LP)$. Again, the smooth curve is the normal distribution, centered on the origin and having the same variance as the distribution of the sample galaxies. The peak close to zero corresponds to objects having same value of $n$ in both the filters. However, the dispersion about the peak is not symmetrical. Note the sharp departure from pure Gaussianity around $-1.0 \leq n(F300W) - n(F850LP) \leq 0.0$. These objects correspond to the clump of objects around $n(F300W) \leq 0.5$ and $n(F850LP) \sim 1.0$ as shown in Figure 6 (right). We quantified this by calculating a measure of skewness9 (Fisher Gamma 1) for this distribution, defined as $\gamma_1 = m_3/m_2^{3/2}$, where $m_2$ and $m_3$ are the second and third moments of the distribution, respectively. We find the value of the skew to be $\gamma_1 = -0.10$. This negative value of skew $\gamma_1$ indicates that the distribution has more area under the left tail than expected from a normal distribution. This implies that $n(F300W) - n(F850LP) < 0.0$ for a larger number of cases than expected by pure chance (normal distribution), i.e., the Sérsic index $n$ is lower in the UV compared to the optical in a large number of cases. This difference is mainly dominated by galaxies with low values of $n(F300W) < 0.5$ that have a value of $n(F850LP) \sim 1.0$, and is not affected by galaxies with high values of $n$.

Similarly, Figure 8 (right) shows a histogram of the difference between $b/a(F300W)$ and $b/a(F850LP)$. Again, the smooth curve is the normal distribution, centered on the origin and having the same variance as the distribution of the sample galaxies. The value of skew in this case is found to be $\gamma_1 = -0.30$ (left skewed). Again, a negative value of $\gamma_1$ implies that the distribution has more area under the left tail than expected from a normal distribution and that the axis ratio $b/a$ is lower in the UV compared to the optical in a larger number of cases than expected by random chance (normal distribution).

Since we are using objects which have a wide range of photometric redshifts, we are probing different rest-frame wavelengths for different objects with the same filter. For example, the $F300W$ band will probe rest-frame 2000 Å (NUV) for a redshift 0.5 object, whereas the same filter will probe rest frame 1200 Å (FUV) for a redshift 1.5 object. We checked whether this could be affecting our interpretation of Figures 6 and 7 by

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9 We would like to inform the reader that while we had to bin the data for the purpose of plotting in Figure 8, the calculation of the skew was done from first principles and no binning was used.
restricting our sample to only objects with \(0.5 \leq z_{\text{photo}} \leq 1.0\). This yields a sample of 58 objects. Using a calculation similar to the one explained above, we find that \(n_{F300W} \leq 0.5\) for 22 objects, whereas \(n_{F850LP} \leq 0.5\) for only nine objects. This yields a factor of \(\sim 2.4\) overestimation of the number of merger candidates in the rest-frame UV (\(1500–2000\) Å) compared to the rest-frame optical (\(4250–5700\) Å). This compares favorably with the factor \(\sim 2\) we had determined using the entire sample of 162 objects. This factor is found to be \(\sim 1.9\), if we employ an \(n \leq 0.8\) as the cutoff for identifying merger candidates, again comparable to the factor we obtained using the entire sample. It is encouraging to see that our results are robust and change little
irrespective of the fact as to whether or not we apply the redshift cutoff. Part of the reason is that the redshift distribution of our sample objects anyway peaks between 0.5 and 1.0 (Figure 1) with a median of 1.02, so that in most cases we are probing rest-frame 1500–2000 Å. Note the fact that our result is stronger (albeit with a smaller sample size) if we use only objects with $0.5 \leq z_{\text{photo}} \leq 1.0$. This means that the use of objects without regard to their redshift dilutes the result (as expected) and must therefore be treated as a lower limit.

5. COMMENTS ON INDIVIDUAL SOURCES

We shortlist objects with $n(F300W) \leq 0.5$ and $0.7 \leq n(F850LP) \leq 1.3$ to check our assertion that these objects are actually patchy star-forming disk dominated galaxies, rather than major merger candidates. There are 17 objects satisfying the above-mentioned criteria. Figure 9 shows the $u-z$ color map stamps (right) of these objects, along with F300W (left) and F850LP (center) imaging gray-level stamps. The
color bar in each color map stamp shows the $u-z$ color range from 0 to 4. A description of each object is presented below.

**J033233.90–274237.9.** This is a smooth face-on disk galaxy as evidenced visually from the F850LP band image with an $n(F850LP) = 1.03$ and a red nucleus seen clearly in the optical image as well as in the $u-z$ color map. There is a blue H\text{\textsc{ii}} region seen in the F300W band image westward from the nucleus. It is this patchy star formation which is responsible for a significantly lower $n(F300W) = 0.30$. The F850LP band image confirms that there is no sign of any merger activity.

**J033244.13–274234.1.** This seems like an edge-on disk galaxy with $n(F850LP) = 0.97$. The light distribution in the F300W band is more diffuse, leading to a lower value of $n(F300W) = 0.38$.

**J033235.98–274217.7.** This is a marginal case, with $n(F300W) = 0.47$ only slightly smaller than $n(F850LP)$. The light distribution is slightly more diffuse in the F300W band compared to the F850LP band. This shows up as blue structure at the northeast edge of the galaxy as seen in the color map. This might be contributing to the marginally lower value of $n(F300W)$ compared to the optical.
**J033237.68–274219.3.** This is a rather diffuse disk galaxy, with a distinct nucleus seen in the F850LP band and $n(F850LP) = 0.90$. The F300W band light distribution is rather patchy with no clear center evident. This is responsible for the low value of $n(F300W) = 0.18$.

**J033236.34–274202.6.** This is a patchy star-forming galaxy with several blue H II regions seen clearly in the F300W band image as well as in the color map (particularly one due northwest of the center). The smooth underlying stellar population is revealed in the F850LP band image with $n(F850LP) = 1.29$. The patchy star formation is responsible for the very low value of $n(F300W)$.

**J033242.23–274130.4.** This is a linear chain-type galaxy with $n(F850LP) = 0.71$. The light distribution is more diffuse in F300W band leading to a lower value of $n(F300W)$. The galaxy as a whole is rather blue with $u - z = 0.38$.
**J033240.57–274131.2.** This is a featureless disk galaxy with \( n(F850LP) = 0.91 \). A nucleus is clearly discernible in the F850LP band, though one is not clearly identifiable in the F300W band. This diffuse distribution of light in the F300W band might be responsible for the low value of \( n(F300W) = 0.25 \). There is no sign of any merger activity.

**J033242.24–274131.1.** This is a linear chain-type galaxy. The F300W band light distribution is more diffuse compared to the F850LP band, leading to a lower value of \( n(F300W) \).

**J033239.04–274132.4.** This object shows clear evidence of patchy star formation in the F300W band as well as in the color map. Multiple H \( \Pi \) regions can be seen leading to a low value of \( n(F300W) = 0.16 \). The F850LP band light distribution is much smoother with a close to exponential light profile \( (n(F850LP) = 1.03) \).

**J033242.77–274144.6.** This is an edge-on disk galaxy with \( n(F850LP) = 0.81 \). This is a marginal case, since the \( n(F300W) \) is only slightly smaller than \( n(F850LP) \), owing probably to the slightly more diffuse light distribution in the F300W band.

**J033231.49–274158.0.** This is a rather compact galaxy with a Sérsic profile slightly steeper than an exponential \( (n(F850LP) = 1.28) \). The F300W band light distribution is more diffuse, showing up as a blue halo conspicuous to the northwest of the galaxy center. In particular, there is no evidence of any merger activity.

**J033238.34–274120.4.** This is an elongated galaxy with \( n(F850LP) = 1.05 \). The patchy light distribution in the F300W band is reminiscent of an irregular, with an ill-defined center and parameterized by a very low value of \( n(F300W) \).

**J033239.25–274059.3.** This looks like a diffuse, low surface brightness disk galaxy with \( n(F850LP) = 0.96 \). A bright H \( \Pi \) region (offset from the center) is clearly seen in the F300W band image as well as in the color map, which might be responsible for the low value of \( n(F300W) \). No sign of any merger activity in the F850LP band.

**J033241.88–274059.9.** This is a rather red \((u-z = 3.34)\), compact, and featureless galaxy. The F300W band light distribution is rather diffuse, probably leading to a low value of \( n(F300W) \). In particular, there are no signs of any merger activity.

**J033241.64–274103.4.** This is an edge-on disk galaxy with \( n(F850LP) = 1.19 \). The F300W band light distribution is more fragmented: note the relatively redder center with bluer edges due northwest and southeast of the center in the color map. Again, there are no signs of any merger activity.

**J033238.75–274027.8.** This is a compact galaxy with a steeper than exponential light profile \( n(F850LP) = 1.10 \). The F300W band light distribution is fragmented, leading to a very low value of \( n(F300W) \).

**J033241.42–274044.8.** This is a very diffuse galaxy, reminiscent of an irregular. This is a marginal case with the \( n(F300W) \) only slightly lower than the \( n(F850LP) \).

As can be seen from the individual description above and from Figure 9, most of the objects with \( n(F300W) \leq 0.5 \) and \( n(F850LP) \sim 1.0 \) are probably clumpy star-forming galaxies with an underlying disk \((n \sim 1.0)\) of older stellar population. Many objects are isolated and compact and the low value of \( n(F300W) \) can be attributed to diffuse/patchy light distribution in the F300W band rather than any merger activity. As mentioned earlier, while it is true that blue neighbors will tend to mimic H \( \Pi \) regions in the rest-frame UV by producing a shallow Sérsic profile, however, the very fact that they contribute little or no flux in the optical (parameterized by a steeper \( n(F850LP) \sim 1.0 \)) means that they cannot be massive systems (as \( z \)-band flux is a better tracer of stellar mass than UV flux) and will constitute minor mergers at best. This analysis should go a long way in convincing the reader that using Sérsic profile fitting in the rest-frame UV is fraught with severe biases and should be used with caution.

6. **SUMMARY AND CONCLUSION**

We have compared the rest-frame UV versus rest-frame optical morphologies of intermediate-redshift (\( z_{\text{median}} = 1.02 \)) UV bright galaxies, selected using the deep \( HST/WFPC2 \) U-band HUDF parallels image in combination with the \( HST/ACS F850LP GOODS \) data set. The UV bright galaxies in this case are at lower redshifts and have lower luminosities than high-\( z \) LBGs (de Mello et al. 2006). We performed the single-component Sérsic fits in both WFPC2/F300W and ACS/F850LP bands for the 162 objects and found the following.

1. In the rest-frame UV, the Sérsic index \( n \) is lower in a large number of cases compared to the rest-frame optical. This is possibly due to the fact that rest-frame UV light is sensitive to star-forming H \( \Pi \) regions which are fragmented and patchy in nature leading to a light distribution which is shallower than the underlying galaxy light distribution seen in the rest-frame optical. This difference is mainly caused by galaxies with low values of \( n(F300W) \leq 0.5 \) that have a value of \( n(F850LP) \sim 1.0 \), and is not affected by galaxies with high values of \( n \), as can be clearly seen in Figure 6 (right). This has serious consequences as the Sérsic index \( n \) is widely used for identifying the morphological properties of galaxies.
class of a galaxy, with $n$ flatter than exponential being used for identifying merger candidates. In particular, we find that the use of rest-frame UV overestimates the number of merger candidates by $\sim 40\%$–$100\%$ compared to the rest-frame optical, depending upon the cutoff in $n$ employed for identifying merger candidates. This shows that the so-called morphological $K$-correction is a serious consideration in constraining galaxy morphology at intermediate redshifts, as shown by Conselice et al. (2008). Using $n \lesssim 0.8$ as the criterion for identifying merger candidates, we recommend a correction factor of $\sim 1.4$ to the result of Ravindranath et al. (2006) for calculating the fraction of LBGs at $z \sim 3$ which are likely to be merger candidates.

2. We also find that in the rest-frame UV, the number of high ellipticity ($e \gtrsim 0.8$) objects is higher by a factor of $\sim 2.8$ compared to the rest-frame optical. This might explain the reported results in the literature that high-$z$ LBGs tend to show a skew toward higher ellipticities (Ravindranath et al. 2006), as most such work has been done using rest-frame UV data sets. We also note that the axis ratio $b/a$ is lower, i.e., ellipticity is higher in rest-frame UV compared to the rest-frame optical. The mean values of the axis ratio are $(b/a)_{F300W} = 0.42 \pm 0.23$ and $(b/a)_{F850LP} = 0.49 \pm 0.22$.

This indicates that the reported dominance of elongated morphologies among high-$z$ LBGs might just be a bias related to the use of rest-frame UV data sets. However, we cannot conclusively exclude the possibility that LBGs might still have intrinsically different or elongated morphologies.

Our results are in agreement with the work of Papovich et al. (2005), who found that $z \sim 1$ galaxies show strong transformation between their rest-frame UV and optical morphologies, using NICMOS observations of HDF-N. It has been reported (Papovich et al. 2005; Conselice et al. 2005) that at redshifts $2.0 \leq z \leq 3.0$, the morphology of a galaxy remains essentially unchanged from rest-frame UV to rest-frame optical. However, one should not neglect the effect produced by the $(1 + z)^{-4}$ surface brightness dimming, which at higher redshifts suppresses the (relatively low surface brightness) underlying galaxian light (by $\sim 6$ magnitudes at $z \sim 3.0$), so that the only parts of a galaxy that are left visible even in the rest-frame optical are the high surface brightness H II regions (while the underlying galaxy remains unconstrained). Future medium depth survey like GOODS (depth $\sim 10$ orbits) using the near-IR channel of the upcoming camera, WFC3 on HST might fail to probe the underlying rest-frame optical galaxian light at $z \sim 3.0$ simply due to $(1 + z)^{-4}$ surface brightness dimming effects. Ultra-deep images (depth $\sim 150$ orbits) with the near-IR channel of WFC3 will be required to constrain the underlying galaxian light at $z \sim 3.0$ and will allow similar analysis of the morphology of galaxies to high-$z$.

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