Surface Brightness Evolution of Galaxies in the CANDELS GOODS Fields up to $z \sim 6$: High-$z$ Galaxies Are Unique or Remain Undetected

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Abstract

We investigate the rest-frame ultraviolet (UV, $\lambda \sim 2000$ Å) surface brightness (SB) evolution of galaxies up to $z \sim 6$ using a variety of deep Hubble Space Telescope (HST) imaging. UV SB is a measure of the density of emission from mostly young stars and correlates with an unknown combination of star formation rate, initial mass function, cold gas mass density, dust attenuation, and the size evolution of galaxies. In addition to physical effects, the SB is, unlike magnitude, a more direct way in which a galaxy’s detectability is determined. We find a very strong evolution in the intrinsic SB distribution that declines as $(1 + z)^3$, decreasing by $4-5$ magn arcsec$^{-2}$ between $z = 6$ and $z = 1$. This change is much larger than expected in terms of the evolution in UV luminosity, sizes, or dust extinction, and we demonstrate that this evolution is “unnatural” and due to selection biases. We also find no strong correlation between mass and UV SB. Thus, deep HST imaging is unable to discover all of the most massive galaxies in the distant universe. Through simulations we show that only $\sim 15\%$ of galaxies that we can detect at $z = 2$ would be detected at high $z$. We furthermore explore possible origins of high-SB galaxies at high $z$ by investigating the relationship between intrinsic SB and star formation rates. We conclude that ultra–high-SB galaxies are produced by very gas-rich dense galaxies that are in a unique phase of evolution, possibly produced by mergers. Analogs of such galaxies do not exist in the relatively nearby universe.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); Hubble Space Telescope (761); Galaxy properties (615)

1. Introduction

When studying and examining galaxy evolution as a function of redshift, it is common to observe and characterize how quantities evolve with redshift to infer evolution. These quantities are most famously the UV luminosity function (LF) (e.g., Arnouts et al. 2005; McLure et al. 2013; Bouwens et al. 2015), the stellar mass function (Duncan et al. 2014; Bhatawdekar et al. 2019), the spectral shape of the UV light distribution (e.g., McLure et al. 2018), morphological evolution (e.g., Conselice & Arnold 2009), and the merger and pair fraction evolution (e.g., Duncan et al. 2019).

Galaxy surface brightness (SB) has previously been studied in the optical and near-infrared at low redshifts (Schade et al. 1995; Roche et al. 1998; Labbé et al. 2003; Barden et al. 2005). Such studies find mixed results, with some suggesting that there is evolution in the SB (e.g., Schade et al. 1996) and others suggesting that it does not exist or is due to selection effects (e.g., Simard et al. 1999). Higher-redshift galaxies have been examined in the context of gas, star formation, and star surface density but rarely explicitly in the form of SB for the past decade or so. However, these density relations are similar to the SB problem. Since the low-redshift studies, larger and deeper surveys have taken place, allowing us to now look further and deeper into the evolution of SB of galaxies, and to do so at a consistent rest-frame wavelength. With modern deep imaging data from the Hubble Space Telescope (HST) we can investigate the evolution of SB as measured in the ultraviolet (UV) and determine how it evolves in terms of intrinsic SB and what this evolution implies for galaxy formation, star formation, dust, and galaxy detection. SB in the UV rest frame is a good indicator of star formation density and gas density (Schmidt 1959; Kennicutt 1998; Leroy et al. 2008; Freundlich et al. 2013) and thus allows us to understand how these quantities change with time to first order. Star formation density has been shown to increase to a peak between $z \sim 1$ and $z \sim 2$, before becoming nearly constant to high redshift for Lyman break galaxies (e.g., Steidel et al. 1999; Giavalisco et al. 2004). Observations from HST show a small amount of evolution at $z > 3$ (Bouwens et al. 2003), and those measurements that are made using photometric redshifts show constant star formation up to $z \sim 6$ (Thompson et al. 2001; Kashikawa et al. 2003). SB also determines how well galaxies can be detected, and in this paper we investigate both of these problems.

When measuring the SB of a given galaxy, it is now well known that this value is constant for the same galaxies seen at different distances in the nearby universe. However, when a galaxy is at cosmological distances, the SB becomes lower by a factor of $(1 + z)^{\alpha}$, where $\alpha$ can range from 3 to 5 depending on the particular circumstances. One result of this is that galaxies that would normally be detectable, would have such a low SB that even with deep HST exposures we would not be able to detect them at higher redshifts.

The literature on the evolution of SB is, however, not entirely consistent on how this evolution occurs. Previous studies of the rest-frame SB evolution of disk galaxies find mixed results ranging from little or no evolution to a difference of $\sim 1–2$ mag between the local universe and $z \sim 1$. For example, Labbé et al. (2003) use ground-based near-infrared
imaging and find an increase of 1 mag out to $z \sim 2$–3 for six Milky Way–type galaxies. Schade et al. (1996) also use ground-based imaging but find a stronger evolution of 1.6 mag from $z \sim 1$ for a larger sample of 143 galaxies (33 early-type and 110 late-type). These results are also found in HST observations by Schade et al. (1995), Lilly et al. (1998), Roche et al. (1998), and Barden et al. (2005), who find an average increase in SB of $\sim 1$ mag by $z \sim 1$ for a mixture of both spiral and elliptical galaxies.

In terms of SB and selection, Simard et al. (1999) identify the need for selection effects to be taken into account when probing higher redshifts, and this is another reason why studying the evolution of SB is important. Before taking selection effects into account, Simard et al. (1999) find a change of 1.3 mag from $z \sim 1$ to $z \sim 0$, but once these effects are considered, they find no evolution in the SB. Similarly, Ravindranath et al. (2004) find a change in SB of $<0.4$ mag over the range $0.2 < z < 1.25$ in the $z$ band for disk-like galaxies when considering selection effects. These studies show that there are relatively bright galaxies in the highest-redshift bins. Trujillo & Aguerri (2004) also take selection effects into account in their analysis; however, they find a change of $\sim 0.8$ mag from $z = 0.7$ to $z = 0$ when measuring the SB in the $V$ band. Models supporting an increase in SB include Bouwens & Silk (2002), who model disk evolution based on two different approaches. Both models find a strong evolution in the $B$-band SB of 1.5 mag by $z = 1$, and they argue that these results are not an artifact of selection effects. These works are limited to relatively low redshift objects, where the cosmological SB dimming is not as dramatic as it is at higher redshifts, and are also limited to the optical rest frame. As we now have access to higher-redshift data from surveys such as the Cosmic Assembly Near-infrared Deep Extragalactic Survey (CANDELS), we can now probe how the SB of galaxies changes with time and infer the processes that cause this evolution over $\sim 12$ Gyr of cosmic time for the UV rest frame.

We examine the evolution of the UV rest frame ($\lambda \sim 2000$ Å) SB through the redshift range of $0.5 < z < 6.5$. We also examine the relationship between the SB and star formation rate (SFR). In this work, we analyze two separate samples: a mass-selected sample and a number-density-selected sample. The mass-selected sample is composed of 1522 galaxies that lie within the mass range $10^{10} M_\odot < M_\star < 10^{11} M_\odot$ to ensure completeness (Duncan et al. 2019). The mass limits for $z < 6$ are considerably lower than our chosen mass limit of $10^{10} M_\odot$. The redshift and mass distributions of the galaxies within this sample are shown in the left panel of Figure 1. The yellow regions indicate a high density of galaxies, and purple indicates a lower density of galaxies. The color scaling is linear.

The number-density-selected sample is generated by using a constant number density of $1 \times 10^{-4}$ Mpc$^{-3}$ (Ownsworth et al. 2016). This sample consists of 400 galaxies that have masses in the range $10^{10.5} M_\odot < M_\star < 10^{11.5} M_\odot$. The redshift and mass distributions within the number-density-selected sample are shown in the right panel of Figure 1. As with the left panel, the yellow regions indicate a high density of galaxies, purple indicates a lower density of galaxies, and the color scaling is linear. This sample is chosen because it potentially allows us to directly track the progenitors and descendants of massive galaxies at all redshifts (e.g., Mundy et al. 2015; Ownsworth et al. 2016). In the following subsections we discuss how we measured photometric redshifts and stellar masses for our sample of galaxies. There are a small number of high-$z$ galaxies with high masses in this sample that are unlikely to be real; however, these galaxies do not affect our results.

### 2.1. Photometric Redshifts

We use the method as described in Duncan et al. (2019) to calculate photometric redshifts for the galaxies within our samples. Template-fitting estimates are determined using the EAZY photometric redshift software (Brammer et al. 2008). Three separate template sets are used and fit to all available photometric bands. These template sets include zero-point offsets to the input fluxes and additional wavelength-dependent errors. We then calculate further empirical estimates using a Gaussian process code (GPz; Almosallam et al. 2016) using a subset of the available photometric bands. Individual redshift posteriors are calibrated, and the four estimates are combined in a statistical framework via a hierarchical Bayesian combination to produce a final redshift estimate. For further details of the process, see Section 2.4 of Duncan et al. (2019).
2.2. Stellar Mass Fitting

The galaxy stellar masses we use are measured by using a modified version of the spectral energy distribution (SED) code described in Duncan et al. (2014). The stellar mass is estimated at all redshifts in the photo-z fitting range as opposed to finding the best-fit mass for a fixed input redshift. Also included in these estimates is a so-called “template error function” to account for uncertainties introduced by the limited template set and any wavelength effects. The method for this error function is outlined in Brammer et al. (2008). This mass-fitting technique uses Bruzual & Charlot (2003) templates, includes a wide range of stellar population parameters, and assumes a Chabrier (2003) initial mass function. The assumed star formation histories follow exponential $\tau$-models for both positive and negative values of $\tau$. Characteristic timescales of $|\tau| = 0.25, 0.5, 1, 2.5, 5,$ and $10$, along with a short burst ($\tau = 0.05$) and continuous star formation models ($\tau \gg 1/H_0$), were assumed.

We compare the mass measurements we make to the average of those determined by the several teams within the CANDELS Collaboration (Santini et al. 2015). This is done in order to ensure that the stellar mass estimates do not suffer from systematic biases. There is some scatter between the two mass estimates; however, our mass estimates are not affected by significant biases. For further details on the method and models used, see Section 2.5 of Duncan et al. 2019 for an extensive discussion.

2.3. Star Formation Rates

The SFRs we use in this paper are determined through SED fitting. The measured rest-frame absolute magnitudes ($M_{r,5000}$) are corrected for dust extinction using the relation determined by Meurer et al. (1999). Where the relation implies a negative extinction, the extinction is set to 0. The UV SFRs are calculated using the following:

$$\text{SFR (}\text{M}_\odot\text{ yr}^{-1}) = \frac{L\text{UV (erg s}^{-1}\text{ Hz}^{-1})}{1.39 \times 10^{27}}.$$  

Table 1

| $z$ | $\mathcal{O}_{ij}^{\text{raw}}$ | $D_{ij}^{\text{raw}}$ | $\lambda_{\text{rest}}$ |
|-----|----------------|----------------|-----------------------------|
| 1   | B435           | ...           | 2175 Å                      |
| 2   | V606           | ...           | 2020 Å                      |
| 3   | I414           | ...           | 2035 Å                      |
| 4   | z450           | B435          | 1700 Å                      |
| 5   | Y105           | B435          | 1750 Å                      |
| 6   | J125           | V606          | 1785 Å                      |

Note. Column (2) gives the band corresponding to the UV rest frame ($\mathcal{O}_{ij}^{\text{raw}}$), and Column (3) gives the band corresponding to the Lyman break where applicable ($D_{ij}^{\text{raw}}$). Column (4) gives the rest-frame wavelength probed.

where the conversion factor of Madau et al. (1998) and Kennicutt (1998) is used. For further details, see Duncan et al. (2014) and Duncan et al. (2019).

3. Methodology

3.1. 2D Lyman Break Imaging

We utilize the image processing technique described in Whitney et al. (2019) in order to produce the images we ultimately use within our analysis. However, we normally only use imaging in the bands corresponding to the UV rest frame as opposed to the optical as is done in Whitney et al. (2019). The bands used are given in Table 1, along with the rest-frame wavelength we probe at each redshift. This 2D Lyman break imaging method removes all nearby galaxies and only retains the original system. We do this to avoid contamination from foreground objects, utilizing the fact that the Lyman break allows us to find which systems are at different redshifts of the principal galaxy we are looking at.

The process makes use of the Lyman break at 912 Å and removes contaminating foreground objects from 100 × 100 pixel postage stamp images of galaxies. This is achieved by
subtracting the band corresponding to the Lyman break from the band corresponding to the UV rest frame and normalizing the resulting image by the UV rest-frame image. Maps of the pixels are created such that the pixels corresponding to the central object are given a value of 1 and the pixels corresponding to the sky are given a value of 0. The pixels corresponding to the central object are identified by selecting those that have a value that is greater than or equal to three times the standard deviation of the background statistics. We use this map, along with the segmentation map of the UV rest frame, to remove the field objects. These removed areas are then replaced with noise that has the same mean and standard deviation as the sky. The process can be described by the equation

\[ O_{i,j}^{\text{analysis}} = \left( \frac{O_{i,j}^{\text{raw}} - D_{i,j}^{\text{raw}}}{O_{i,j}^{\text{raw}}} \right) \cdot S_{ij} + f(O_{i,j}^{\text{raw,sky}}), \]

where \( O_{i,j}^{\text{raw}} \) is the original optical rest-frame image or its substitute, \( D_{i,j}^{\text{raw}} \) is the original drop-out image, \( S_{ij} \) is the segmentation map, and \( f(O_{i,j}^{\text{raw,sky}}) \) is some function of the raw optical rest-frame image. The function \( f(O_{i,j}^{\text{raw,sky}}) \) creates an image in which the pixels corresponding to the central object are 0, the pixels corresponding to the sky are those of the raw optical rest-frame image, and the pixels corresponding to the field objects are noise that has the same mean and standard deviation of the sky. Examples of this image processing technique are shown in Figure 2 for galaxies at redshifts of 7.0 and 4.5. Each column \( (D_{i,j}^{\text{raw}}, O_{i,j}^{\text{raw}}, S_{ij}, O_{i,j}^{\text{analysis}}) \) corresponds to the central galaxy’s redshift, the second column shows the original \( V_{606} \) image, the third column shows the segmentation map corresponding to the optical rest frame, and the fourth column (right) shows the result of the image processing whereby all galaxies that appear below the Lyman break are removed (see Equation (2) for details). The field of view is 60″ on a side.

This is due to the fact that we are unable to observe the Lyman break for these galaxies; however, there are much fewer foreground galaxies at these redshifts, and thus contamination is not a serious concern. For further details and example images, see Whitney et al. (2019).

3.2. Size Measurement and Magnitude Determination

In this work we use the Petrosian radius \( (R_{\text{Pet}}(\eta)) \) to measure the sizes of our galaxies (e.g., Whitney et al. 2019). The radius we use for sizes, defined by the Petrosian index, is also the radius we use to measure the magnitude of the galaxy. The Petrosian radius is defined as the radius at which the SB at a given radius is a particular fraction of the SB within that radius (e.g., Bershady et al. 2000; Conselice 2003). The radius measured depends on a defined ratio of SB, \( \eta(r) \). This ratio is defined as

\[ \eta(r) = \frac{I(r)}{\langle I(r) \rangle}, \]

where \( I(r) \) is the SB at radius \( r \) and \( \langle I(r) \rangle \) is the mean SB within that radius. By this definition, \( \eta(r) = 1 \) at the center and 0 at large \( r \) (Kron 1995). The Petrosian radius at \( \eta = 0.2 \) contains at least 99% of the light within a given galaxy (Bershady et al. 2000). Throughout this paper, we set the size of a given galaxy to its Petrosian radius at \( \eta = 0.2 \), and we refer to such size as \( R_{\text{Pet}} \).

The Petrosian radius is determined using the CAS (concentration, asymmetry, and clumpiness) code (Conselice 2003). The Petrosian radius differs from the more

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**Figure 2.** Examples of our image processing technique for four galaxies at redshifts of 7.0 and 4.5. Each column \( (D_{i,j}^{\text{raw}}, O_{i,j}^{\text{raw}}, S_{ij}, O_{i,j}^{\text{analysis}}) \) corresponds to the parameters of Equation (2). The first column (left) shows the original \( V_{606} \) or \( B_{435} \) image showing the light below the Lyman break rest-frame wavelength for the central galaxy’s redshift, the second column shows the original \( H_{160} \) band image, the third column shows the segmentation map corresponding to the optical rest frame, and the fourth column (right) shows the result of the image processing whereby all galaxies that appear below the Lyman break are removed (see Equation (2) for details). The field of view is 60″ on a side.
commonly used half-light radius in that the former is a redshift-independent measure of galaxy size. By measuring the sizes of galaxies in this way, we can assume that the measurement would be the same no matter at what redshift it was placed, whereas by using the half-light radius there is the potential for the size measurement of a particular galaxy to decrease as redshift increases as outer light is lost (Buitrago et al. 2013; Whitney et al. 2019). We correct the sizes for point-spread function (PSF) effects by simulating a sample of galaxies and applying the WFC3 PSF to images of these galaxies, as described in Whitney et al. (2019). All of our galaxies are resolved, and as such, the Petrosian radius is never so small that it is dominated by noise rather than galaxy light.

In order to calculate the SB, we first calculate the magnitude, \( m \), within an aperture of radius \( R_{\text{pet}} \) by measuring the flux within this aperture. From this magnitude, we are able to determine the observed SB and the intrinsic SB, as explained below.

### 3.3. Surface Brightness Dimming

Below we give a description of our derivation for how the SB of a galaxy changes owing to cosmological effects, with a more detailed explanation in the Appendix. There have been many papers on this in the past (Tolman 1930, 1934; Giavalisco et al. 1996; Conselice 2003); however, we redefine the net correction for the dimming in our own specific situation whereby we are observing the same rest-frame wavelength, but in different observed filters, at different redshifts. Note that all situations in SB dimming are unique and the derivation below is focused on our own situation.

It is well known that the measured SB of a given galaxy is not constant with redshift, and that objects are subject to SB dimming whereby an object at redshift \( z_1 \) is a factor \( f \) dimmer in SB than the same object at redshift \( z_2 \), where \( z_1 > z_2 \) (Tolman 1930, 1934). There are five factors of \( (1 + z) \) that need to be taken into account when considering SB dimming. Two factors of \( (1 + z) \) arise from the fact that the source was closer to the observer when the light was emitted. This causes the object to look larger by a factor of \( (1 + z) \) in two dimensions. One factor of \( (1 + z) \) arises from a change in the rate of photons being received from the source. Another factor is the result of photons shifting to a lower energy as they propagate from the source to the observer. The final factor comes from the change in the unit wavelength bandpass. When considering the integrated flux, the final factor does not apply. This is consistent with the argument made by Tolman (1930) whereby galaxies dim with redshift by a factor of \( (1 + z)^4 \). Here we consider the flux density measured in units of \( f_\nu \). Therefore, the redshift dependence is reduced to \( (1 + z)^3 \).

When considering the spectral flux density in units of \( f_\nu \) (erg s\(^{-1}\) cm\(^{-2}\) \( \text{Å} \)^\(-1\)), as used in Space Telescope (ST) magnitudes, we must consider all five factors of \( (1 + z) \) described above when calculating how much the SB reduces by in terms of a bolometric flux. As such, the intrinsic SB goes as

\[
\mu_{\text{int}} \propto (1 + z)^{-3} \tag{5}
\]

in units of erg s\(^{-1}\) cm\(^{-2}\) \( \text{Å} \)^\(-1\), or ST magnitudes, where \( \mu_{\text{int}} \) is the intrinsic SB.

In the case of the spectral flux density in units of \( f_\nu \) (erg s\(^{-1}\) cm\(^{-2}\) Hz\(^{-1}\)), as used in AB magnitudes, we must consider the first four factors described above (one due to energy, one due to time dilation, and two due to the change in angular size). However, we must consider the change in unit frequency as opposed to the change in unit wavelength. As frequency is inversely proportional to wavelength, the frequency interval decreases by a factor of \( (1 + z) \) from emission to detection. From this, we find that

\[
\mu_{\text{int}} \propto (1 + z)^{-3} \tag{6}
\]

where \( m \) is the apparent magnitude discussed in Section 3.2 and \( R_{\text{pet}} \) is the Petrosian radius of the galaxy in which that magnitude is measured. The apparent magnitude is calculated from the measured flux within the measured Petrosian radius \( R_{\text{pet}} \). As we are measuring fluxes in the AB magnitude system, this SB should be corrected by SB dimming of the form

\[
\mu_{\text{int}} = m + 2.5 \log_{10}(\pi R_{\text{pet}}^2) - 2.5 \log_{10}((1 + z)^3) \tag{7}
\]

We use Equation (7) to calculate the intrinsic SB for the systems we detect, within the observed SB given by Equation (6). Throughout the rest of this paper we use these SB values to understand the physical evolution and selection effects present within deep surveys such as CANDELS. As explained in Section 3.3, we use a factor of \( (1 + z)^3 \) to determine the amount of cosmological dimming experienced by a galaxy when being artificially redshifted from a redshift \( z_{\text{low}} \) to a higher redshift \( z_{\text{high}} \).

### 3.4. Surface Brightness: Observed and Intrinsic

One of the main goals of this paper is to examine the intrinsic evolution of the SB for galaxies up to \( z = 6.5 \). However, this is a derived quantity that must be calculated based on the observed SB and assuming that cosmological dimming is taking place. As such, we examine in this paper both the observed and the derived intrinsic SB evolution.

First, we describe the method that we use to derive the intrinsic SB from the observations. The observed SB is given by

\[
\mu_{\text{obs}} = m + 2.5 \log_{10}(\pi R_{\text{pet}}^2) \tag{8}
\]

We carry out a detailed derivation in the Appendix on a step-by-step basis so that other situations can be adopted using our methodology.

### 3.5. Artificially Redshifted Galaxies

One of the tools we use to determine whether galaxies observed at low redshift (\( z_{\text{low}} \)) would be detectable at higher redshift (\( z_{\text{high}} \)) is by artificially redshifting galaxies in our sample from low redshift to high redshift. We start by examining a representative simulation by taking galaxies from \( z_{\text{low}} = 2 \) and simulating how they would appear within the CANDELS data at \( z_{\text{high}} = 6 \). This procedure is done by...
multiplying the $V_{606}$ image by the factor $\left(\frac{1+z_i}{1+z_{bc}}\right)^4$ and inserting
this into the background of the $I_{125}$ mosaic image, whose noise
is reduced by a factor defined as

$$f = \frac{1}{1 - \left(\frac{1+z_i}{1+z_{bc}}\right)^4},$$

(8)
to ensure that we are not overestimating the background. We
also include luminosity evolution in the form of the difference
between the characteristic magnitudes ($\Delta M'$) of the UV
luminosity functions for each redshift. The values for $1 \leq z \leq 3$ are taken from Arnouts et al. (2005), and the values
for $4 \leq z \leq 6$ are taken from Bouwens et al. (2015). The
redshifting process is therefore described by the equation

$$R_{ij} = UV_{ij} \cdot \left(\frac{1+z_{lo}}{1+z_{hi}}\right)^4 \cdot \Delta M^* + N_{ij} / f,$$

(9)
where $R_{ij}$ is the redshifted image, $UV_{ij}$ is the rest-frame UV
image at $z = 2$, and $N_{ij}$ is the background noise. Figure 3
shows an example of this redshifting technique, beginning at
$z = 2$ and ending at $z = 6$. We then measure these galaxies
using the CAS code (Conselice 2003) in the same way we
would for actual galaxies. We use this to measure the size (in
this case, the Petrosian radius at $r = 0.2$, $R_{pet}$) and flux of each
galaxy from which we can determine the measured SB.

We calculate an SB completeness limit by examining the whole
sample from which the two subsamples are selected and
determining at which magnitude the SB function declines. This
magnitude is then used to calculate the equivalent intrinsic SB
at each redshift.

4. Results
In this section we present the results we find when measuring
the SB of the galaxies using the two separate samples described
in Section 2: a mass-selected sample where the galaxies lie
within a mass range of $10^{10.6} M_{\odot} \leq M_* \leq 10^{11.1} M_{\odot}$, and a number-
density-selected sample where each redshift bin contains
galaxies such that a number density selection is used at the
constant value of $1 \times 10^{-4} \text{Mpc}^{-3}$ with a mass range of
$10^{9.5} M_{\odot} < M_* < 10^{11.8} M_{\odot}$. This particular method of selecting
galaxies allows us to trace how the most massive galaxies have
evolved in SB over time.

4.1. Observed Surface Brightness as a Function of Redshift

Throughout this work we measure all sizes and fluxes in the
UV rest frame between 1785 and 2175 Å. SB is variant with
wavelength, hence the need for a consistent rest-frame wavelength
across redshifts. The UV rest frame is also useful for tracing
the star formation within galaxies. One downside of using the UV is that we are not able to trace the underlying
older stellar mass formed within these galaxies. We are only
tracing the young stars and the effects of dust on this light.

Before applying mass and number density cuts to the data, we
examine the observed SB distribution of the full sample of
$\sim 34,000$ galaxies obtained from the CANDELS GOODS-
North and GOODS-South fields. These galaxies lie in the
redshift range $0.5 \leq z \leq 6.5$ and have stellar masses in the
range $10^9 M_{\odot} < M_* < 10^{12} M_{\odot}$. The observed SB for each of
these galaxies can be seen in Figure 4 before any cuts are
performed. The average observed SB of each redshift bin is
given as a blue triangle, with an error of $1\sigma$. There is a jump in
$\mu_{obs}$ between redshifts $z = 3$ and $z = 4$ owing to a difference in
limiting magnitude of the filters, whereby F814W probing $z \sim 3$ is more sensitive than any redder filter with WFC3.

The evolution of the observed SB ($\mu_{obs}$) of the mass-selected
sample can be seen in the left panel of Figure 5, with the mean
SB indicated for each redshift as orange circles. The same plot
for the number-density-selected sample can be seen in the right
panel of Figure 5, with the mean SB shown by green circles.
Both forms of the evolution are fit with a power law of the form

$$\mu = \alpha (1 + z)^{-\beta}.$$  

(10)
The parameters determined for the fits are shown in Table 2. Both samples show a relatively flat evolution, increasing by $0.9 \pm 1.5 \text{mag arcsec}^{-2}$ and $1.2 \pm 1.4 \text{mag arcsec}^{-2}$, respectively. We correct the observed SB for size evolution by setting
the size of each galaxy to the mean size of the $z = 6$
galaxies such that Equation (6) becomes

$$\mu_{obs} = m + 2.5 \log_{10}(\pi R^2_{z=6}).$$

(11)
We plot these size-corrected values as open circles and fit these
points with the power law given in Equation (10), and this is
shown as a dashed line in both the left and right panels of
Figures 5. We see that the size-corrected values yield a shallower evolution whereby the difference between the SB at
$z = 1$ and $z = 6$ is now $0.4 \pm 1.8 \text{mag arcsec}^{-2}$ and $0.1 \pm 1.9 \text{mag arcsec}^{-2}$ for the mass-selected and number-density-
selected samples, respectively.

When using the more direct physical value of SB in the form
of measured flux per unit area in real units rather than logged,
we find that the mass-selected sample evolves as

$$(1 + z)^{0.25 \pm 0.07}$$

and the number-density-selected sample evolves as

$$(1 + z)^{0.07 \pm 0.73}.$$  

This method also suggests that the flux per unit area decreases with time; however, this evolution is much steeper than the evolution in logged units, particularly in the case of the mass-selected sample.

4.2. Intrinsic Surface Brightness as a Function of Redshift
The intrinsic SB ($\mu_{int}$) varies with redshift such that galaxies
at a low redshift are ~5 mag dimmer than those at the highest
redshift. The evolution of $\mu_{int}$ can be seen in the left panel of
Figure 6 for the mass-selected sample and in the right panel of
Figure 6 for the number-density-selected sample. The mean
intrinsic SB is indicated by the orange and green circles, respectively.

We fit a power law to these mean values, and these fits are
indicated by a solid line in both cases. The parameters of
the power-law fits for both figures are shown in Table 2. Both samples show a similar evolution, with the mass-selected
sample evolving as

$$(1 + z)^{-0.18 \pm 0.01}$$

and the number-density-selected sample evolving as

$$(1 + z)^{-0.19 \pm 0.01}.$$  

No matter the selected method, the intrinsic SB changes by several mag arcsec$^{-2}$, with the mass-selected sample changing by $4.8 \pm 1.5 \text{mag arcsec}^{-2}$ and the number-density-selected sample changing by $5.0 \pm 1.4 \text{mag arcsec}^{-2}$.

As for the observed SB, we correct for size evolution for
both samples by setting the size of each galaxy to the mean size
of the $z = 6$ bin. Equation (7) therefore becomes

$$\mu_{int} = m + 2.5 \log_{10}(\pi R^2_{z=6}) - 2.5 \log_{10}((1 + z)^3).$$

(12)
This is shown in the left (mass-selected) and right (number-density-selected) panels of Figure 6 by the open circles, and a fit of the form $(1 + z)^{-\beta}$ is shown as a dashed line for both samples. This size correction causes the evolution to flatten for both samples, with $\beta$ changing from $0.18 \pm 0.01$ to $0.13 \pm 0.01$ and from $0.19 \pm 0.01$ to $0.15 \pm 0.01$ for the mass-selected and number-density-selected samples, respectively. This size correction also causes the difference in SB between $z = 1$ and $z = 6$ to change to $3.5 \pm 1.8$ mag arcsec$^{-2}$ and $3.9 \pm 1.9$ mag arcsec$^{-2}$ for the two samples. This means that size can only account for about a magnitude of the evolution of galaxy SB, with $3$–$4$ mag arcsec$^{-2}$ unaccountable for the fact that galaxies are growing in size within their Petrosian radius as they evolve from high to low redshift (e.g., Whitney et al. 2019). By examining the evolution of the size-corrected SB, a quantity that is linearly proportional to the luminosity, we are effectively examining the evolution of the absolute magnitude at a fixed size.

We also show the distribution of the SB for the full mass-selected sample in Figure 7. This demonstrates a systematic evolution at all galaxy masses in SB, such that, on average, galaxies at higher redshifts exhibit a higher intrinsic SB, which

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**Figure 3.** Example of the redshifting process beginning with a $z = 2$ galaxy (top left) and ending with the same galaxy redshifted to $z = 6$ (bottom right). The images in between correspond to the original galaxy redshifted in $\Delta z = 0.5$ intervals. The image at each redshift interval has been evolved with the characteristic magnitude of that redshift (Arnouts et al. 2005; Bouwens et al. 2015).
then declines at lower redshifts. One caveat to this observation is that this is not necessarily a complete sample, as we would naturally be missing galaxies lower than the SB completeness limit. At high redshift this limit is quite high—20 mag arcsec$^{-2}$, which appears to be the limit in which we can still detect intrinsically faint galaxies at $z > 3$. What remains to be known or determined is whether there are indeed galaxies at these redshifts that have an intrinsic SB that is lower than this value and therefore unobservable with our current deep imaging. We investigate this question later in the paper.

4.3. Artificially Redshifting Galaxies

We examine the effects of redshift by simulations described in Section 3.5. We carry out these simulations by artificially redshifting galaxies at low redshifts at $z = 2$ and imaging them to how they would appear in our data at $z = 6$. This is done primarily using the techniques described in Section 3.5, whereby the galaxy is reduced in SB by $(1+z)^3$ and then reimaged into our data.

When we carry out this process, we find that there are few galaxies obviously visible in the resulting images. This implies that without some type of luminosity evolution we would only be able to detect a few galaxies with properties similar to the ones we can detect at $z = 2$ and higher redshifts. However, in addition to our visual determination of whether a galaxy has been detected, we measure the signal-to-noise ratio (S/N) of each of the objects after they are simulated. We measure the flux within $R_{200}$ as $0.2$. The average S/N for the redshifted sample is ~3, which is barely detectable at best, and which is a significant decrease when compared to the original sample of galaxies that have an average S/N of ~100. We find that 16% of the artificially redshifted galaxies are detectable (defined as having an S/N >5), compared to 94% of the original sample of $z = 2$ galaxies.

We measure a difference of $3.5 \pm 1.6$ mag arcsec$^{-2}$ in intrinsic SB between $z = 6$ and $z = 2$ for the mass-selected sample, and so we apply this difference to the $z = 6$ simulated galaxies in the form of an increase of brightness by a factor of $\sim 24$ using the relation

$$\frac{L_{z=6}}{L_{z=2}} = 10^{0.4 \Delta M}.$$  \hspace{1cm} (13)

As a result, the S/N of the artificially redshifted galaxies increases to about ~50 after this luminosity evolution is included. We also measure a mean observed SB of 26.3 mag arcsec$^{-2}$ and a mean intrinsic SB of 19.9 mag arcsec$^{-2}$. Both results are ~0.3 mag dimmer than the values we see for the actual $z = 6$ sample of galaxies. This implies that most of these galaxies would be observable at $z = 6$ just using the amount of decrease in the observed SB and correcting for it.

However, we know from various studies of the luminosity function in the UV that the intrinsic average brightness of galaxies on average changes as we go to higher redshifts, with galaxies becoming brighter (e.g., Arnouts et al. 2005; Bouwens et al. 2006; McLure et al. 2013; Duncan et al. 2014; Bouwens et al. 2015; Bhatawdekar et al. 2019). This observed brightening of the average galaxy population is, however, much less than the amount we observe in terms of the SB evolution.

To see the effect of this on the detectability of our sample of galaxies after being simulated from $z = 2$ to $z = 6$, we increase the brightness of our images by the observed amount from LF evolution. We take the $z = 2$ characteristic magnitude, $M_{\text{UV}}^*$, to be $-20.33 \pm 0.50$ (Arnouts et al. 2005) and set this value to be the zero-point. We take the $z = 6$ characteristic magnitude to be $-20.94 \pm 0.20$ (Bouwens et al. 2015) and calculate the change in magnitude between the two redshifts to be $0.61 \pm 0.54$ mag. We are then able to calculate the factor by which the brightness changes ($\frac{L_{z=6}}{L_{z=2}}$) from the lowest redshift to the highest redshift. We determine this value to be $1.75 \pm 0.87$, which is much less than the factor of 24 observed, as discussed above. We calculate this factor for each redshift interval and multiply the redshifted images by this factor to simulate the evolution of the luminosity function.

We show the evolution of both the observed and intrinsic SB of the artificially redshifted sample of galaxies that have been evolved with the luminosity function in Figure 8. Unlike the actual observed SB evolution, the measured SB for the simulated sample increases by $1.0 \pm 1.9$ mag arcsec$^{-2}$ from $z = 6$ to $z = 2$, and we find that the evolution goes as $(1+z)^{0.05 \pm 0.01}$; therefore, these simulated galaxies appear to get brighter with redshift. This is due to the method used when artificially redshifting the galaxies; the overall factor the images are multiplied by decreases as redshift increases, leading to a smaller measured flux and therefore a dimmer SB. The real mass-selected sample, on the other hand, decreases by $0.7 \pm 1.6$ mag arcsec$^{-2}$ over the same redshift range. The intrinsic SB, however, follows the trend seen in the real sample, but the evolution is not as steep; the evolution goes as $(1+z)^{-0.09 \pm 0.02}$ and the SB decreases by $1.9 \pm 1.9$ mag arcsec$^{-2}$ over the redshift range from $z = 6$ to $z = 2$, whereas the real sample decreases by $3.5 \pm 1.6$ mag arcsec$^{-2}$ over the same redshift range.

Based on this, there are approximately 1.6 mag of intrinsic SB evolution unaccounted for in the simulated images. We find from this that 84% of the $z = 2$ galaxies would not be detected.
The error bars shown are indicated by the green circles. The error bars shown are μFits Determined for Both the Mass-selected mean values, and we find μobs = 27.44 ± 0.34(1 + z)^−0.03±0.01. This fit is shown as a solid line. The SB is corrected for size by setting the sizes of all galaxies to the mean z = 6 galaxy size. These points are shown as open circles. The fit to the points is shown as a dashed line and is found to be μobs = 25.35 ± 0.01(1 + z)^0.01±0.01. The error bars shown are 1σ from the mean. Right: evolution of the average observed SB for the number-density-selected sample. The mean SB for each redshift is indicated by the green circles. The error bars shown are 1σ from the mean, and a fit of the form (1 + z)^−β (solid line) has been fit to the data. The fit is found to be μobs = 27.94 ± 0.39(1 + z)^−0.04±0.01. The observed SB is corrected for size, as shown by the open circles. The power-law fit of these values yields μobs = 26.09 ± 0.57(1 + z)^−0.01±0.01 and is shown as a dashed line.

Table 2
Fits Determined for Both the Mass-selected (M) and Number-density-selected (ND) Samples as Given by Equation (10)

| Sample       | α      | β       |
|--------------|--------|---------|
| μobs         |        |         |
| M            | 27.44 ± 0.34 | −0.03 ± 0.01 |
| ND           | 27.94 ± 0.39 | −0.04 ± 0.01 |
| μintrinsic   |        |         |
| M            | 27.91 ± 0.51 | −0.18 ± 0.01 |
| ND           | 28.34 ± 0.57 | −0.19 ± 0.01 |

at z = 6 if evolved with the luminosity function (where detected galaxies are determined as being those with an S/N >5), with only the highest-SB ones being detectable. This implies that there is a either a significant amount of galaxies being missed in deep HST imaging that exist at high redshifts, or that some galaxies have evolved significantly more than others. We will further discuss this in the discussion section of this paper.

We also alternate how much evolution we add to determine how much brighter the galaxies at z = 2 would need to be in order to be considered significant detections. We find that a factor of 6 is required for a mean S/N value of 10. This factor of 6 in brightness equates to a change in magnitude of ~2, which is much larger than the change of 0.61 in magnitude seen for the characteristic magnitudes between z = 2 and z = 6. Thus, it cannot be the case that SB evolution is determined simply by an evolving luminosity and size within the Petrosian radius.

The limiting magnitudes for an extended source for the J125 filter of GOODS-South and GOODS-North fields are 27.9 and 28.0 mag, respectively. These values are 5× the photometric error within a 0.2 arcsec² aperture (Grogin et al. 2011). This equates to limiting observed SB to 26.2 mag arcsec⁻² and 26.3 mag arcsec⁻² within a 0.2 arcsec² area, respectively. However, this is not a proper limit owing to various factors. We thus empirically determine the SB completeness limit for our data by examining at which magnitude the SB function declines. We find that 90% of the simulated galaxies that have been evolved with the luminosity function correction have an observed SB that is lower than the limiting SB. Therefore, if these galaxies were real, we would not be able to detect the vast majority of these galaxies using the J125 filter of WFC3.

In the next section of this paper we investigate the relationship of SB to other galaxy properties. One reason we do this is to try to make sense of this evolution in observed SB and what it might imply regarding the galaxy population at high redshift.

4.4. Correlation with Other Parameters

The first part of this paper is about the use of SB measures as a way to detect galaxies. We discuss how it is likely that many galaxies are likely missing and whether the evolution of luminosity is consistent with the intrinsic SB evolution. In this section, we explore the relationship between the intrinsic SB and other galaxy parameters such as SFR. This is the second part of this paper, whereby we examine how the SB reveals information about the physical state of the galaxies and how they are evolving.

First, we determine the relationship between intrinsic SB and the stellar mass of the mass-selected sample of galaxies for each redshift bin, as shown in Figure 9. Each panel shows the relationship for each redshift bin, with the final panel giving the evolution of the slope of the relationship. The fits for each redshift are shown as dashed lines, and the SB completeness limit described in Section 3.4 is shown by a solid line. We find a slight dependence of SB on galaxy stellar mass whereby...
lower SB galaxies have a higher mass; however, this is a very small dependence. In general, a galaxy of any given mass could have a range of SB at all redshifts. This suggests that the stellar mass of a galaxy does not heavily influence the evolution of its intrinsic SB. It also implies that by only reaching a certain SB limit are we not solely missing low-mass galaxies, but high-mass galaxies are missing too. This has important consequences for understanding the fact that we are missing galaxies at high redshift under the SB completeness limits.

As we probe the universe with deeper observations, we are able to detect galaxies with lower SB. However, as we are only looking at objects in the UV rest frame at the highest redshifts with HST, we can conclude that we are missing galaxies at all stellar masses. To highlight this, we compare the...
relationship between the stellar mass and intrinsic SB measured in the UV rest frame (B435) and the $H_{160}$ band, as shown in Figure 10. The slope for the $H_{160}$ band is negative, as expected, as opposed to positive as seen for the B435 band. This is such that within the $H$ band those galaxies with the highest masses exhibit a higher SB. We do not witness this when observing galaxies in the rest-frame UV, where there is a large scatter and no obvious trend. From this we can conclude that it is thus likely that observations are missing low-SB galaxies in the UV that span all stellar masses.

We also examine the evolution of SFR density, $\Sigma_{\text{SFR}}$, of the two samples. $\Sigma_{\text{SFR}}$ is defined as the SFR per unit area, where the area used is the region bound by a circle of radius $R_{\text{Pet}}(\eta = 0.2)$. In the left panel of Figure 11, we show the mean SFR density for the mass-selected sample as orange circles. In the right panel of Figure 11, we show the same relation but for the number-density-selected sample. For both samples, we see decreases in $\log_{10}(\Sigma_{\text{SFR}})$ of $1.4 \pm 0.6 M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$ and $1.5 \pm 1.0 M_\odot \, \text{yr}^{-1} \, \text{kpc}^{-2}$ for the mass-selected and number-density-selected samples, respectively. Both results show that a higher SB correlates with a larger SFR and a larger SFR per unit mass. The upper limit of our star formation density as shown in Figure 11 broadly corresponds to that found by Meurer et al. (1997), who suggest that this limit is caused by some form of self-regulatory feedback.

The relationship between the SFR and the intrinsic SB is shown in Figure 12 for the seven redshift bins. On top we show the results for the mass-selected sample, and the bottom shows the same results for the number-density-selected sample. Each panel shows the relationship between the two variables for each redshift bin, along with a fit to the data. The final panel shows the evolution of the slope of these fits with redshift. On average, the slope gets steeper with time for the mass-selected sample. The slope for the number-density-selected sample, however, remains approximately constant with time.

We also show the relationship between the intrinsic SB and specific SFR (sSFR, defined as the SFR per unit mass) for both samples in Figure 13. As for Figure 12, on the top we show the relationship for the mass-selected sample, and on the bottom we show the relationship for the number-density-selected sample. Each panel shows the relationship between SFR and intrinsic SB for each of the seven redshift bins, and the bottom
right panel shows the evolution of the slope with redshift. The slopes of both samples get steeper with time; however, the mass-selected sample changes by a greater amount.

5. Discussion

In this section we discuss our results, including what the meaning of the SB evolution implies for detection of missing galaxies at high redshift, as well as for what the correlation of SB with other parameters means for the origin of the changes in observed intrinsic SB.

5.1. Surface Brightness Evolution

The observed SB evolution for both the mass-selected and number-density-selected samples decreases with time by $0.7 \pm 1.5$ mag arcsec$^{-2}$ with evolution of the form $(1+z)^{-0.03 \pm 0.01}$ for the mass-selected sample and decreases by $1.2 \pm 1.4$ mag arcsec$^{-2}$ with evolution of the form $(1+z)^{-0.04 \pm 0.01}$ for the number-density-selected sample. This suggests that the observed SB remains almost constant with a slight decrease at low redshifts, which is certainly due to the more sensitive optical filters on HST.

However, that is the observed SB evolution, and what we really want to study and understand is the intrinsic evolution of SB once it has been corrected for redshift effects, what we call the intrinsic SB, $\mu_{\text{int}}$. The change in the mean $\mu_{\text{int}}$ from $z = 6$ to $z = 1$ for the mass-selected sample is $4.7 \pm 1.5$ mag arcsec$^{-2}$. The intrinsic SB evolution of the number-density-selected sample changes by $5.0 \pm 1.4$ mag arcsec$^{-2}$ over the same range. This is a very large change in SB over this redshift range, where $\mu_{\text{int}}$ decreases by $0.5 - 0.7$ mag arcsec$^{-2}$ per redshift interval.

This is consistent with previous studies using both ground-based and HST observations that find an evolution of 1–2 mag between $z = 0$ and $z = 1$ (e.g., Schade et al. 1996; Lilly et al. 1998; Labbé et al. 2003; Barden et al. 2005), but now extended to much higher redshifts. This change in intrinsic SB is likely due to the fading of sources or an intrinsic luminosity difference. The question is, what is producing this change in intrinsic SB evolution, and what does it imply for our detectability for distant galaxies? To answer this, we consider the effects of size, dust, star formation, and detection limits in order to understand these issues.

5.1.1. Effects of UV Luminosity Evolution

As we are examining the evolution of the UV luminosity SB, one area where we must first try to understand the evolution of the SB is within the UV luminosity itself. As explained in Section 4.3, we are able to trace the evolution of this UV luminosity function and, more importantly, the value of $M^*_{\text{UV}}$ and how it evolves with time. Although the total SFR decreases at $z > 2$ overall per unit volume, the UV flux of individual galaxies increases, as characterized by the UV luminosity function. Using these data, we know that the $z = 2$ characteristic magnitude $M^*_{\text{UV}} = -20.33 \pm 0.50$ (Arnouts et al. 2005), and at higher redshifts this becomes brighter to $-20.94 \pm 0.20$ (Bouwens et al. 2015), as discussed in Section 3.5. Thus, a representative amount of evolution is for galaxies to become fainter, on average, by about 0.61 mag over this epoch. This is certainly much less than the 4–5 mag of observed SB evolution. Therefore, the intrinsic SB evolution cannot be accounted for solely or even primarily by an evolution in UV flux.

5.1.2. Size Corrections

The size evolution of galaxies is well documented (e.g., Trujillo et al. 2007; Buitrago et al. 2008; van Dokkum et al. 2008; Cassata et al. 2010; Whitney et al. 2019). Because galaxies evolve in size to become larger at lower redshifts, this will in principle act to decrease the SB of galaxies. Thus, we test to determine whether this observed size evolution is

Figure 11. Left: evolution of the logarithm of the SFR density, $\Sigma_{\text{SFR}}$, for the mass-selected sample. Individual points are shown as gray circles. The orange circles show the mean $\Sigma_{\text{SFR}}$ for each redshift bin. The error bars on these points are given as 1σ from the mean. Right: evolution of the logarithm of the SFR density for the number-density-selected sample. Green circles show the mean SFR density for each redshift. The error bars on these points are given as 1σ from the mean.
causing an "artificial" evolution in the SB. To determine this, we correct both the observed and intrinsic SB values by setting the size of all galaxies to that of the median size at $z = 6$ as measured in Whitney et al. (2019). In all cases (for both samples and for both measures), we find that the fit to the evolution becomes less steep, and the change in intrinsic SB decreases from $\Delta \mu_{1-6} = 4.7 \pm 1.5$ mag arcsec$^{-2}$ to $\Delta \mu_{1-6} = 3.5 \pm 1.8$ mag arcsec$^{-2}$ for the mass-selected sample and decreases from $\Delta \mu_{1-6} = 5.0 \pm 1.4$ mag arcsec$^{-2}$ to $\Delta \mu_{1-6} = 3.9 \pm 1.9$ mag arcsec$^{-2}$ for the number-density-selected sample. Therefore, the value of mag arcsec$^{-2}$ changes by $\sim 1$ mag arcsec$^{-2}$ for both samples. This suggests that while

\begin{figure}[h]
\centering
\includegraphics[width=\textwidth]{mass_selected.png}
\includegraphics[width=\textwidth]{number_density_selected.png}
\caption{Top: SFR vs. intrinsic SB for the mass-selected sample. Bottom: SFR vs. intrinsic SB for the number-density-selected sample. Each redshift bin is given as a separate panel, and a straight line fit (dashed line) to the fits is given for each. The final panels give the evolution of the slope of these fits. The error bars on these points are 1σ from the mean. For the mass-selected sample, the slope of the fits for each redshift bin gets steeper with time, on average, suggesting that the dependence of SB on SFR gets stronger with time. For the number-density-selected sample, the slope remains roughly constant with time, suggesting that, for this sample, there is little dependence on the relationship between SFR and SB with time.
}
\end{figure}
the size evolution is causing some of the evolution we see in the SB, it is not the primary cause. When we account for the size and luminosity evolution, this still leaves ~3.5 mag of SB unaccounted for that must be due to other effects.

By correcting the SB using Equation (12), we are effectively examining the absolute magnitude at a fixed size. Ultimately, we find that there is a small difference between the size-corrected and uncorrected SB evolution, indicating that the effect of size evolution and SB evolution on incompleteness is small. If the SB were the main contributor to the incompleteness, low-SB galaxies would be outnumbered by high-SB galaxies. Our results seem to indicate that this is not what is happening. Instead, our findings seem to be a result of the intrinsic faintness of the rest-frame UV magnitudes of all galaxies, including massive systems.
5.2. Effects of Dust

Here we explore the possibility of dust extinction producing an apparent decrease in the SB from $z = 6$ to $z = 1$. In this work we use the UV rest frame, and as such, the light is significantly affected by dust attenuation.

We calculate the estimated dust extinction using the relation between dust extinction and the UV-continuum slope $\beta$ from Meurer et al. (1999):

$$A_{1600} = 4.43 + 1.99\beta,$$  \hspace{1cm} (14)

where $A_{1600}$ is the dust extinction at the rest-frame wavelength $\lambda = 1600$ Å. In the case where this relation implies a negative extinction, $A_{1600}$ is assumed to be 0. Typically, higher-redshift objects are found to have bluer UV-continuum slopes than lower-redshift objects, implying the presence of younger stellar populations and lower metallicities in higher-redshift objects (Wilkins et al. 2013). A smaller value of $\beta$ therefore suggests that there is less dust extinction at high $z$ (Meurer et al. 1999; Lehnert & Bremer 2003; Bouwens et al. 2009). This implies that as dust grows in importance with time it will have more of an effect on the measured UV luminosity, which will therefore also produce a change in the SB of the galaxies.

To determine the effect of this, we consider the measured extinction for $z \geq 3$ galaxies owing to the fact that the $\beta$ is a measure of evolved populations, and as such, the high values of $\beta$ measured at low redshift are artificially inflated by the abundance of early-type galaxies. We find that for the mass-selected sample there is an increase of 0.1 ± 3.4 mag between $z = 6$ and $z = 3$. When fitting the values of $A_{1600}$ to a straight line, we calculate a best-fit slope of $-0.15 \pm 3.4$, so, on average, there is an increase in the extinction, but it is not significant. The value of $A_{1600}$ for the number-density-selected sample increases by 2.6 ± 4.3 mag from $z = 6$ to $z = 3$. The dust extinction therefore plays a small role in the decrease in intrinsic SB, with $\sim -0.1$ mag being accounted for in the mass-selected sample and $\sim 2.6$ mag being accounted for in the number-density-selected sample when considering the redshift range $3 \leq z \leq 6$. After considering size and dust corrections, we are left with $\sim 3.4$ mag arcsec$^{-2}$ of SB evolution unaccounted for within the mass-selected sample and $\sim 1.3$ mag arcsec$^{-2}$ unaccounted for within the number-density-selected sample.

5.3. UV Magnitude Evolution Modeled

We model the apparent magnitude evolution for the redshift range $1 \leq z \leq 6$ for a number of different star formation histories using SMPy,$^6$ (Duncan et al. 2014). The SED is convolved at each redshift, with the filter corresponding to the UV rest-frame wavelength at that redshift. The filters are given in Table 1. We use the same simple stellar population models and initial mass function used when completing the stellar mass fitting as described in Section 2.2. We model the evolution of the rest-frame magnitude using a star formation history given by

$$\text{SFR} \propto e^{-\tau}$$  \hspace{1cm} (15)

and vary the value of $\tau$. The evolution of the magnitude using star formation histories with $\tau = -10$, $-5$, 1, 5, and 10 Gyr is shown in Figure 14, where $\tau = -10$ Gyr is shown as a green dashed line, $\tau = -5$ Gyr is shown as an orange dashed line, $\tau = 1$ Gyr is shown as a red solid line, $\tau = 5$ Gyr is shown as a black dotted line, and $\tau = 10$ Gyr is shown as a blue dashed line. The magnitude values on the y-axis are not representative of the true values; however, the relative change is accurate for all systems.

![Figure 14. Evolution of the apparent magnitude for five different star formation histories. The SED is convolved at each redshift with the filter that corresponds to the UV rest-frame wavelength at that redshift. We use three decreasing star formation histories: $\tau = 1$ Gyr is shown as a solid red line, $\tau = 5$ Gyr is shown as a dotted black line, and $\tau = 10$ Gyr is shown as a dashed blue line. We also show two examples of increasing star formation histories: $\tau = -5$ is shown as a dashed orange line, and $\tau = -10$ is shown as a green dashed line. There is a significant difference between $|\tau| = 1$ Gyr and $|\tau| > 1$ Gyr whereby the UV rest-frame magnitude decreases in brightness from $z = 6$ to $z = 1$ for $\tau = 1$ Gyr but increases in brightness for the other scenarios. The rising star formation histories (negative $\tau$) yield a greater increase in magnitude than for the decreasing star formation histories. These star formation histories all give an evolution in SB that is opposite to what we observe. The magnitude values on the y-axis are not representative of the true values, as this is mass dependent, but the change in magnitude modeled is accurate for all systems.](https://github.com/dunkenj/smpy)
increases with time, as explained in Section 5.2, and also scales with metallicity, so the evolution may be steeper than seen here.

If we assume a star formation history with $\tau = 1$ Gyr, we see a decrease of 1.1 mag from $z = 6$ to $z = 1$, which would partially account for the evolution seen in the SB not already accounted for by size and dust. However, our systems are known to be star-forming over a long period of time, and therefore the $\tau$ value would be larger. If we take the information from empirical measurements of the value of $\tau$ (e.g., Ownsworth et al. 2016), we find that $\tau \sim 2$ -- $5$ Gyr. If we assume that our galaxies have a similar $\tau$, which is the case for systems at these mass ranges at $z < 3$, then we would find that the star formation history would increase the SB by a few magnitudes. This would only exacerbate the problem of understanding the decline of the SB for these galaxies at lower redshifts. We have nonetheless already accounted for the decline in the UV brightness from using the luminosity function changes from $z \sim 6$ to lower redshifts. Thus, we can conclude from this section that the decline in SB we observe in our selections is not due to an evolution in the SFR. If anything, these estimates are the maximum change in the brightness, as the star formation history is known to increase from $z = 6$ to $z = 3$, which would have the effect of only increasing further the brightness of our sample.

5.3.1. Image Simulations—How Many Galaxies Are We Missing?

By artificially redshifting a sample of galaxies, we are able to determine whether the same galaxies we see at low redshift are detectable at high redshift. As a fiducial experiment we simulate the galaxies in our $z = 2$ sample to $z = 6$ and determine how many of these we would detect, at what $S/N$, and at what measured SB, as described in Section 4.3.

When we do this experiment, we find that only $\sim16\%$ of these simulated $z = 2$ galaxies are still detectable when simulated to be at $z = 6$ (at an $S/N > 5$), compared to $94\%$ of the original galaxies at $z = 2$ with an $S/N > 5$, with the remaining $6\%$ of detected galaxies at an $S/N < 5$ down to our magnitude limit. This suggests that we are not detecting a significant number of galaxies at these high redshifts owing to their observed low SB produced by the effects of redshift.

The characteristic luminosity ($L$), as determined from the characteristic magnitudes given by Arnouts et al. (2005) and Bouwens et al. (2015), decreases by a factor of 1.75 from $z = 6$ to $z = 2$. By calculating the equivalent change in luminosity of the redshifted sources using

$$\frac{L_{z=6}}{L_{z=2}} = 10^{0.4 \Delta M},$$

we measure that the intrinsic luminosity of all galaxies artificially redshifted to $z = 6$ is 5.75 times brighter in SB than that of the original galaxies at $z = 2$. Therefore, the evolution we see in the artificially redshifted galaxies is greater than that of the characteristic luminosity. This strongly implies that the galaxies at $z = 2$ are not the descendants of the galaxies at $z = 6$ just by examining how much evolution they would have undergone.

When artificially redshifting the sample of $z = 2$ galaxies, we find that the change in SB, both observed and intrinsic, does not correlate with the change we see in the real galaxies. For the observed SB, we see a decrease in SB of $1.0 \pm 1.9$ mag arcsec$^{-2}$ when comparing the redshifted $z = 6$ galaxies (evolved with the luminosity function correction) to the original $z = 2$ galaxies, as shown in Figure 8. For the real sample, we see an increase in SB of $0.7 \pm 1.1$ mag arcsec$^{-2}$ over the same redshift range. For the intrinsic SB, we see a change of $1.9 \pm 1.5$ mag arcsec$^{-2}$ in the simulated sample, whereas for the real sample, there is a change of $3.5 \pm 1.6$ mag arcsec$^{-2}$ over the same redshift range.

We conclude from this analysis that there are a significant number of missing galaxies at high redshifts that are driving the intrinsic average SB evolution. Because it is only the brightest galaxies we are detecting at $z \sim 6$ owing to our SB limits, this drives up the intrinsic measurement of the average SB. This is true even when examining a mass- or number-density-selected sample. It is thus not simply due to missing lower-mass galaxies. In fact, as our simulations show, we are missing $84\%$ of the $z = 2$ galaxies when they are simulated to $z = 6$ even when we take into account the average increase in magnitude from the UV luminosity function. From this we conclude that there is a significant population of galaxies that remain undetected at these higher redshifts (e.g., Conselice et al. 2016). Most of these galaxies are likely to span our entire mass range and not just be low-mass systems. Therefore, our previously stated mass completeness limit underestimates selection effects.

The density of our detected galaxies (those with $S/N > 5$) at $z = 2$ is measured as $3.2 \times 10^{-3}$ Mpc$^{-3}$. The density of our detected galaxies at $z = 6$ is almost a factor of 10 smaller at $2.5 \times 10^{-4}$ Mpc$^{-3}$. The measured density of the simulated $z = 6$ galaxies (evolved with the luminosity function) is $4.1 \times 10^{-3}$ Mpc$^{-3}$. This is 1.6 times greater than the real $z = 6$ galaxies. This suggests that we are missing a significant number of high-redshift galaxies in the real observations. The fact that there are undetected galaxies at high redshift is consistent with the actual number of galaxies being higher than the number we can actually see (Conselice et al. 2016). Many of these missing galaxies will be lower mass, but a significant fraction will be high-mass systems.

5.4. The Origin of High-SB Galaxies

In this section we discuss how to measure how the SB evolves intrinsically and what this implies for the evolution of galaxies in terms of their SFR and gas densities that produce this star formation. One issue is that it is clear that at the highest redshifts we are only observing galaxies at the highest redshifts with the very highest intrinsic SB levels. These are much higher in SB than galaxies in the nearby universe, and the question is, what is the origin of these systems, and how do they relate to lower-redshift galaxies?

5.4.1. Star Formation Rate Density

For both mass- and number-density-selected samples, we find that, on average, there is a decrease in the SFR density (\(\Sigma_{\text{SFR}}\)) over time. The gas density and fraction are observed to be greater at higher redshifts (Tacconi et al. 2013; González Delgado et al. 2017), which leads to a higher \(\Sigma_{\text{SFR}}\) by extrapolating from the Kennicutt–Schmidt law (Barden et al. 2005; Mosleh et al. 2012). Increased size at low redshift also contributes to the lower \(\Sigma_{\text{SFR}}\) we see at low redshift. However, from the change we see in the SFR over redshift (Figure 11),
this size evolution is unlikely to be a significant cause of the decrease in $\Sigma_{\text{SFR}}$ at lower redshifts. We find a difference in $\Sigma_{\text{SFR}}$ of 1.4 $\pm$ 0.6 $M_\odot$ yr$^{-1}$ kpc$^{-2}$ for the mass-selected sample and a difference of 1.5 $\pm$ 1.0 $M_\odot$ yr$^{-1}$ kpc$^{-2}$ for the number-density-selected sample over the redshift range 1 $< z <$ 6. This suggests that the evolution in luminosity cannot be solely driven by the SFR density. This reinforces our conclusion from the previous argument that there are multiple factors contributing to the origin of the 4–5 mag of evolution in intrinsic SB observed.

5.4.2. Star Formation Rate and Specific Star Formation Rate

As we have shown, the SB of a galaxy depends strongly on the SFR, particularly in the UV. In the case of the mass-selected sample, this relationship appears to grow stronger as time progresses, with galaxies that have a high SFR generally exhibiting a brighter SB. In the case of the number-density-selected sample the slope of the relationship between these quantities remains approximately constant with time, suggesting that there is little dependence on the relationship between SFR and intrinsic SB with time.

The two samples differ in that one contains galaxies that are at the same mass and one contains galaxies of differing mass, depending on the number density requirement, with the lower-redshift bins containing galaxies of a higher mass than the higher-redshift bins. From this, we can infer that the SB of galaxies at high redshift of a given mass depends less on the SFR than galaxies of the same mass at lower redshifts. On the other hand, if we directly track galaxies through time, we infer that the relationship between SFR and SB does not change as the galaxies evolve and grow in mass.

The evolution of the relationship between the sSFR and intrinsic SB is similar to that between the SFR and $\mu_{\text{int}}$, whereby the mass-selected sample shows a stronger dependence between the two at lower redshifts and the number-density-selected sample remains roughly constant with time.

6. Conclusions

We present an analysis of the SB evolution of two separate samples (a mass-selected sample and a number-density-selected sample) of galaxies taken from the GOODS-North and GOODS-South fields of the Cosmic Assembly Near-infrared Deep Extragalactic Legacy Survey. We examine UV rest-frame ($\lambda \sim 2000$ Å) images and find that strong evidence for SB evolution, whereby, on average, galaxies get intrinsically brighter per unit area with time. This is the case for both the mass-selected and number-density-selected samples. The evolution is consistent with the form given by $\propto (1 + z)^{-0.18 \pm 0.01}$ and $\propto (1 + z)^{-0.19 \pm 0.01}$ for each sample, respectively. We explore possible causes of this evolution.

Size evolution is well known, and it is now well quantified, so we test to determine whether this is producing the SB evolution by setting the size of all galaxies to that of the average size of the galaxies at $z = 6$ (Whitney et al. 2019). We find that SB evolution is not significantly changed when accounting for this; thus, the increase in the size of galaxies is not producing an “artificial” SB evolution. We also find that dust extinction is a possible cause of the evolution we see in $\mu_{\text{int}}$, but we find that it plays a small role, contributing 0.1 mag of evolution between $z = 6$ and $z = 3$ for the mass-selected sample and 2.6 mag for the number-density-selected sample over the same redshift range.

We find that the SFR density ($\Sigma_{\text{SFR}}$) decreases with time; however, the change does not completely explain the significant evolution we see in the intrinsic SB. Thus, a large portion of the intrinsic evolution for SB within galaxies is left unexplained. Thus, we are seeing an unnatural evolution in the amount of SB changes, which thus must be due to an observational bias—we are missing high-redshift galaxies in our observations, some of which are likely quite massive systems.

The stellar mass is known to be the cause of differences in galaxy evolution and is a measure of the formation and merging history of a galaxy (Bhatawdekar et al. 2019). We find that the intrinsic SB of galaxies in the mass-selected sample does not rely heavily on the stellar mass; for each redshift bin, the slope of the relationship between the two quantities is very close to zero. This suggests that the stellar mass of a galaxy does not correlate with a galaxy’s SB. It also implies that the selection in the UV at these redshifts does not give mass completeness at any mass, even for the most massive, star-forming galaxies.

To further demonstrate this, we artificially redshift a sample of $z = 2$ galaxies to $z = 6$ to determine the level of SB and what fraction of these would still be detected at the higher redshift. We find that the SB of these redshifted galaxies is much lower than that of the real $z = 6$ galaxies, suggesting that we are not detecting the low-SB galaxies we see at low redshift. This remains true when we consider the amount of evolution in the UV luminosity function when carrying out these simulations.

In the case of the mass-selected sample, the SFR and sSFR of galaxies depend strongly on the SB at low redshift; however, this relationship gets weaker as redshift increases. We find that the relationship between these parameters is approximately constant for the number-density-selected sample, so while there is a dependence on SFR and $\mu_{\text{int}}$, this dependence does not change with time.

Overall, we conclude that the high-SB galaxies we find at high redshift are not perfectly analogous to starburst galaxies seen at lower redshifts. It is also likely that there are many missing galaxies at these redshifts that will be discovered with telescopes that can probe deeper than HST, such as the forthcoming James Webb Space Telescope (JWST). Uncovering these galaxies will require that we obtain fundamentally much deeper imaging, which will be carried out with first-generation imaging with JWST. This may reveal a new population of distant high-redshift galaxies that are not just lower mass, but including lower-SB massive systems. These results may in fact lead us to alter our understanding of galaxy formation and the history of star formation and mass assembly in our universe’s history.

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Appendix

Surface Brightness Dimming Derivation

As explained in Section 3.3, there are five factors of \((1 + z)\) to take into consideration when determining the extent of SB dimming. One term of \((1 + z)\) originates from the energy reduction of a photon. When a photon is emitted, it has a wavelength \(\lambda_1\) and has energy \(E_{\text{emit}}\) given by

\[
E_{\text{emit}} = \frac{hc}{\lambda_{\text{emit}}}. \quad (A1)
\]

We know that observed wavelength, \(\lambda_{\text{obs}}\), is a factor of \((1 + z)\) larger than the emitted wavelength due to redshift; therefore, the observed energy, \(E_{\text{obs}}\), is given by

\[
E_{\text{obs}} = \frac{hc}{\lambda_{\text{emit}}(1 + z)}. \quad (A2)
\]

From this, we can say that the energy is a factor of \((1 + z)\) smaller at the time of observation than at the time of emission, giving the first factor of \((1 + z)\). Another factor is due to time dilation; two photons emitted in the same direction \(\delta t_{\text{emit}}\) are separated by a proper distance \(c \delta t_{\text{emit}}\). At observation, the proper distance is \(c \times \delta t_{\text{emit}}(1 + z)\). The two photons are then detected at a rate of

\[
\delta t_{\text{obs}} = \delta t_{\text{emit}}(1 + z). \quad (A3)
\]

This yields a second factor of \((1 + z)\). The two factors that are due to energy reduction and time dilation are the two factors associated with the luminosity distance \(d_L\). The luminosity distance \(d_L\) is used when determining the flux emitted from an object with luminosity \(L\):

\[
f = \frac{L}{4\pi d_L^2}. \quad (A4)
\]

The luminosity distance is related to the proper distance \(r\) by the relation

\[
d_L = r(1 + z). \quad (A5)
\]

We can therefore express the flux in terms of the luminosity distance as

\[
f = \frac{L}{4\pi r^2(1 + z)^2}. \quad (A6)
\]

The two factors in the denominator are due to the energy and time dilation effects as described above. The third and fourth factors arise from the change in angular size of the object; for an object of diameter \(d\) and angular size \(\theta\), the angular diameter distance is given as

\[
d_\alpha = \frac{d}{\theta}. \quad (A7)
\]

From the Robertson–Walker metric the distance between the two ends of the object can be defined as

\[
ds = a(t_0)S_c(r)\theta, \quad (A8)
\]

where \(a(t_0)\) is the scale factor (equivalent to \((1 + z)^{-1}\)) and \(S_c(r)\) is some function of the proper distance that is dependent on the geometry of the universe. We set the distance \(ds\) to be the diameter of the observed object. Therefore,

\[
d_\alpha = \frac{S_c(r)\delta \theta}{(1 + z)}. \quad (A9)
\]

For a flat universe, \(S_c(r)\) is equal to the proper distance \(r\), so the angular diameter distance is given by

\[
d_\alpha = \frac{r}{(1 + z)}. \quad (A10)
\]

Substituting this into Equation (A6), we see that the flux is reduced by a factor of \((1 + z)^3\) owing to redshift:

\[
f = \frac{L}{4\pi d_L^2(1 + z)^4}. \quad (A11)
\]

The fifth and final factor arises owing to the change in unit bandpass wavelength from emission to detection. A filter has central wavelength \(\lambda\) and width \(\Delta \lambda\). Both the observed central wavelength and the observed bandwidth increase by a factor of \((1 + z)\). For a fixed filter width this results in a reduction of observed flux from a galaxy. The observed bandpass wavelength can therefore be given as

\[
\lambda_{\text{obs}} = \lambda_{\text{emit}}(1 + z) + \Delta \lambda_{\text{emit}}(1 + z). \quad (A12)
\]

From these arguments, we can see that

\[
\mu_{\text{int}} \propto (1 + z)^{-5} \quad (A13)
\]

in units of erg s\(^{-1}\)cm\(^{-2}\) \(\AA\)^\(^{-1}\), or ST magnitudes, where \(\mu_{\text{int}}\) is the intrinsic SB. As shown in Section 3.3,

\[
\mu_{\text{int}} \propto (1 + z)^{-3} \quad (A14)
\]

in units of erg s\(^{-1}\)cm\(^{-2}\) Hz\(^{-1}\), or AB magnitudes, where \(\mu_{\text{int}}\) is the intrinsic SB.

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