UV Spectral Slopes at \( z = 6-9 \) in the Hubble Frontier Fields: Lack of Evidence for Unusual or Population III Stellar Populations

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Abstract

We present new measurements of the UV spectral slope \( \beta \) for galaxies at \( z = 6-9 \) in the Frontier Field cluster MACS J0416.1–2403 and its parallel field to an unprecedented level of low stellar mass. We fit synthetic stellar population models to the observed spectral energy distribution and calculate \( \beta \) by fitting a power law to the best-fit spectrum. With this method, we report the derivation of rest-frame UV colors of galaxies for the Frontier Fields program extending out to \( z = 9 \), probing magnitudes as faint as \( M_{\text{UV}} = -13.5 \) at \( z = 6 \). We find no significant correlation between \( \beta \) and rest-frame UV magnitude \( M_{1500} \) all redshifts, but we do find a strong correlation between \( \beta \) and stellar mass, with lower-mass galaxies exhibiting bluer UV slopes. At \( z = 7 \), the bluest median value of our sample is redder than the previously reported values in the literature, whereas at \( z = 9 \), our bluest data point has a median value of \( \beta = -2.65^{+0.52}_{-0.43} \). Thus, we find no evidence for extreme stellar populations at \( z > 6 \). We also observe a strong correlation between \( \beta \) and star formation rate (SFR), such that galaxies with low SFRs exhibit bluer slopes. Additionally, there exists a star formation main sequence up to \( z = 9 \) with SFRs correlating with stellar mass. All of these relations show that \( \beta \) values correlate with a process that drives both the overall SFR and stellar mass assembly. Furthermore, we observe no trend between \( \beta \) and specific SFR, suggesting that \( \beta \) is getting set by a global process driven by the scale of the galaxy.

Unified Astronomy Thesaurus concepts: High-redshift galaxies (734); Galaxy evolution (594); Galaxy formation (595); Ultraviolet color (1737); Early universe (435)

1. Introduction

At the highest redshifts, where only the rest-frame UV (dominated by emission from the most massive, young, but short-lived hot stars) is currently accessible with high-resolution imaging, one of the few characteristics of the physical properties of galaxies available is the UV color, which is sensitive to star formation, dust, and metallicity. Traditionally, changes in the UV colors are thought to be due to dust absorption. The inspection of dust in the early galaxies can be carried out through the measurement of the UV spectral slope, \( \beta \), such that the UV spectral energy distribution (SED) has the form \( f_{\lambda} \propto \lambda^{-\beta} \) (e.g., Calzetti et al. 1994). It has also been found that these slopes are strongly correlated with dust extinction in galaxies at low redshift (e.g., Meurer et al. 1995, 1997, 1999), as well as at high redshift at \( z \sim 2 \) (e.g., Daddi et al. 2004; Reddy et al. 2012). Therefore, these values can be used to measure dust obscuration or extreme stellar populations at even higher redshifts.

The UV continuum slope \( \beta \) has been extensively studied at high redshift (\( z \gtrsim 2 \); e.g., Bouwens et al. 2009, 2010, 2012, 2014a; Finkelstein et al. 2010; Wilkins et al. 2011, 2016; Finkelstein et al. 2012; Dunlop et al. 2013; Oesch et al. 2013; Kurczynski et al. 2014; Rogers et al. 2014; Jiang et al. 2020). For example, Bouwens et al. (2009) reported a strong evolution in the average values of \( \beta \) from \(-1.5 \) at \( z \sim 2 \) to \(-2.4 \) at \( z \sim 6 \). In their study, they also found that lower-luminosity galaxies appeared to be bluer than higher-luminosity galaxies. Similarly, Wilkins et al. (2011) used single colors to measure the rest-frame UV colors of galaxies at \( 4.7 < z < 7.7 \) and found that the mean UV continuum colors are approximately equal to zero (AB) for their highest-redshift sample. At lower redshift, on the other hand, they found that the mean UV continuum colors of galaxies are redder and, furthermore, that galaxies with higher luminosities are also slightly redder, on average. At \( z \sim 7 \), Bouwens et al. (2010) measured \( \beta \) for their sample of galaxies, finding that the very low luminosity galaxies exhibited UV continuum slopes as steep as \( \beta = -3 \). Finkelstein et al. (2010) also reported similar steep values of \( \beta \) at \( z \sim 6-7 \), albeit with larger uncertainties.

More recently, Jiang et al. (2020) studied six luminous Ly\( \alpha \) emitters (LAEs) at \( z \sim 6 \) and reported very blue UV continuum slopes in a range of \(-3.4 \leq \beta \leq -2.6 \) at \( M_{\text{UV}} < -20 \).

However, these findings are not without controversy. One example of this is that McLure et al. (2011) and Dunlop et al. (2012) found a variance-weighted mean value of \( \beta \sim -2 \) at \( z \sim 7 \) and that \( \beta \) shows no significant trend with either redshift or \( M_{\text{UV}} \). Similarly, using the imaging from the UDF12 campaign with improved filter coverage and depth, Dunlop et al. (2013) calculated the UV colors of galaxies at redshifts \( z > 6.5 \) and reported similar redder colors with an average value of \( \beta \sim -2 \).

In another study, Bouwens et al. (2012) measured UV continuum slopes at \( z \sim 4-7 \) and found that \( \beta \) measurements for faint sources are likely to suffer large biases if the same passbands are used to select the sources as well as to measure \( \beta \). They found that their high-redshift galaxies show a well-defined rest-frame UV color–magnitude (CM) relationship that becomes systematically bluer toward fainter UV luminosities and that the dust extinction is zero at low luminosities and high redshifts. Alternatively, Finkelstein et al. (2012) reported no significant evolution of \( \beta \) for galaxies at all luminosities within the GOODS-South and HUDF09 surveys at \( z = 4-8 \). However, they suggested a significant correlation with stellar mass, such
that more massive galaxies appeared redder. On the other hand, Bouwens et al. (2014a) measured a significant CM relation, with fainter galaxies displaying bluer slopes, such that the relation steepens at \( z = 4–8 \). Wilkins et al. (2016) studied the rest-frame UV colors of four bright galaxies at \( z \sim 10 \) in the GOODS fields and a CLASH source behind the MACS 1149 cluster and reported a measured \( \beta \) of these candidates to be \(-2.1 \pm 0.3\). More recently, Carvajal et al. (2020) stacked the Lyman break galaxies found in the Hubble Frontier Fields (HFF) clusters with the Atacama Large Millimeter/submillimeter Array and reported no trend between \( \beta \) and redshift but a clear trend between stellar mass and \( \beta \) similar to Finkelstein et al. (2012).

Regardless of the varying results, there is now a broad agreement that, at least out to \( z = 6 \), the values of \( \beta \approx -2 \) are measurable for even the faintest galaxies detected with the Hubble Space Telescope (HST), and at high redshift, the dust extinction is significantly less than at lower redshift. However, the numbers of such faint sources are still quite small (\( \sim 30 \) in the HUDF plus its two parallel fields) and only found at \( M_{\text{UV}} < -17 \).

With the use of gravitational lensing, the HFF has propelled the limits of current astronomical facilities until the James Webb Space Telescope (JWST) is launched by boosting the fluxes of the faint galaxies. Therefore, the HFF data can offer the first insights into the rest-frame UV colors of galaxies at \( -17 < M_{\text{UV}} < -13 \). This is particularly exciting because models predict that galaxies with \( \beta \approx -3 \) only exist at \( M_{\text{UV}} > -17 \) (Dunlop et al. 2013). If we detect such blue slopes from the faint HFF galaxies, we will potentially discover the first evidence for unusual stellar populations: very low metallicity, Population III, extreme initial mass function (IMF), or low dust star formation in the early universe.

With the subtraction method that we have developed in Bhatawdekar et al. (2019), we have been able to probe magnitude as faint as \( M_{\text{UV}} = -13.5 \) in the HFF MACS J0416.1–2403 cluster and its parallel field. In this paper, we use these data from the HST imaging along with the Spitzer and VLT data. We note that the 5σ limiting magnitudes for the seven fields and a CLASH source behind the MACS 1149 image, and 174 radius apertures in the IRAC images.

and \( \Omega_\Lambda = 0.7 \) is assumed, and a Chabrier (2003) stellar IMF is used.

## 2. The Data Set

### 2.1. HST Imaging

As a part of the HFF program, MACS J0416.1–2403 (hereafter MACS J0416; R.A. 04:16:08.9, decl. \(-24:04:28.7\)) and its parallel field (R.A. 04:16:33.1, decl. \(-24:06:48.7\)) were observed between 2014 January–February (epoch 1) and 2014 July–September (epoch 2). In this work, we use the drizzled 60 mas pixel-scale v1.0 mosaics along with their rms and weight maps provided on the HFF website\(^4\) by the Space Telescope Science Institute (STScI). We refer the reader to the STScI release documentation\(^5\) for a detailed description of the data release.

The depths of these HST images are calculated with hundreds of 0"2 radius apertures placed in random positions in the images and estimating the fluxes in them. In Table 1, we specify the resulting 5σ limiting magnitudes for the seven bands using our method. We note that the 5σ limiting magnitudes of the cluster are brighter than the field, which is due to the fact that the cluster is overshadowed by the light of bright foreground galaxies (Bhatawdekar et al. 2019).

### 2.2. VLT Imaging

Traditionally, to study the stellar masses and populations of \( z \geq 6 \) galaxies, the best approach is to use Spitzer/IRAC data at \( >3 \mu \text{m} \) in combination with HST imaging and \( K_s \)-band data. To fully exploit the poorer-resolution Spitzer/IRAC data and put tight constraints on redshift measurements, we introduce the longer-wavelength \( K_s \)-band data at \( 2.2 \mu \text{m} \), which help fill the gap between the 1.6 \( \mu \text{m} \) (F160W) band and the 3.6 \( \mu \text{m} \) (IRAC) channel. For this, the fully reduced \( K_s \)-band images made available through the phase 3 infrastructure of the ESO Science Archive Facility (ESO program 092.A-0472; PI: Brammer) are used in this work. For a detailed description of the observations, we refer the reader to Brammer et al. (2016).

The depth of the image is measured by placing hundreds of 0"4 radius apertures in random positions in the image and

### Table 1

| Filter | MACS J0416 Cluster 5σ Depth | MACS J0416 Parallel 5σ Depth | Instrument |
|--------|-----------------------------|-------------------------------|------------|
| F435W  | 28.87                       | 28.91                         | ACS        |
| F606W  | 28.95                       | 29.01                         | ACS        |
| F814W  | 29.35                       | 29.40                         | ACS        |
| F1050W | 29.22                       | 29.30                         | WFC3       |
| F125W  | 28.95                       | 28.92                         | WFC3       |
| F140W  | 28.85                       | 28.93                         | WFC3       |
| F160W  | 28.65                       | 28.75                         | WFC3       |
| Hawk-I | 26.25                       | 26.35                         | HAWK-I     |
| IRAC 3.6 | 25.10                     | 25.16                         | IRAC       |
| IRAC 4.5 | 25.13                     | 25.20                         | IRAC       |

**Note.** The 5σ depths are estimated by placing hundreds of 0"2 radius apertures in random positions in the HST images, 0"4 radius apertures in the HAWK-I image, and 174 radius apertures in the IRAC images.

\(^4\) [http://www.stsci.edu/hst/campaigns/frontier-fields/FF-Data](http://www.stsci.edu/hst/campaigns/frontier-fields/FF-Data)

\(^5\) [https://archive.stsci.edu/pub/hstsp/frontier/](https://archive.stsci.edu/pub/hstsp/frontier/)
estimating the fluxes in them, similar to the HST bands. In Table 1, we list the $5\sigma$ limiting magnitudes for the $K_s$ band.

2.3. Spitzer Imaging

The Spitzer Space Telescope has devoted ~1000 hr of Director’s Discretionary Time to observe the Frontier Fields at 3.6 and 4.5 $\mu$m. As the Balmer break is vital in the estimation of galaxy stellar mass and observed at wavelengths beyond 2.4 $\mu$m at $z > 5$, we include the final reduced mosaics of Spitzer data made available through the IRSA website\(^6\) (Program ID 90258; PI: T. Soifer). In addition to getting robust stellar mass measurements, IRAC data are also crucial to putting better constraints on redshift estimates.

Analogous to HST and the $K_s$-band data, the depth of the Spitzer images is also calculated by placing hundreds of 1″4 apertures in random positions in the images and measuring the fluxes in them. We list the $5\sigma$ limiting magnitudes for both channels in Table 1.

3. Methods

3.1. Subtraction of Massive Galaxies

While the power of gravitational lensing of massive clusters enables us to find and study the faintest galaxies in the universe by providing a magnified boost to light from the background galaxies, in practice, the light of the massive foreground galaxies in clusters makes this process difficult. Thus, it is essential to model and subtract these massive galaxies before doing any further analysis.

For this, we developed a technique that accurately removes the most massive foreground galaxies from the critical lines of the MACS J0416 cluster (as shown in Figure 1), allowing for a deeper detection of the faint background galaxies in the $H$ band (reddest detection band). This is described in detail in Bhatawdekar et al. (2019), but, briefly, we use an iterative process in which we divide the image into small regions with the target bright galaxy in the center along with the small neighboring galaxies. We then use GALAPAGOS (Barden et al. 2012) and GALFIT (Peng et al. 2002) on those rectangular regions to first model the small galaxies before trying to model the massive galaxies. The small galaxies are fitted one at a time with one or more Sérsic (Sersic 1968) components until a reasonable residual is obtained. This process is carried out until all of the small galaxies are fitted accurately, and we are left with the central bright galaxy. The process is then repeated on the central galaxy until we get a good fit, after which we do a massive simultaneous fitting with all of the neighbors. An image is then created with all of these objects subtracted from the original image before moving on to fit the next rectangular patch to repeat the process in iteration. We refer the reader to Bhatawdekar et al. (2019) for the complete details of our subtraction procedure.

3.2. Multiwavelength Photometry, Photometric Redshifts, and Stellar Mass

After subtracting the massive galaxies from the $H$ band of the MACS J0416 cluster, we construct a multiwavelength photometry catalog from 0.4 to 4.5 $\mu$m. The details of how we obtain the photometric measurements are explained in Bhatawdekar et al. (2019), but, briefly, for HST images, SExtractor (Bertin & Arnouts 1996) is used in dual-image mode with the subtracted $H$ band as the detection image and by using the same apertures to execute photometry on the rest of the bands for the MACS J0416 cluster. The same method is applied on the parallel field, except for the subtraction process applied on the cluster.

For photometry on the $K_s$ band and Spitzer imaging, we use the T-PHOT code (Merlin et al. 2015). We refer the reader to Bhatawdekar et al. (2019) for the details of the photometric measurements with T-PHOT. Finally, we construct a catalog of fluxes combining the photometry of HST, VLT, and Spitzer imaging for the MACS J0416 cluster and the parallel field.

After the photometry catalog is constructed, we estimate the photometric redshifts for our multiwavelength photometric

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\(^6\) http://irsa.ipac.caltech.edu/data/SPITZER/Frontier/
measurements using EAZY (Brammer et al. 2008). Dahlen et al. (2013) showed that no specific set of template SEDs or code produces considerably better estimates of photometric redshifts compared to others. But they found that the codes that result in the lowest scatter and outlier fraction typically use a training sample to optimize the photometric redshifts. Therefore, in our work, to calibrate the photometric redshifts, we use the CANDELS data set (Guo et al. 2013) trimmed down to only the filters we have and use those to optimize the EAZY parameters, which are then applied to our data. We then use EAZY and build a sample of galaxies in the redshift range 5.5 \( \leq z \leq 9.5 \) using a sample selection criterion described in detail in Bhatawdekar et al. (2019). Briefly, we use the full redshift probability distribution function (PDF; \( P(z) = \exp(-\chi^2/2) \)) using the \( \chi^2 \) distribution from EAZY and form galaxy samples in four redshift bins centered at \( z = 6, 7, 8, \) and \( 9 \) with \( \Delta z = 1 \) for both the MACS J0416 cluster and the parallel field by applying a set of additional selection criteria as follows:

\[
\int_{z_s}^{z_s+0.5} p(z)dz > 0.4, \\
\int_{z_p}^{z_p+0.5} p(z)dz > 0.6, \\
(\chi^2_{\text{min}}/N_{\text{filters}} - 1) < 3,
\]

where \( z_s = 6, 7, 8, \) and \( 9 \) for the respective bins, and \( z_p \) is the primary redshift peak.

The first criterion ensures that a significant area of the PDF lies within the redshift range of our interest. With the second criterion, we ensure that at least 60\% of the PDF lies near the peak of the distribution, such that the high-redshift solution is the dominant one. The third criterion is to make sure that EAZY provides a reasonable fit. Additionally, we place a signal-to-noise ratio (S/N) cut such that S/N (\( J_{125} \)) > 3.5 and S/N (\( H_{160} \)) > 5.

Following the above selection criteria, we also visually inspect each object to exclude potential contaminants such as stars, stellar diffraction spikes, sources at the edge of the images, sources with flagged photometry, etc. Our final sample contains 134 galaxies: 92 at \( z = 6, 26 \) at \( z = 7, 10 \) at \( z = 8, \) and 8 at \( z = 9.\)

We also compare our estimated photometric redshifts with available spectroscopic redshifts using the published redshift catalog of the MACS J0416 cluster that combines the VIMOS CLASH-VLT campaign (Balestra et al. 2016) and the MUSE spectroscopic study (Caminha et al. 2017). Following Dahlen et al. (2013), we compute \( \Delta z/(1+z_{\text{spec}}) \) (where \( \Delta z = z_{\text{spec}} - z_{\text{phot}} \)) and find that our redshift accuracy is quite good, with a scatter of \( \sigma_{\Delta z}/(1+z_{\text{spec}}) = 0.041. \) This is explained in detail in Bhatawdekar et al. (2019).

Finally, we measure the stellar masses and rest-frame magnitudes for our sample by using a stellar population fitting technique as described in detail in Bhatawdekar et al. (2019). Briefly, the stellar masses and rest-frame magnitudes are calculated using the custom template fitting routine SMpy\(^7\) (Duncan et al. 2014). We first use the single stellar population models of Bruzual & Charlot (2003) to construct synthetic SEDs for a user-defined combination of parameters, such as metallicity, age, and star formation history (SFH), adopting a Chabrier IMF (Chabrier 2003). We allow the ages to vary from 5 Myr up to the age of the universe at the redshift step being fit. We then vary dust attenuation in the range \( 0 \leq A_V \leq 2, \) and metallicities of 0.02, 0.2, and 1 Z\(_\odot\) are used.

Typically, while modeling SEDs, we need to assume some parameterization of the SFH, and this can introduce systematics. Nonparametric SFH reconstruction techniques therefore offer the best prospects of delivering less biased results, but they are computationally expensive and also require data of very high quality with a wide wavelength coverage, high S/N (>50 \AA\), and high spectral resolution to accurately retrieve complex SFHs (e.g., Ocvirk et al. 2006; Tojeiro et al. 2007). Due to these constraints, we choose to characterize the SFH with the widely adopted \( \tau \)-model. Previous work (e.g., Lee et al. 2009) has shown that single-component exponentially decreasing SFHs result in significantly underestimated SFRs, while Maraston et al. (2010) concluded that models with exponentially rising SFHs provide better fits to the observed SFHs of high-redshift galaxies and also produce SFRs consistent with other methods. Thus, the conclusions from these analyses are that the model SFH must be adequately diverse to allow for a broad range in SFH forms. Therefore, while we choose to use the \( \tau \)-model in this work, we incorporate a wide range of SFHs in our work by considering various SFHs; exponentially decreasing, exponentially increasing, as well as constant SFR. To do this, we use the universally assumed parameterization of the SFH (\( SFR \propto e^{-\tau t} \)) with \( \tau = 0.05, 0.25, 0.5, 1, 2.5, 5, 10, -0.25, -0.5, -1, -2.5, -5, -10, \) and 1000 (constant SFR) Gyr. Here negative \( \tau \) values are used to represent exponentially increasing histories.

While recovering complex SFHs with nonparametric methods is outside the scope of this study, it is worth considering whether our choice of \( \tau \)-model with a wide range of SFHs has any influence on the derived stellar masses, as well as SFRs. It is well known that the outshining effect results in underestimated stellar masses when single-component SFH models are used (Papovich et al. 2001). However, as pointed out in Madau & Dickinson (2014), even with complex SFHs, the outshining effect will tend to underestimate the galaxy stellar mass. Nevertheless, at very high redshifts, such as the redshifts probed in this work, the uncertainties due to SFH are reduced simply because the universe is too young, such that even the oldest stars in galaxies must be younger than that. This therefore sets a limit on the \( M/L \) ratio for older stars and their possible contribution to the stellar mass of a galaxy. Additionally, Lee et al. (2010) reported that stellar mass appears to be the most robustly measured parameter irrespective of the assumptions in the SFH. For these reasons, we conclude that our choice of \( \tau \)-model with a wide range of SFHs does not influence the stellar mass estimates in this work. Furthermore, as will be shown in Section 4.5, we find that models with a wide range of SFHs used in our work produce SFRs that are in good agreement with the SFRs estimated with other methods, apart from a few galaxies with very high SFRs (SFR > 100 \( M_\odot/\text{yr} \)).

While analyzing a large sample of Lyman break galaxies, Schaerer & de Barros (2012) reported that the majority of objects were better fit with SEDs that accounted for nebular emission. Other previous studies also found that including nebular emission lines in SED fitting results in considerably younger ages and lower masses (e.g., Schaerer & de Barros 2009, 2010; Ono et al. 2010; McLure et al. 2011; 2012)

\(^7\) https://github.com/duncanj/smypy
We therefore choose to apply nebular emission lines on the model SEDs in this work. We refer the reader to Duncan et al. (2014) for a detailed description of the method employed to include nebular emission lines. We then apply dust extinction using the law described by Calzetti et al. (2000).

Each model SED is then redshifted in the range $0 \leq z \leq 11$ in steps of $\Delta z = 0.02$, and attenuation by neutral hydrogen is applied according to Madau (1995). Lastly, each model spectrum is convolved through the photometric filters, and the following SED grid is fitted to the photometry. For each model, the absolute magnitude at 1500 Å is estimated by fitting a 100 Å wide top-hat filter centered on 1500 Å. With a Bayesian-like approach, the model SEDs are then fitted to the observed photometry, which results in a likelihood distribution of stellar mass and rest-frame magnitudes. Additionally, we calculate the SFRs from the SED fitting code by obtaining the SFR from the best-fitting template for each galaxy.

Finally, for the Frontier Fields program, lensing models were produced by seven independent teams, and we make use of all the models to calculate the median magnification value with which we demagnify the rest-frame magnitudes, stellar masses, and SFRs of our sample in the MACS J0416 cluster.

### 3.3. Calculating UV Spectral Slope $\beta$

Once we have the multiwavelength photometry catalog and the sample of high-redshift galaxies in the redshift range $5.5 \leq z \leq 9.5$, the next step is to estimate the UV spectral slope $\beta$. The UV continuum, approximately between 1250 and 2600 Å, was first parameterized by Calzetti et al. (1994) as a power law of the form $f_{\lambda} \propto \lambda^{-\beta}$ to study the effects of dust extinction in starbursting galaxies. The UV spectral slope $\beta$ was designed to be measured from spectra in the specified wavelength windows defined by Calzetti et al. (1994). However, because continuum spectroscopy is exceptionally challenging at high redshift, $\beta$ is usually determined by three main methods, each with its own advantages and disadvantages.

The first method is by fitting a power law to all of the available photometry redward of the Lyman break to measure $\beta$ (e.g., Bouwens et al. 2014A). A direct fit to the photometry can hence allow for measurements of $\beta$ for faint galaxies that are close to the detection limit. Translating the $f_{\lambda} \propto \lambda^{-\beta}$ relation into magnitude units gives a linear relationship between $\beta$ and colors. Therefore, another way of estimating $\beta$ is via a single color (e.g., Hathi et al. 2008; Dunlop et al. 2012). The third method of calculating $\beta$ is by performing SED fitting (e.g., Finkelstein et al. 2012). In this method, single stellar population models are first constructed by varying parameters such as age, metallicity, SFH, and dust. The best-fit model is then found via $\chi^2$ minimization, and the value of $\beta$ is measured directly from this best-fit spectrum by fitting a power law to the spectrum using the 10 wavelength windows specified by Calzetti et al. (1994). A primary difficulty in determining $\beta$ for faint galaxy populations results from the noisy photometry that makes inferring colors between bands particularly fraught. This method of fitting SED models to the data and using the models to infer $\beta$ has the potential to overcome this issue by using additional information from the rest-frame optical to model the overall spectrum of each galaxy, or at least to ameliorate the effects of filter-to-filter scatter on the inferred $\beta$. The advantage of this method is that because all of the available photometric bands are used, this should, in principle, yield more robust estimates of $\beta$. The disadvantage, however, is that because this method is based on synthetic models, we are confined to a limited range of $\beta$ values allowed by the models. Therefore, this method may not be suitable to the population of objects close to the epoch of first star formation that may have unique spectral features.

In our work, because we have multiple photometric bands, and hence multiple rest-frame UV colors redward of the Lyman break, we choose to use the SED fitting method and follow the procedure described in Finkelstein et al. (2012), who showed with the help of simulations that SED fitting is a superior choice over the other two methods.

To measure $\beta$, we perform SED fitting on our sample of high-redshift galaxies at $z = 6–9$ to find the best-fitting synthetic stellar population models of Bruzual & Charlot (2003). With the help of synthetic SEDs constructed from the single stellar population models of Bruzual & Charlot (2003), explained in Section 3.2, we find the best-fit model via $\chi^2$ minimization and measure the value of $\beta$ directly from this best-fit spectrum by fitting a power law to the spectrum using the 10 wavelength windows specified by Calzetti et al. (1994).

In order to estimate the uncertainty on $\beta$, we perform a Monte Carlo analysis in which we perturb the observed flux of each source by randomly choosing a point from a Gaussian distribution, the standard deviation of which is the 1σ uncertainty on the flux in any given filter. The UV slope $\beta$ for each source is then estimated with the simulated photometry by deriving a best-fit model. This process is repeated 500 times, and the final uncertainty is then taken as the standard deviation of the distribution of these 500 values. While we do a careful subtraction of the foreground cluster galaxies such that there are no oversubtracted residuals (as seen Figure 1), which could lead to noisy photometry, this step ensures that the photometric errors are taken into account while estimating the uncertainty on $\beta$.

As identified by Finkelstein et al. (2012), this SED fitting method has a disadvantage in that we are confined to the limited range of $\beta$ values that are allowed in the chosen model. Therefore, the UV colors of galaxies bluer than the allowed $\beta$ values in a particular model will not be recovered precisely. For our set of models, the bluest value is $\beta = -3.1$, but since we are not finding extreme blue colors, the bluest value we find in our sample is $\beta = -2.82^{+0.65}_{-0.25}$; we are not affected by this limitation, as we are not approaching our limit of bluest parameter space. Similarly, we explore whether the choice of a particular IMF could have any impact on the derived values of $\beta$. To do this, we estimate our $\beta$ values with a Salpeter (1955) IMF in our SED fitting code and find that the choice of IMFs has no affect on the measured values of $\beta$ as long as the model fits the data well. This is ensured by our third selection criterion (see Section 3.2), with which we make sure that EAZY provides a reasonable fit to the data. As pointed out in Finkelstein et al. (2012), this will also be true for the choice of models, as presuming that the model is a good fit to the data, two models with different ages or SFHs will have comparable UV slopes. These results are also consistent with Jerábková et al. (2017), where they computed the UV slope for various IMFs and showed that the $\beta$ values are dominated by the age of the stellar population, and, apart from very early phases...
(<10 Myr), the difference is overall very small, irrespective of the choice of IMFs.

Figure 2 shows the estimated values of the UV slope $\beta$ for each of our high-redshift sources at $z = 6−9$ as a function of $M_{1500}$. As the errors on individual measurements of $\beta$ are large, notably at higher redshifts and fainter magnitudes (see Section 3.4), we follow Finkelstein et al. (2012) and calculate the median values of $\beta$ in three different bins, separated by 25% and 75% of the characteristic magnitude $L^*$ values, using our derived luminosity functions in Bhatawdekar et al. (2019). Regardless of our choice of bins, we do test whether a choice of different bin size could affect our results, and we find that our results are consistent irrespective of the choice of bins.

We perform bootstrap Monte Carlo simulations to calculate the errors on our median values of $\beta$ by accounting for Poisson noise, as well as photometric noise. For this, we take our original sample of galaxies in each luminosity bin and create new simulated samples from them to account for the Poisson noise. We do this by first random sampling with replacement from a normal distribution. To account for the photometric error, we then take this modified sample and remeasure $\beta$, again by random sampling from a normal distribution and taking into account the photometric uncertainty in $\beta$ for each galaxy. This process is repeated $10^4$ times for each luminosity and redshift bin, as well as for all of the galaxies. The final uncertainty is then taken as the standard deviation of these new simulated values of $\beta$.

In Figure 2, we show these median values of $\beta$ with the associated uncertainty with black circles. Similarly, in Table 2, we list the median values of $\beta$ for all of the galaxies in each redshift bin, along with the median values in the three different bins. Additionally, we specify the median $M_{1500}$ values at each redshift.

### 3.4. Goodness of Method

In order to test the level of quality of our method of estimating $\beta$, we construct a simulated catalog of high-redshift galaxies using the Theoretical Astrophysical Observatory (TAO; Bernyk et al. 2016). For this, we use the existing CANDELS mock light cone on the TAO from redshift $z = 0$ to 9 and create SEDs from the single stellar populations of Bruzual & Charlot (2003) with the IMF of Chabrier (2003), similar to our selection efficiency method in Bhatawdekar et al.
(2019). We then apply dust with the dust model of Calzetti et al. (2000) and make the final catalog with an H-band distribution of magnitudes in the range 21 < H_{160} < 35. The magnitudes in the remaining filters are then deduced from the range of H-band magnitudes. We then directly fit this spectrum to get the known input value of \( \beta \).

To generate errors for the simulated photometry catalog, we bin the object fluxes from our real catalog and compute the mean and standard deviation of the error on fluxes in those bins. This provides us with a Gaussian distribution of the errors. We then simulate the photometric errors in the fake catalog by choosing random errors each time from the Gaussian distribution. This simulated catalog is then run through EAZY to get the photometric redshifts.

Lastly, we run the high-redshift sources from the simulated catalog through the same sample selection criteria (see Section 3.2) as our original sample. We then carry out SED fitting on the galaxies that pass the selection criteria to measure \( \beta \), as we did on our real sample. Figure 3 shows the results of these simulations at \( z = 6-9 \), showing the difference between the input value of the UV spectral slope \( \beta \) and that recovered from the SED fitting as a function of input \( H_{160} \) magnitude. The orange circles represent the mean difference between input and recovered values of \( \beta \), as well as the scatter in bins of \( \Delta m = 1 \). As expected, through these simulations, we find that the scatter increases at higher redshifts and faint magnitudes (see Figure 3) but is generally quite good at recovering the correct values of \( \beta \).

### 4. Results

#### 4.1. Correlation between Rest-frame UV Magnitude and UV Colors \( \beta \)

As seen from Figure 2, previous studies investigating the rest-frame UV colors of galaxies at high redshifts were limited to fainter sources at \( M_{UV} < -17 \) (shown by the dashed blue line in Figure 2 in the \( z = 6 \) bin). Our sample allows us, for the first time, to probe a wide range of magnitudes at \( -22 < M_{UV} < -13.5 \) at \( z = 6 \). While there are large uncertainties on sources fainter than \( M_{UV} > -17 \) due to lensing (shown by a representative error bar at the bottom left of each panel in Figure 2), it is clear that we do not find a correlation between rest-frame UV magnitude \( M_{1500} \) and \( \beta \) at \( z = 6 \) (Kendall \( \tau = -0.33 \)). We note that at \( z = 7, 8, \) and 9, the dynamic range in \( M_{UV} \) is reduced. However, the fact that we are finding galaxies as faint as \( M_{UV} = -13.5 \) at \( z = 6 \) strongly implies that we will be able to find these faint UV galaxies at \( z > 6 \) with JWST. Nevertheless, from the current data, there appears to be no correlation between rest-frame UV magnitude \( M_{1500} \) and \( \beta \) at \( z = 7 \) and 9, but there does appear to be some correlation at \( z = 8 \), such that fainter galaxies have bluer values of \( \beta \).

To quantify this, we first check whether our data have a Gaussian distribution. There are a range of normality tests, like the Shapiro–Wilk or Anderson–Darling test, of the residuals that can tell whether the data are unlikely to have come from a normal distribution. However, if the test is not significant, that does not necessarily mean that the data came from a normal distribution, or vice versa. It could also mean that we just do not have enough power to see the difference. Larger sample sizes give more power to detect the nonnormality. For small sample sizes such as ours, quantile–quantile (Q-Q) plots can be good diagnostics. Thus, we use Q-Q plots to check for skewness, and as there was not too much observed skewness in our data, we choose to fit a first-order polynomial through the median data points at each redshift to estimate the slope and its associated uncertainty. The values of the slope along with its uncertainty are listed in Table 2. Although there may appear some correlation at \( z = 8 \), from Table 2, we conclude that there is no significant correlation \(( < 2\sigma )\) between rest-frame UV magnitude \( M_{1500} \) and \( \beta \) at all redshifts probed in this study. We also test whether the choice of IMFs has any effect on the estimated rest-frame UV magnitudes and thus the relation between \( \beta \) and \( M_{1500} \). We test this at \( z = 6 \), where the measurement is easiest, and find that the rest-frame UV magnitudes get slightly fainter when using a Salpeter IMF. This is consistent with Jefábková et al. (2017), who compared different fluxes with variable IMFs. Our results are understandable, as Salpeter would produce a relative overabundance of low-mass stars and, consequently, an underabundance of high-mass stars in comparison to Kroupa/Chabrier if the systems have the same total stellar mass. However, we find that the difference between the rest-frame UV magnitudes with Chabrier and Salpeter is very small \(( < 0.15 \) and therefore does not affect the \( \beta^{-M_{UV}} \) relation in this work. The difference in magnitudes likely will be more pronounced when the most massive stars are still alive (i.e., in the first few megayears).

At \( z = 6 \), our results are in agreement with Dunlop et al. (2012) and Finkelstein et al. (2012) but in disagreement with Wilkins et al. (2011), who used near-infrared (near-IR) imaging to measure the rest-frame UV continuum colors of galaxies at \( 4.7 < z < 7.7 \) using a single-color technique and found lower-luminosity galaxies to be bluer than higher-luminosity galaxies. Our results are also in disagreement with Bouwens et al. (2012), who determined the UV continuum slopes at \( z \sim 4-7 \) by fitting a power law to the observed photometry and reported a well-defined rest-frame UV CM relationship that becomes systematically bluer toward fainter UV luminosities. Similarly,

### Table 2

| \( z \) | Median \( \beta \) All Galaxies | Median \( \beta \) \( L > 0.75 L^* \) | Median \( \beta \) \( 0.25 L^* < L < 0.75 L^* \) | Median \( \beta \) \( L < 0.25 L^* \) | \( \beta^{-M_{1500}} \) Slope All Galaxies | Median \( M_{1500} \) |
|---|---|---|---|---|---|---|
| 6 | \(-2.25^{+0.08}_{-0.12}\) | \(-2.18^{+0.16}_{-0.15}\) | \(-2.53^{+0.17}_{-0.15}\) | \(-2.26^{+0.21}_{-0.17}\) | \(-0.01 \pm 0.06\) | \(-17.96\) |
| 7 | \(-2.31^{+0.21}_{-0.16}\) | \(-1.92^{+0.20}_{-0.19}\) | \(-2.26^{+0.24}_{-0.20}\) | \(-2.32^{+0.25}_{-0.23}\) | \(-0.11 \pm 0.07\) | \(-18.53\) |
| 8 | \(-2.41^{+0.26}_{-0.25}\) | \(-2.10^{+0.34}_{-0.30}\) | \(-2.26^{+0.43}_{-0.22}\) | \(-2.51^{+0.45}_{-0.29}\) | \(-0.13 \pm 0.07\) | \(-18.77\) |
| 9 | \(-2.51^{+0.32}_{-0.20}\) | \(-2.13^{+0.45}_{-0.42}\) | \(-2.63^{+0.43}_{-0.31}\) | \(-2.51^{+0.68}_{-0.56}\) | \(-0.19 \pm 0.11\) | \(-19.44\) |

Note. Column (1) lists the redshifts. Column (2) lists the median \( \beta \) values for all galaxies in each redshift bin. Columns (3)–(5) list the median values of \( \beta \) in three different bins, separated by 25% and 75% of the characteristic magnitude \( L^* \) values, using our derived luminosity functions in Bhatawdekar et al. (2019). Column (6) lists the values of the fitted slope and its associated uncertainty, and Column (7) lists the median \( M_{1500} \) values for all galaxies in each redshift bin.
more recently, Bouwens et al. (2014a) found a significant CM relation, such that fainter galaxies displayed bluer slopes, with the relation steepening at $z = 4–8$, and our results are in disagreement with them.

In a similar way, at $z = 7$, our results are in agreement with Dunlop et al. (2012, 2013) and Finkelstein et al. (2012), who did not find a significant correlation between rest-frame UV and UV colors, but in disagreement with Wilkins et al. (2011) and Bouwens et al. (2012, 2014a), who reported a significant CM relation. Finally, at $z = 8$, our results are in agreement with Finkelstein et al. (2012) and Dunlop et al. (2013) but in disagreement with Bouwens et al. (2014a), who found that fainter galaxies have bluer slopes.

As stated earlier, we follow the method of Finkelstein et al. (2012) and derive our UV slopes using an SED fitting method and also measure $M_{UV}$ by fitting a 100 Å wide top-hat filter centered on 1500 Å (see Section 3.3). As pointed out in Finkelstein et al. (2012), the way we measure $M_{UV}$ may have an effect on whether any correlation between $\beta$ and $M_{UV}$ is observed. For example, Bouwens et al. (2012) probed different parts of the rest-frame UV depending on the redshift and observed a correlation between $\beta$ and $M_{UV}$. Following the method of Bouwens et al. (2012), Finkelstein et al. (2012) were able to recover a correlation between $M_{UV}$ and $\beta$, albeit not as strong as that of Bouwens et al. (2012). Similarly, Finkelstein et al. (2012) also found a CM relation when they used a single color to derive $\beta$ and therefore argued that these factors may affect whether a trend may or may not be observed. Thus, these factors could likely be the reason for the observed disagreement between our results and other studies.

However, while in this study, we choose to use the SED fitting method to derive $\beta$, we test whether deriving $\beta$ with and without the longer-wavelength data has any effect on the estimated values of $\beta$. This test is motivated by the fact that while Finkelstein et al. (2012) showed, with the help of simulations, that SED fitting is a superior choice over the power-law and single-color methods, they reported error bars in excess of unity on $\beta$, as they were affected by the lack of VLT or Spitzer data. Therefore, since we use all of the photometric bands, including VLT and Spitzer, in our SED fitting in this work, it is worth checking if these bands indeed have any effect on the estimated values of $\beta$. We explore two scenarios in this case.

1. Deriving $\beta$ when sources are detected in VLT or Spitzer.

In this case, we find that if there are detections in longer wavelengths, and if these data are being used in the SED fitting to derive $\beta$, it invariably leads to better estimates of $\beta$, such that the $\beta$ values are redder with smaller error bars. We find that the error bars are indeed $\geq$unity when we do not include the longer-wavelength data. However, the error bars are reduced by as much as 50% when

Figure 3. Results of our simulations at $z = 6–9$, showing the difference between the input value of the UV spectral slope $\beta$ and that recovered from SED fitting as a function of input $H_{160}$ magnitude. The orange circles represent the mean difference between input and recovered values of $\beta$, as well as the scatter in bins of $\Delta m = 1$.
longer-wavelength information is included. This is shown by red circles in Figure 4, clearly demonstrating that the estimated values of $\beta$ for sources that are detected in longer wavelengths are redder with smaller uncertainties when the colors are estimated with the inclusion of longer-wavelength data.

2. Deriving $\beta$ when sources are not detected in VLT or Spitzer. It can be argued that using the longer-wavelength data would be useful only if there is actually some useful information present in the data (i.e., if sources are detected in them) to constrain the best-fitting SED. We therefore test this for our sample of galaxies that are not detected in longer wavelengths by still including this information in our SED fitting. We find that in this case, the estimated values of $\beta$ are also redder (albeit not as red as if they had been detected in VLT or Spitzer), but their error bars are reduced by as much as 35%. This is shown by the black circles in Figure 4, showing that the estimated $\beta$ values are slightly redder, with smaller uncertainties, when colors are measured with longer wavelengths.

This shows that while it is important to have real detections in longer wavelengths to notice significant improvement in the estimated values of $\beta$ and their uncertainties, we can still derive better estimates of $\beta$ values with reduced uncertainties even if sources are not detected in longer wavelengths but the information is still being used in SED fitting.

We also caution that care has to be taken when there are no detections in the longer wavelengths but this information is still being used. We find that in such cases, this can lead to biased bluer values of $\beta$ if the photometric measurements are unreliable. For example, as identified in Bhatawdekar et al. (2019), when doing photometry with T-PHOT on clusters, if the bright sources are near the faint sources, then the photometry of the nearby faint sources is affected by the residuals of the bright sources. In such cases, the recovered S/N from T-PHOT is significantly high or significantly negative even if the sources are not present in the longer-wavelength channels, suggesting that their photometry is unreliable. We find that if photometric measurements of such contaminated sources are used, they not only cause some unfortunate high-$\beta$ solutions (as noted in Bhatawdekar et al. 2019), but the derived $\beta$ values of such sources will also be biased blue. We therefore carefully inspect the photometric measurements of such sources, and our final sample consists of only those sources whose photometric measurements are reliable, leading to more robust estimates of $\beta$.

4.2. Correlation between $\beta$ and Redshift

From Figure 2, we find that there is no significant correlation of $\beta$ with UV luminosity. We now therefore examine whether there is any evolution of $\beta$ with redshift by plotting the median $\beta$ values of all galaxies as a function of redshift. To do this, we first interpolate the results from previous literature at the median value of $M_{1500}$ for our sample, except for the $z = 9$ result of Dunlop et al. (2013) shown at $M_{1500} = -18$. The blue dashed line suggests the expected colors if the galaxies had stars with very low metallicities ($\sim 10^{-2} Z_{\odot}$).

![Figure 5](image-url)  
**Figure 5.** Evolution of the median $\beta$ of all galaxies with redshift, shown by yellow circles, and the mean $\beta$ of all galaxies at a magnitude cut of $M_{1500} = -18$, shown by red pentagons. The median $M_{1500}$ for these points are $-17.96, -18.53, -18.77,$ and $-19.44$ at $z = 6, 7, 8,$ and $9$, respectively. Also shown are the results from the literature interpolated at the median value of $M_{1500}$ for our sample, except for the $z = 9$ result of Dunlop et al. (2013) shown at $M_{1500} = -18$. The blue dashed line suggests the expected colors if the galaxies had stars with very low metallicities ($\sim 10^{-2} Z_{\odot}$).
value of $\beta = -2.05 \pm 0.1$ at all redshifts. Our $\beta$ values are bluer than theirs at all redshifts. We note that they apply stringent selection criteria and restrict their sample to contain objects that have at least one $8\sigma$ near-IR detection in the WFC3/IR data, which may have excluded many of the faint galaxies, causing $\beta$ to have a redder value. We therefore test this by applying the same cut on our sample and find that our $\beta$ changes from $\beta = -2.20^{+0.10}_{-0.10}$ at $z \sim 6$ to $\beta = -2.51^{+0.30}_{-0.21}$ at $z \sim 9$ when we restrict our sample with the same criteria as Dunlop et al. (2012). With these results, we conclude that applying stringent criteria does not cause $\beta$ to have a redder value. Similarly, our results are also not in agreement with Dunlop et al. (2013), who used the imaging from the UDF12 campaign to calculate the UV colors of galaxies at redshifts $z > 6.5$ and reported an average value of $\beta = -2.1 \pm 0.2$, $-1.9 \pm 0.3$, and $-1.8 \pm 0.6$ at $z \sim 7$, 8, and 9, respectively.

At $z \sim 6$, our $\beta$ values are bluer than those of Wilkins et al. (2011), Dunlop et al. (2012), and Finkelstein et al. (2012) but redder than those of Bouwens et al. (2012). Comparing at $z \sim 7$, our estimated UV slopes are redder than those of Finkelstein et al. (2010, 2012), Bouwens et al. (2012), and Wilkins et al. (2011) but bluer than those of Dunlop et al. (2012, 2013) and Bouwens et al. (2014a). At $z = 8$, our $\beta$ values are bluer than those of Finkelstein et al. (2012), Dunlop et al. (2013), and Bouwens et al. (2014b), and finally, at $z \sim 9$, our UV slopes are bluer than those of Dunlop et al. (2013). As stated in Section 4.1, these differing results are likely due to our use of all of the photometric bands, including data from VLT and Spitzer, yielding more robust estimates of $\beta$. In Figure 5, the blue dashed line suggests the expected colors if galaxies had stars with very low metallicities ($\sim 10^{-2} Z_{\odot}$). Although our estimated value of $\beta$ has large uncertainties at $z \sim 9$, our results show that the UV colors of galaxies at the highest redshifts probed with HFF are not blue enough to have stars with very low metallicities, and only JWST will be able to provide a clear picture of this by probing higher redshifts and deeper magnitudes.

4.3. $\beta$ of Faintest Galaxies

In this subsection, we compare the $\beta$ values for the faintest galaxies, as these are the systems that are thought to have unusual spectra or are responsible for reionizing the universe. At $z \sim 7$, Bouwens et al. (2010) measured $\beta$ for their sample of galaxies, finding that the very low luminosity galaxies exhibited UV continuum slopes as steep as $\beta = -3$, and argued the likelihood of the presence of extremely metal-poor stars or a top-heavy IMF in these galaxies, supporting that such exotic populations might be crucial to yielding such blue values. Finkelstein et al. (2010) also reported similar steep values of $\beta$ at $z \sim 6$ to $7$ by examining the same data set, albeit with larger uncertainties, and therefore concluded that exotic populations were not necessary for such bluer values of the UV slope $\beta$. Furthermore, with the help of simulations, Dunlop et al. (2012) showed that there is a bias toward artificially blue slopes for faint galaxies and argued that the very blue colors are likely overestimated. To look into this in more detail, with the help of an improved data set and with the SED fitting method, Finkelstein et al. (2012) reexamined this and reported a value of $\beta = -2.68^{+0.39}_{-0.24}$ for faint galaxies at $z \sim 7$, redder than their previously reported results. Similarly, more recently, Bouwens et al. (2014a) measured the UV continuum slopes of their sample of galaxies at $z = 4$–$8$ and reported that their $\beta$ values are redder than their previously reported values ($\beta = -2.42 \pm 0.28$ at $z = 7$).

In this work, we employ the SED fitting method similar to Finkelstein et al. (2012) but also use all of the photometric bands, including data from VLT and Spitzer, to derive more robust values of UV slopes for our sample of galaxies. As shown in Table 2, at $z \sim 7$, the bluest value of our sample is $\beta = -2.32^{+0.30}_{-0.23}$ which is redder than Finkelstein et al. (2012) and Bouwens et al. (2010, 2014b). Similarly, at $z \sim 9$, we find that our bluest data point has a value of $\beta = -2.63^{+0.52}_{-0.43}$ at $z \sim 9$ (see Table 2), finding no evidence as for yet for unusual or Population III stellar populations (with values $\beta \leq -3$) at $z > 6$ with HFF.

4.4. Correlation of $\beta$ with Stellar Mass

In Section 4.1, we determined that there is no strong correlation of $\beta$ with UV luminosity. In this section, we therefore proceed to determine whether there is any trend between $\beta$ and stellar mass. To do this, we use the wide dynamic range in stellar masses $(10^{6.8} – 10^{10} M_{\odot})$ estimated for our sample of high-redshift galaxies at $z = 6$–$9$ from Bhatawdekar et al. (2019) and plot $\beta$ as a function of redshift, as shown in Figure 6. Here we compute the median values of $\beta$ in different mass bins of $6 < \log M/M_{\odot} < 7$, $7 < \log M/M_{\odot} < 8$, $8 < \log M/M_{\odot} < 9$, $9 < \log M/M_{\odot} < 10$, and $10 < \log M/M_{\odot} < 11$, similar to Finkelstein et al. (2012). The median values of $\beta$ are as listed in Table 3 along with the associated uncertainties, which were estimated by bootstrap simulations described in Section 3.3.

As seen in Figure 6, our sample allows us to probe a wide range of stellar masses at $z = 6$, and a strong correlation between $\beta$ and stellar mass is apparent at this redshift, such that lower-mass galaxies exhibit bluer UV slopes. At $z = 7$, 8, and 9, although the dynamic range in stellar mass is reduced, the current data show a correlation between $\beta$ and stellar mass.

To quantify this, we fit a first-order polynomial through the median data points at each redshift to estimate the slope and its associated uncertainty. The best-fit line at each redshift—except $z = 8$, since there is only one median data point—is shown Figure 6, and the values of the slope along with its uncertainty are listed in Table 3. We also show the best-fit lines of Finkelstein et al. (2012) in Figure 6 for comparison. As seen from Table 3, we find a $>5\sigma$ significance dependence between $\beta$ and stellar mass at $z = 6$ and 7 and a $>2\sigma$ significance at $z = 9$. We also check whether the choice of IMFs has any effect on the observed correlation between $\beta$ and stellar mass. To do this, we use the Salpeter IMF to reestimate our $\beta$ values at $z = 6$ and find that, as expected, the stellar masses are higher by 0.24 dex. This is understandable because, for a given total mass of a stellar system, the rest-frame magnitudes would get fainter for a Salpeter IMF relative to Chabrier/Kroupa. However, if we observe a system with a given UV luminosity, that is, with observationally fixed high-mass stellar content dominating the UV emission, the inferred SFR and stellar mass of this system would be higher when using a Salpeter IMF. This is because, for the same number of high-mass stars, Salpeter contains a larger number of low-mass stars, which then inflates the total stellar mass and thus also the SFR relative to Chabrier/Kroupa. Therefore, with a Salpeter IMF, our $\beta$–stellar mass correlation slope changes slightly from $0.34 \pm 0.05$ at $z = 6$ to $0.32 \pm 0.05$.

To check if our observed $\beta$ and stellar mass relation is affected by incompleteness, we calculate the ratio of the
number of recovered galaxies to the number of input galaxies from our simulations performed in Section 3.4. The estimated 20% completeness level is shown in Figure 6 with a red curve. For comparison, we also show the completeness curves derived by Finkelstein et al. (2012) in purple. Inspecting the plot, it appears that we would have discovered red low-mass galaxies \((-2.0 < \beta < -1.5\) and \(7.5 < \log M/M_\odot < 8.5\)) if they were present; therefore, we conclude that our stellar mass–\(\beta\) relation is true.

To investigate this further, we once again plot \(\beta\) as a function of redshift by splitting our sample into the same mass bins, \(6 < \log M/M_\odot < 7\), \(7 < \log M/M_\odot < 8\), \(8 < \log M/M_\odot < 9\), \(9 < \log M/M_\odot < 10\), and \(10 < \log M/M_\odot < 11\), as shown in Figure 7. Examining the plot, it appears that low-mass galaxies at \(\log M/M_\odot < 9\) become bluer with increasing redshift, whereas the massive galaxies at \(\log M/M_\odot > 9\) appear to exhibit approximately constant \(\beta\) at each redshift. Finkelstein et al. (2012) noticed a similar effect and suggested that this is likely because feedback from supernova explosions is driving the dust out of low-mass galaxies, whereas massive galaxies are able to retain this dust due to their higher gravitational potential.

Table 3

| \(\dot{z}\) | Median \(\beta\) | Median \(\beta\) | Median \(\beta\) | Median \(\beta\) | Median \(\beta\) | \(\beta\)-Stellar Mass Slope |
|---|---|---|---|---|---|---|
| 6 | \(-2.77^{+0.22}_{-0.13}\) | \(-2.48^{+0.04}_{-0.11}\) | \(-2.30^{+0.07}_{-0.10}\) | \(-1.97^{+0.18}_{-0.13}\) | \(-1.61^{+0.15}_{-0.11}\) | \(0.34 \pm 0.05\) |
| 7 | \(...\) | \(-2.61^{+0.12}_{-0.05}\) | \(-2.31^{+0.20}_{-0.11}\) | \(-1.92^{+0.18}_{-0.20}\) | \(...\) | \(0.38 \pm 0.06\) |
| 8 | \(...\) | \(...\) | \(-2.41^{+0.17}_{-0.13}\) | \(...\) | \(...\) | \(...\) |
| 9 | \(...\) | \(...\) | \(-2.56^{+0.30}_{-0.09}\) | \(-1.90^{+0.28}_{-0.13}\) | \(...\) | \(1.21 \pm 0.50\) |
and SFR relation. We find that the estimates obtained from the SED fitting code and Kennicutt (1998) equation are in good agreement for all galaxies, apart from a few galaxies with very high SFRs (SFR > 100 \( M_{\odot} \) yr\(^{-1}\)). As seen from Figure 8, we do not find any galaxies with SFR > 100 \( M_{\odot} \) yr\(^{-1}\); therefore, we conclude that our observed SFR-to-\( \beta \) correlation is not affected by the choice methods used for estimating SFRs.

Additionally, we investigate whether any relation exists between \( \beta \) and specific SFR (sSFR = SFR/\( M_{\odot} \)) by plotting \( \beta \) as a function of sSFR. However, no trend is observed at \( z = 6, 7, 8, \) and 9, irrespective of the choice of IMFs. This suggests that whatever is setting \( \beta \) is not a local process but a global one. This might be due to feedback or the halo retaining gas and dust, which otherwise would be ejected by supernovae. These features make it unlikely that a variation of the IMF is what is producing the \( \beta \) values we calculate. Star formation is in itself a local process, and the range and types of stars formed in a star formation event do not vary much, if at all, due to the property of the host galaxy. Because our trends correlate with the entire scale of the galaxy, namely its stellar mass, the processes determining the scale of \( \beta \) must be due to features that scale with this, such as the total halo mass, or dust/metals and not the IMF.

Finally, as an additional check, we also conduct a principal component analysis (PCA) to see what the principal features are among \( \beta, M_{1500} \) stellar mass, and SFR. By carrying out a PCA analysis, we find that in the principal component space, the variance is maximized along principal component 1 (PC1), which explains 54% of the variance, and principal component 2 (PC2), explaining 26% of the variance. Inspecting the absolute values of the eigenvector components in PC1, we observe that the principal features contributing to PC1 are stellar mass, SFR, \( \beta \), and \( M_{1500} \) with values of 0.61, 0.50, 0.45, and 0.40, respectively, confirming that stellar mass is the main principal feature.

### 4.5. Correlation of \( \beta \) with SFR

We now investigate whether there exists any correlation between \( \beta \) and ongoing star formation by plotting \( \beta \) as a function of SFR. To do this, we use the dust-corrected SFRs (further corrected for magnification) from Bhatawdekar et al. (2019) and compute the median values of \( \beta \) of our sample in bins of \(-2.0 < \log \text{SFR} < -1.0, -1.0 < \log \text{SFR} < 0.0, 0.0 < \log \text{SFR} < 1.0, \) and \(1.0 < \log \text{SFR} < 2.0\). This is shown by black circles in Figure 8. Similarly, in Table 4, we list the median values in the mentioned SFR bins along with the associated uncertainties estimated with our bootstrap simulations.

Inspecting Figure 8, there is a reasonably wide range of SFRs at \( z = 6 \) and 7, and there appears to be a strong correlation between \( \beta \) and SFR at these redshifts, such that galaxies with low SFRs exhibit bluer slopes. At \( z = 8 \) and 9, although the dynamic range in SFRs is reduced, a correlation between SFR and \( \beta \) is apparent. To quantify this, we fit a first-order polynomial through the median data points at each redshift to estimate the slope and its associated uncertainty. The best-fit line at each redshift is shown in Figure 8, and the values of the slope along with its uncertainty are listed in Table 4. As seen from Table 4, we find a \( 5\sigma \) significance dependence between \( \beta \) and SFR at \( z = 6, a > 5\sigma \) significance at \( z = 7, \) and a \( > 3\sigma \) significance at \( z = 8 \) and 9. We also check whether the choice of IMFs has any effect on the observed correlation between SFR and \( \beta \) by rederiving our SFR values with a Salpeter IMF at \( z = 6 \). As explained in Section 4.4, the estimated SFRs are higher by 0.24 dex, and this changes the slope from 0.20 ± 0.04 to 0.17 ± 0.04 at \( z = 6 \).

Furthermore, to test whether our SFR-to-\( \beta \) correlation is real and not a result of our applied dust correction to the SFRs, in addition to the dust-corrected SFRs obtained from the Kennicutt (1998) and Meurer et al. (1999) relations, we also use the SFRs obtained from our SED fitting code (see Section 3.2) to see if they have any effect on the observed \( \beta \)
Bauer et al. (2011), and Santini et al. (2017), respectively, for comparison. As seen, our main-sequence relation is in agreement with Lee et al. (2015) and Bauer et al. (2011) at \( z \sim 6 \) but not with Santini et al. (2017). Considering that Santini et al. (2017) estimated their SFRs with the new Kennicutt & Evans (2012) factor, we recalculate our SFRs with this relation to see if this has any effect on the main-sequence comparison. As demonstrated in Kennicutt & Evans (2012), we confirm that the ratio of SFRs derived with the new equation to that with the old Kennicutt (1998) equation is 0.63. These lower SFRs are a result of updated single stellar populations (SSPs) and a different IMF; however, the trend for rising SFRs with increasing stellar mass is unaffected.

Similarly, to examine whether there is any evolution in the main-sequence relation, we extrapolate the Bauer et al. (2011) relation to lower masses and copy it onto the other redshifts as a reference point. It is clear from Figure 9 that there is no evolution in the main-sequence relation from \( z = 6-9 \).

We derive the stellar masses of our sample of galaxies with our SED fitting code (see Bhatawdekar et al. 2019 for more details), which, for objects at these redshifts, in most cases will likely fit SFHs that are effectively constant SFRs. Similarly, the calibration between UV luminosity and SFRs derived by the Kennicutt (1998) equation is also fundamentally based upon the assumption of a constant SFH. Therefore, it is important to investigate whether our observed correlation between stellar masses and SFRs holds at these redshifts.

![Figure 8](image-url)  
*Figure 8. Measured UV slope \( \beta \) vs. SFR at \( z = 6-9 \). The filled yellow circles show the results for individual galaxies, whereas the black circles show the median value of \( \beta \) in each SFR bin of \( 1 M_\odot \) yr\(^{-1} \). The vertical error bars denote the errors on the median estimated with bootstrap Monte Carlo simulations, whereas the horizontal error bars represent the width of the bins. The solid red lines show a linear fit through the median \( \beta \) points. There is a strong correlation between \( \beta \) and SFR, such that galaxies with low SFRs exhibit bluer slopes. The best-fit line at \( z = 6 \) is copied on other redshifts as a reference point, shown by the dashed blue line.*

### Table 4

| \( z \) | Median \( \beta \) | Median \( \beta \) | Median \( \beta \) | Median \( \beta \) | \( \beta \)-SFR Slope |
|-------|----------------|----------------|----------------|----------------|----------------|
| 6     | -2.55±0.11    | -2.31±0.10    | -2.15±0.15    | -2.11±0.25    | 0.20±0.04      |
| 7     | -2.71±0.13    | -2.32±0.17    | -2.05±0.22    | -1.52±0.38    | 0.39±0.06      |
| 8     | ...           | -2.56±0.22    | -2.23±0.28    | ...           | 1.09±0.36      |
| 9     | ...           | ...           | -2.57±0.10    | -1.91±0.18    | 0.85±0.17      |
Thus, to examine whether our choice of SFR estimation method is affecting the observed stellar mass–to–SFR relation, we also use the SFRs obtained from our SED fitting code. As stated in Section 4.5, the estimates obtained from our SED fitting code and the Kennicutt (1998) equation agree well, with the exception of a few galaxies with very high SFRs ($\text{SFR} > 100 M_\odot \text{yr}^{-1}$). As we are not finding any galaxies with SFR $> 100 M_\odot \text{yr}^{-1}$, we conclude that our stellar mass–to–SFR relation remains unaffected, irrespective of the choice of methods.

4.7. Physical Meaning of $\beta$

There are a number of factors that influence the rest-frame UV colors. The UV continuum produced by young and massive but short-lived O and B stars is dependent on the surface temperature, mass, and metallicity of stars. This means that the stellar population continuum will also be dependent on the distribution of the masses (determined by the IMF and SFH) and metallicities. The nebular emission also has an impact on the UV continuum such that a very blue slope suggests that the UV light is not significantly contaminated by a redder nebular continuum (Robertson et al. 2010; Dunlop et al. 2012). Finally, the UV continuum is also affected by the distribution of dust with respect to the galaxies.

For example, since the UV continuum is dependent on its IMF, with massive stars producing bluer slopes, the IMF of a stellar population can likely affect the slope of a composite stellar population. Thus, a top-heavy IMF (with a larger number of massive stars) will produce bluer values of $\beta$.

The UV continuum slope is also affected by the SFH such that with extended periods of star formation, the massive stars will evolve quickly from the main sequence, resulting in a redder slope, while continuous bursts of shorter duration will produce a bluer slope.

Similarly, the overall metallicity will also affect the UV colors such that a higher-metallicity star will generate reduced energy, resulting in a redder slope, and vice versa.

Finally, since the reddening (caused by extinction due to dust grains) of an object is inversely proportional to the wavelength of optical light, the UV continuum is most affected by dust. The shape of the dust attenuation curve, on the other hand, is sensitive to the source dust geometry, grain size distribution, etc. Due to these factors, estimating dust attenuation in external galaxies is much more complicated.

Since the Calzetti attenuation law (Calzetti et al. 1994) is
derived from a sample of nearby starburst galaxies, to what extent it is applicable to other systems at high redshift is debatable.

All of these factors—the IMF, SFH, metallicity and dust—affect the UV slope $\beta$ of stellar populations. Establishing the effects of these factors is challenging, particularly at high redshift. With increased spectral coverage beyond 1.6 $\mu$m, the JWST will provide better constraints on the UV slope $\beta$ for objects at $z > 8$.

5. Summary

In this paper, we investigate the UV spectral slope $\beta$ for a sample of high-redshift galaxies we previously located at $z = 6 - 9$ in the MACS J0416 cluster and its parallel field. With this study, we offer insight into the rest-frame UV colors of galaxies with low SFRs exhibit bluer slopes. It also appears to exhibit a nearly constant $\beta$ values at $z > 6$ with HFF.

1. We find no significant correlation between $\beta$ and rest-frame UV magnitude $M_{1500}$ at all redshifts probed in this work. However, some evidence for a mild evolution of the median $\beta$ values (from $\beta = -2.22^{+0.08}_{-0.12}$ at $z = 6$ to $\beta = -2.52^{+0.32}_{-0.20}$ at $z = 9$) for galaxies at all luminosities from $z = 6 - 9$ is observed, presumably due to rising dust extinction. The average value of $\beta$, however, becomes redder at a upper luminosity cut of $M_{UV} = -18$, suggesting that faint galaxies in our sample are likely causing this apparent evolution.

2. At $z = 7$, the bluest median value of our sample is $\beta = -2.32^{+0.03}_{-0.23}$, which is redder than the previously reported values at this redshift in the literature. Similarly, with the help of our SED fitting method, we find that our bluest data point has a median value of $\beta = -2.63^{+0.52}_{-0.43}$ at $z = 9$, implying no evidence as yet for extreme stellar populations at $z > 6$ with HFF.

3. Fitting for a linear correlation, we find a strong correlation between $\beta$ and stellar mass, such that lower-mass galaxies exhibit bluer UV slopes. It also appears that low-mass galaxies at $\log M/M_\odot < 9$ become bluer with increasing redshift, whereas the massive galaxies at $\log M/M_\odot > 9$ appear to exhibit a nearly constant $\beta$ at each redshift.

4. We investigate the correlation between $\beta$ and SFR and find that there is a strong correlation, such that galaxies with low SFRs exhibit bluer slopes.

5. Examining the relation between $\beta$ and sSFR, we observe no trend between these quantities at $z = 6$, 7, 8, and 9, suggesting that whatever is setting $\beta$ is not a local process but a global one.

6. Finally, we investigate the main-sequence relationship between stellar mass and SFR and find an overall trend for rising SFRs with increasing stellar mass at $z = 6 - 9$. However, more data are needed to confirm the trend at the highest redshifts.

All of these results suggest that even with the deepest HST imaging possible, combined with the power of gravitational lensing, we are still not reaching the first stars and galaxies at $z > 9$. While the sample size of this study is small, and future studies including the complete HFF data set will shed further light on these issues at the highest redshifts we probe in this study, it is clear that galaxy and structure formation predate even this very early redshift. The JWST will certainly provide a clearer picture of this when it examines galaxies at even higher redshifts where, ultimately, Population III stellar populations will be discovered.

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