The 2175 Å dust feature in star-forming galaxies at $1.3 \leq z \leq 1.8$: the dependence on stellar mass and specific star formation rate

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ABSTRACT

We present direct spectroscopic measurements of the broad 2175 Å absorption feature in 505 star-forming Main Sequence galaxies at $1.3 \leq z \leq 1.8$ using individual and stacked spectra from the zCOSMOS-deep survey. Significant 2175 Å excess absorption features of moderate strength are measured, especially in the composite spectra. The excess absorption is well described by a Drude profile. The bump amplitude expressed in units of $k(\lambda) = A(\lambda) / E(B-V)$, relative to the featureless Calzetti et al. (2000) law, has a range $B_k \approx 0.3–0.8$. The bump amplitude decreases with the specific star formation rate (sSFR) while it increases moderately with the stellar mass. However, a comparison with local “starburst” galaxies shows that the high-redshift Main Sequence galaxies have stronger bump features, despite having higher sSFR than the local sample. Plotting the bump strength against the $\Delta \log$ sSFR $\equiv \log(\text{SFR}/\text{SFR}_{\text{MS}})$ relative to the Main Sequence, however, brings the two samples into much better concordance. This may indicate that it is the recent star formation history of the galaxies that determines the bump strength through the destruction of small carbonaceous grains by supernovae and intense radiation fields couple with the time delay of $\sim 1$ Gyr in the appearance of carbon-rich Asymptotic Giant Branch stars.

Keywords: galaxies: evolution, high-redshift — ISM: dust, extinction

1. INTRODUCTION

A broad excess in the extinction curve at a rest wavelength $\lambda_{\text{rest}} \approx 2175$ Å (often called “the ultraviolet (UV) bump”) is the strongest signature of dust in the interstellar medium (ISM). It has attracted attention since its discovery by Stecher (1965) as a unique probe of the nature of dust in galaxies (see Salim & Narayanan 2020 for the latest review). Direct measurements of the extinction curves towards individual stars are limited in our Milky Way (MW) Galaxy and a few very nearby extragalactic objects. The strong UV bump is ubiquitously seen in the extinction curves of stars in the MW (Fitz-
Notable work by Noll et al. (2009b) used a statistical approach, and Battisti et al. (2017) showed that dust attenuation in Lyman Break Galaxies (LBGs) at high redshifts ($z > 2$) is also consistent with that predicted with dust that has SMC-like, rather than MW-like, characteristics. The Calzetti et al. (2000) attenuation curve with no bump feature has thus been commonly assumed for both local and distant star-forming galaxies.

More recent observations, however, have detected and measured the UV bump feature for low- and high-redshift star-forming galaxies based on both photometry and spectroscopy (Noll et al. 2007, 2009b; Buat et al. 2011, 2012; Scoville et al. 2015; Battisti et al. 2017; Salim et al. 2018; Battisti et al. 2020; Shivaei et al. 2020). Notable work by Noll et al. (2009b) used a statistical sample of $\sim 200$ star-forming galaxies at $1 < z < 2.5$ to show that at least 30% of the sources exhibit a significant attenuation bump feature in their spectra and to directly determine the UV bump profiles using stacks. Another approach has been to fit a galaxy’s spectral energy distribution (SED) measured in multiple photometric bands with stellar population synthesis models while applying different attenuation laws in which UV bump features of different strengths are implemented (e.g., Buat et al. 2011; Salim et al. 2018). All these studies, however, have indicated that the strengths of the UV bump feature in $z > 1$ galaxies are typically much weaker than observed in the MW extinction curve, usually of intermediate strength between the LMC2 supershell and the SMC extinction curves, with the latter having no bump at all.

Measurement of the UV bump across a range of redshifts is important for understanding the formation of dust grains through cosmic time. The bump feature is known to be reproduced by resonant absorption by carbon $sp^2$ bonds that efficiently occurs on the surfaces of carbonaceous small grains (grain size $a \lesssim 10 \, \text{nm} \ll \lambda$; Gilra 1971; Draine & Lee 1984; Papoular & Papoular 2009). However, the carrier(s) of the bump feature is still under debate, and other potential species have also been proposed (e.g., Bradley et al. 2005). Regardless of the precise identification of the bump carrier, analysis of the likely evolution of the distribution of grain sizes in a galaxy has succeeded in reproducing the observed extinction curves (e.g., Asano et al. 2013, 2014; Hirashita 2015). This suggests that the bump strength is linked to the relative abundance of small dust grains. The main processes determining the grain size distribution include dust production by stellar sources (see Gall et al. 2011, for a review), grain growth through metal accretion (e.g., Dwek 1998; Inoue 2011), grain destruction in the hot ISM (Dwek & Scalo 1980; McKee 1989), coagulation (e.g., Ormel et al. 2009), shattering (e.g., Yan et al. 2004$^1$), and possible selective removal by galactic winds (e.g., Bekki et al. 2015). The efficiencies of many of these different processes will depend on the properties of the host galaxies. However, our knowledge on the link between the galaxy properties and the UV bump characteristics is currently limited, particularly at high redshifts.

In this work, we directly measure the UV bump profiles for a large sample of star-forming galaxies at $1.3 \leq z \leq 1.8$ and correlate the derived bump strength with the global properties of the galaxies, specifically the stellar mass and star-formation rate (SFR). We utilize the rest-frame UV spectra that have been obtained by the VIsible Multi-Object Spectrograph (VIMOS) mounted on the Very Large Telescope (VLT) UT3 in the zCOSMOS-deep survey (Lilly et al. 2007; Lilly et al., in prep).

The paper is organized as follows. Section 2 presents an overview of the observations and describes the sample selection. Section 3 describes our spectral analysis, including the SED fitting for the sample. The results are presented in Section 4. These are discussed in Section 5, and Section 6 provides a summary of the paper. This paper uses a standard flat cosmology.

$^1$ See e.g., Hirashita (2015) for a brief summary of all these processes on dust in different size regimes.
The redshift range for the current analysis is limited to \(1.3 \leq z \leq 1.8\) to ensure that the spectral window of the VIMOS LR-blue grism covers the rest-frame wavelength interval around the 2175 Å feature. To spectro-photometrically calibrate the spectra, we exclude a handful of targets that are not clearly associated to a source in the COSMOS2015 photometric catalogue (Laigle et al. 2016). Galaxies detected in X-rays are also excluded using column type in the COSMOS2015 catalogue to remove possible AGNs from the sample.

For the majority of the sample, we use the spectroscopic redshift (\(z_{\text{spec}}\)) measurements from zCOSMOS-deep. We use all objects with a very secure zCOSMOS-deep redshift (class=3 or 4) within the selection range. For those with confidence class=2, we use only those that are consistent to within \(|z_{\text{phot}} - z_{\text{spec}}|/(1 + z_{\text{spec}}) \leq 0.1\) of the photometric redshift in the COSMOS2015 catalogue. The redshifts in these two categories are both estimated to be \(\geq 99\%\) reliable (Lilly et al., in prep).

For some sources without reliable zCOSMOS-deep redshifts, we use the \(z_{\text{spec}}\) measurements from the FMOS-COSMOS survey (Silverman et al. 2015; Kashino et al. 2019), which is a near-infrared (IR) spectroscopic survey of star-forming galaxies and covers most of the zCOSMOS-deep survey field. These spectroscopic redshifts are based on the detection of the H\(\alpha\) emission line and some additional rest-frame optical lines (e.g., [N\(\text{II}\)]\(\lambda\)6584, H\(\beta\), and [O\(\text{III}\)]\(\lambda\)5007) in the H- and J-band medium-resolution (\(R \approx 3000\)) spectra. We accepted the FMOS \(z_{\text{spec}}\) measurements if the quality flag (zFlag) is \(\geq 3\) (which corresponds to detecting \(\geq 1\) line at \(\geq 5\sigma\)) and the \(z_{\text{spec}}\) is consistent with \(z_{\text{phot}}\). Figure 1 shows the flow chart of selecting the sample and determining which zCOSMOS-deep or FMOS-COSMOS measurement of \(z_{\text{spec}}\) is adopted.

Finally, we excluded 17 sources for which the UV continuum is barely detected, which suffered from severe spectral contamination, or presented strong broad emission lines.

The final sample consists of 505 galaxies, of which \(z_{\text{spec}}\) comes from the FMOS-COSMOS catalog for 160...
The zCOSMOS-deep spectroscopic catalog is limited to mostly between 1.4 \lesssim z \lesssim 1.7. The median redshift of the entire sample is \langle z \rangle_{med} = 1.556. As shown below in Section 3.3, the galaxies in our sample are typical Main Sequence galaxies in the range of 9.5 \lesssim \log(M_*/M_\odot) \lesssim 11.

2.3. Local sample

Our goal is to measure the excess absorption due to the UV bump with respect to the so-called Calzetti law that is often adopted as a baseline attenuation curve. We thus compiled nearby ((z) = 0.012) starburst galaxies from Calzetti et al. (1994), Calzetti (1997), and Calzetti et al. (2000). The Calzetti et al. series of papers utilized in total 47 local “starburst” galaxies to infer the featureless attenuation curve.\footnote{The sample sizes in three Calzetti et al. (1994, 1997, and 2000) papers are, respectively, 39, 24, and 8. Excluding duplicates, the number of unique starburst galaxies is 47.} For 23 of these, Calzetti et al. (1994) measured the excess absorption in their spectra and showed that the bump feature is, on average, negligible compared to that seen in the MW and LMC extinction laws (see their Figure 13). We will utilize these measurements together with the available reddening E(B − V) measurements (see Table 1 of Calzetti et al. 1994) for comparisons with our own results.

For these local sources we adopted the estimates of the stellar mass (M_*) and SFR inferred from GALEX and WISE photometry by Leroy et al. (2019), which are available for 28 sources. Within the subset of 23 for which the bump strength has been measured, the M_* and SFR estimates are available for 17 out of them. We ignored 13 sources for which neither the bump measurements nor the M_* and SFR estimates are available.

3. METHODOLOGY

In this section, we describe the method used to measure the 2175 Å bump feature in the spectra. We also describe how other galaxy properties are derived. In the following subsections, we will first introduce the formulation of the attenuation curves and the approach to determining the attenuation curve from precisely spectrophotometrically calibrated spectra.

We will then move to analyzing the VIMOS spectra themselves. Every single spectrum is carefully corrected for slit losses in a way that will not introduce artificial effects which may mimic the UV bump. After the correction, we then characterize the shapes of the UV continua of the individual galaxies, and also employ stacking analysis to increase the signal-to-noise ratios and measure precisely the UV bump profiles of aggregates of galaxies. Each step of the analysis is described in detail below.

Figure 1. Flow chart of the sample selection. The consistency with \zpho is examined based on a threshold of |\zpho − \zspec|/(1 + \zspec) \leq 0.1 against the photometric redshift in the COSMOS2015 catalog.

Figure 2. Spectroscopic redshift distribution of our zCOSMOS-deep sample of 505 star-forming galaxies at 1.3 \leq \zspec \leq 1.8. The filled blue histogram indicates the subset (N = 345) for which the zCOSMOS-deep \zspec measurements were adopted, and the orange hatched histogram indicates the additional sources (N = 160) whose \zspec comes from the FMOS-COSMOS catalog.
3.1. Dust attenuation prescription

As usual, we define the attenuation at a given wavelength in magnitudes, \( A(\lambda) \), to be

\[
A(\lambda) = 2.5 \log \left( \frac{f^\text{int}(\lambda)}{f^\text{obs}(\lambda)} \right),
\]

where \( f^\text{int} \) and \( f^\text{obs} \) are the intrinsic flux density (before dust obscuration) and the observed flux density (after dust obscuration), respectively.

The wavelength dependence of dust attenuation is formulated in different ways in the literature (see Salim et al. (2018) for a brief summary). Since the effects of dust are multiplicative, the observed \( A(\lambda) \) is normalised by some measure of the overall amount of extinction present (such as \( E(B - V) \)) to obtain the wavelength-dependence of the extinction, independent of the overall amount of extinction. Throughout the paper, we will refer to \( k(\lambda) \equiv A(\lambda)/E(B - V) \) as an extinction curve if it is measured towards individual stars, and as an attenuation curve if it is for the integrated spectra of galaxies.

In this work, we will assume that the dust attenuation curves \( k(\lambda) \) of high-redshift star-forming galaxies have two components: one with a smooth dependence on wavelength, which is assumed to be common to all sources, and another “excess” component from the UV bump feature at \( \lambda_{\text{rest}} \approx 2175 \, \text{Å} \), whose strength we wish to determine. For the smooth component, we adopt the Calzetti et al. (2000) attenuation curve, \( k_{\text{Cal}}(\lambda) \), and thus denote the observed attenuation curve as a sum of \( k_{\text{Cal}}(\lambda) \) and an excess \( (k_{\text{bump}}(\lambda)) \) due to the UV bump:

\[
k(\lambda) = k_{\text{Cal}}(\lambda) + k_{\text{bump}}(\lambda).
\]

For the bump component, we employ a Drude profile with a parametrization of Fitzpatrick & Massa (1990):

\[
k_{\text{bump}}(\lambda) = c_3 D(x; x_0, \gamma),
\]

\[
D(x; x_0, \gamma) = \frac{x^2}{(x^2 - x_0^2)^2 + x^2 \gamma^2},
\]

where \( x, x_0, \) and \( \gamma \) are expressed in units of inverse wavelength: \( x_0 \) is the inverse of the central wavelength \( (x_0 = \lambda_0^{-1}) \) and \( \gamma \) is the FWHM of the UV bump in \( \lambda^{-1} \) space. The FWHM in wavelength is therefore given as \( w_\lambda \approx \gamma/\lambda_0^2 \). The parameter \( c_3 \) is related to the peak amplitude of the excess, \( B_k \), as \( B_k = c_3/\gamma^2 \), measured from the \( k(\lambda) \) attenuation curve. The fraction of the total absorption at 2175 Å that is due to the bump feature, which is denoted as \( f_{\text{bump}} \), is therefore given by \( f_{\text{bump}} = B_k/(B_k + k_{\text{Cal}}(2175 \, \text{Å})) \), where \( k_{\text{Cal}}(2175 \, \text{Å}) \) is fixed to have a value of 8.48.

Observationally, we require the knowledge of \( E(B - V) \) to derive \( k(\lambda) \), and thus \( k_{\text{bump}}(\lambda) \) and \( B_k \), from the “observed” \( A(\lambda) \). We could instead directly measure the absolute level of the excess absorption, \( A_{\text{bump}}(\lambda) \) in \( A(\lambda) \). We therefore define \( B_A \) as the amplitude of the bump in the observed \( A(\lambda) \). By definition, this means that \( B_A = B_k \times E(B - V) \).

It is important to note that the measurement of \( B_k \) depends on the assumed shape of the baseline smooth attenuation curve over a wide range of wavelengths (i.e., \( k_{\text{Cal}}(\lambda) \) in our case). For a given observed UV continuum, with a certain slope and bump signature, an application of a baseline curve that has a steeper rise towards the far-UV (FUV), such as the SMC extinction curve, will result in a lower estimated \( E(B - V) \), and thus require a higher \( B_k \) to account for the same level of the absolute excess absorption seen in \( A(\lambda) \). On the other hand, the estimate of \( B_A \) does not depend much on the shape of the baseline curve.

Our primary goal is to measure the strength of the UV bump that manifests itself in the attenuation curves, i.e., \( B_k \), as a function of galaxy properties. However, we will also show the corresponding \( B_A \) measurements for reference, as this is the more fundamental observable quantity and largely independent of the assumptions about the shape of the smooth attenuation curve. We will later discuss the effects of possible changes in the overall UV slope of the attenuation curve in Section 5.3.

3.2. SED fitting

In order to measure the UV bump in an individual spectrum, or stack of spectra, we require a model for the underlying “intrinsic” spectrum. Our approach is to determine this model as follows. We first fit the observed photometric SED of the galaxies with a stellar population model including the effects of a featureless attenuation curve, i.e., \( k_{\text{Cal}}(\lambda) \), without any bump feature. This SED fit excludes all the photometric bands in the rest-frame region of the bump feature. If we then compare the observed spectrum with this fitted model SED through the region of the bump, we will be able to detect whether there is any excess absorption relative to the model spectrum, i.e., whether there is any excess absorption that can be attributed to a bump feature in the attenuation law.

One could, of course, have used the excluded photometric bands in the region of the bump for this purpose (Noll et al. 2009a; Buat et al. 2011, 2012) but by using the spectra, a high resolution spectrum of the absorption bump can be obtained, in which, for instance, the effect of discrete absorption or emission lines in the galaxy, both of variable strength, can be easily isolated and the shape of the underlying bump feature precisely determined. This method of course requires a high degree
of spectrophotometric consistency between the photometry and the spectra, and this will be constructed in Section 3.4 below.

In this section, we first describe our photometric SED fitting to obtain the best-fit stellar template. We employ the software LePhare (Arnouts et al. 2002; Ilbert et al. 2006) with a template library containing synthetic spectra generated using the population synthesis model of Bruzual & Charlot (2003), assuming a Chabrier (2003) IMF. We considered 12 models, combining a constant star-formation history (SFH) and delayed SFHs \((t/r^2e^{-t/\tau})\) with \(\tau = 0.1–3\) Gyr) with two metallicities \((Z = 0.008 \text{ and } 0.004)\) applied. As explained in Section 3.1, we considered a single featureless attenuation curve from Calzetti et al. (2000) in LePhare so that none of the resulting model “template” spectra can possibly contain a bump feature. We allowed the reddening value to vary among \(E(B-V) = 0, 0.01, 0.02, 0.06, 0.08 \text{ and } 0.10–0.70\) in fine steps of 0.025. \(A(5500\,\text{Å}) = 0–2.83\) mag. The effects of possible variations in the overall shape of the baseline attenuation curve will be discussed later in Section 5.3.

We used photometry from the COSMOS2015 catalog (Laigle et al. 2016) measured within 30 broad-, intermediate-, and narrow-band filters from GALEX NUV to Spitzer/IRAC ch2 (4.5 μm), as listed in Table 3 of Laigle et al. (2016). For CFHT, Subaru, and UltraVISTA photometry, we used the fluxes measured in 3″-diameter aperture and applied the offsets provided in the catalog to convert them to the total fluxes.

As noted above, a key feature of the analysis is that we exclude all the photometric bands whose rest-frame central wavelengths are within 1960Å ≤ \(\lambda_{\text{cen}}/(1+z)\) ≤ 2440Å to ensure that the SED fitting is not affected by the SED of the galaxy in the region of the 2175 Å bump feature. The resulting SED fit is therefore quite independent of whether the actual attenuation curve of the galaxy in question does or does not have a UV bump feature.

One complicating fact is the presence of several sharp spectral features in the galaxy spectra, arising from absorption and emission in the ISM, which are not included in the stellar templates. This was dealt with in the SED fitting by applying small corrections to the photometry of the filters whose rest-frame central wavelengths are in the range 1500–2900 Å. Applying this correction is important in order to obtain the best possible continuum template for comparison with the observed spectrum. These corrections were determined using a stacked spectrum of the entire sample (see Section 3.6) to estimate the effects of these spectral lines for each of the photometric bands at the redshift of a given galaxy. In doing so, we ignore the possible variation of the strengths of the spectral features from galaxy to galaxy. Although these effects are small (<5%) in most photometric bands, some strong absorption lines in the red side (i.e., Fe IIλ2344,2374,2382,2586,2600 and Mg IIλ2796,2803) could cause ≥10% reduction of the fluxes in the intermediate and/or narrow bands that sample these particular wavelengths.

For each galaxy, the best-fit template spectrum is then obtained from the best-fit choices of the stellar mass (i.e., overall normalization), stellar metallicity, star-formation history, age and reddening \(E(B-V)\). We will use this best-fit template for our analysis of the UV bump profiles as described below in Section 3.6.

### 3.3. Stellar masses and SFR

For estimating the stellar masses of the galaxies, we again rely on SED fitting with LePhare. In the last subsection, our purpose was to obtain the best fits to the UV continuum of the individual galaxies. However, it is well known that unconstrained SED fitting often leads to unrealistically young ages, and thus low stellar masses, for \(z \geq 1\) star-forming galaxies when the age is left as a free parameter\(^3\). This is because the SED of such galaxies is dominated by the youngest stellar populations which outshine the older ones (e.g., Maraston et al. 2010). It has been demonstrated that limiting the starting times of star formation in such SED fitting to \(z \sim 3–5\) better recovers stellar masses of high-z star-forming galaxies (e.g., Pför et al. 2012).

We therefore impose a lower limit on the age of a given galaxy to estimate the stellar mass. The fitting procedure and the photometric data are the same as used to derive the best-fit spectral templates in the last subsection, but now we restrict the star formation history to begin before a redshift of 3 (i.e., \(Z_{\text{FORM}} = 3\)). The resulting stellar masses of the galaxies are on average \(\sim 0.3\) dex larger than those derived with age as a free parameter. This level of the systematic offset is consistent with what has been found in previous work (Pför et al. 2012).

Throughout the paper, the stellar mass represents the mass of living stars at the time of observation.

The total SFR is estimated from the UV luminosity as follows. Dust attenuation is accounted for based on the UV slope \(\beta_{\text{UV}}\) of the rest-frame UV continua, which is defined as \(f_\lambda \propto \lambda^{\beta_{\text{UV}}}\). We measured the rest-frame FUV (1600 Å) flux density and \(\beta_{\text{UV}}\) by fitting

\(^3\)Note that here the age represents the time elapsed since the onset of the star formation history, which is thus the age of the oldest stellar population present in the template.
a power-law function to the broad- and intermediate-band fluxes within 1200Å ≤ λcen/(1 + z) ≤ 2700Å, but excluding the bands around the 2175 Å feature, i.e., 1960Å ≤ λcen/(1 + z) ≤ 2440Å. The slope βUV is converted to the attenuation at 1600 Å following Calzetti et al. (2000):

\[ A_{1600} = 4.85 + 2.31 \beta_{UV}. \]  

The dust-corrected UV luminosity density, \( L_{1600} \), at rest-frame 1600 Å is then converted to SFR using a relation from Daddi et al. (2004),

\[ \text{SFR}_{UV,corr}(M_\odot \text{ yr}^{-1}) = \frac{L_{1600} \text{ (erg s}^{-1} \text{ Hz}^{-1})}{1.7 \times 8.85 \times 10^{27}}, \]  

where a factor of 1/1.7 is applied to convert from a Salpeter (1955) IMF to a Chabrier (2003) IMF.

Figure 3 summarizes the distribution of stellar mass, SFR, and sSFR for our sample. Our sample includes galaxies with 9.5 ≤ \( \log(M_*/M_\odot) \) ≤ 11.0 and 0.72 ≤ \( \log \text{SFR}_{UV,corr} \left[ M_\odot \text{ yr}^{-1} \right] \) ≤ 2.19 (the 2.5–97.5th percentiles) with median values of \( \langle \log(M_*/M_\odot) \rangle_{\text{med}} = 10.18 \) and \( \langle \log(\text{SFR}_{UV,corr}/M_\odot \text{ yr}^{-1}) \rangle_{\text{med}} \). The sSFR ranges across −9.2 ≤ \( \log \text{sSFR}_{UV,corr} \right[ \text{ yr}^{-1} \] ≤ −8.5 with a median sSFR of \( 10^{-8.78} \) yr\(^{-1}\). Note that the subset that is based on the FMOS zspec measurements has compensated at some level for the lack of the massive dusty population. The FMOS subset is biased towards higher stellar masses (+0.2 dex) and SFR (+0.07 dex), and lower sSFR (−0.05 dex) relative to the remaining subset.

Figure 4 shows the distribution of the \( M_\star \) and UV-based dust-corrected SFR for the sample together with the local starburst sample (Section 2.3). Our galaxies lie closely along a linear relation (cyan line in the figure)

\[ \log \text{ SFR}_{UV,corr} = 1.25 + 0.94(\log M_*/M_\odot - 10) \]  

with standard deviation of 0.18 dex. For reference, the main sequence \( M_\star \)–SFR relations from the literature are shown, which are all converted to a Chabrier (2003) IMF if necessary. Our sample is in good agreement with the relation derived at \( z = 1.5 \)–2.0 by Whitaker et al. (2014). The Whitaker et al. (2014) relation precisely matches in normalization at \( M_\star \sim 10^{10} M_\odot \) the relation at the median redshift (\( z = 1.56 \)) based on the time-dependent parametrization derived by Speagle et al. (2014), while better recovering the low-mass end slope. The agreement of our sample with the literature main sequence relations demonstrates that our sample is representative of main-sequence galaxies at these epochs. We will use the Whitaker et al. (2014) relation to compute the offsets \( \Delta \log \text{sSFR} \equiv \log (\text{sSFR}/(\text{sSFR})_{MS}) \) where the subscript MS stands for Main Sequence) from the main sequence for our sample in Section 5.1. For local sources, we constructed the main sequence relation combining the Speagle et al. (2014) relation at \( z = 0.01 \) \( (M_\star \geq 10^{9.66} M_\odot) \) and the one from Renzini & Peng (2015) \( (< 10^{9.66} M_\odot) \) for better reproducing the low-mass slope.

It should be noted that our sample of galaxies at high redshift have higher sSFRs, by roughly \( \sim 0.5 \) dex, than the local “starburst” sample. However, relative to the evolving main sequence, it is the local starburst sample that has the higher \( \Delta \log \text{sSFR} \) on average. One might surmise that the high redshift galaxies have had a more steady recent SFR history than the local starbursts which have indeed likely experienced a recent short-lived
shift of the sample (thin dotted lines indicate the relations at the median red-
cal starburst galaxies (see Section 2.3). For reference, the linear fit to the data points. Orange diamonds indicate lo-
corrected UV luminosity. The cyan solid line indicates the

Figure 4. Stellar mass versus SFR based on the dust-
corrected UV luminosity. The cyan solid line indicates the linear fit to the data points. Orange diamonds indicate loc-
corrected UV luminosity. The cyan solid line indicates the

“burst” in SFR. This distinction will become significant in our interpretation (Section 5.2).

A final point to note is that the dust correction to the UV luminosity can be quite large ($A_{1600} > 2.5$ mag) in some galaxies in our sample. We have thus checked that the conclusions do not change even if we replace the dust-corrected UV-based SFRs ($SFR_{UV,corr}$) with the UV+IR-based SFRs ($SFR_{UV+IR}$; if available) which are the sum of the UV-based SFR but not corrected for dust attenuation and the SFR based on the total IR luminosity. For the latter, we utilized the public “superdeblended” catalog presented in Jin et al. (2018). These two SFRs are in broad agreement, and no substantial population of heavily obscured starbursting galaxies were not found in our sample. We present SFRs using the IR photometric data and the corresponding results from the reanalysis in Appendix A.

3.4. Flux calibration of the VIMOS spectra

In this study, we will measure the excess absorption based on the comparison between the observed zCOSMOS spectra (and stacks of spectra) and the best-fit templates that were obtained from the broad-, medium-, and narrow-band SED fitting. It should be recalled that these SED fits neither included a UV bump feature in the assumed attenuation curve, nor considered photometric filters that were in the vicinity of the (rest-frame) wavelength of the UV bump feature. The comparison requires an accurate spectro-photometric calibration of the observed spectrum and, in particular, correction of the slit-losses which are likely to depend on the wavelength. This correction is also based on the broad- and medium-band photometry, and is separately calculated for each of the individual spectra that are produced from the standard zCOSMOS-deep reduction process. These spectra do have a nominal flux calibration applied to all spectra based on standard star observations, but do not include effects such as slit-width, inaccuracies in slit-centering and the effects of atmospheric dispersion. It is clear that a key requirement is that this correction must not induce any spurious feature in the spectra that may mimic any excess absorption due to the UV bump.

In constructing this correction, we make use of ~5,000 spectra available in zCOSMOS-deep, regardless of whether there was a successful measurement of the spectroscopic redshift and whether the object lies in the redshift range used in the present study. For each object, we use the available photometry in four broad-bands (CFHT/MegaCam $u^*$ and Subaru/Suprime-Cam $B, V, r$) and eight intermediate-bands (Subaru/Suprime-Cam IA427, IA464, IA484, IA505, IA527, IA574, IA624, and IA679), which lie within the spectral coverage of the VIMOS LR blue grism used in zCOSMOS-deep. As was done for SED fitting (Section 3.2), we adopted the photometric flux measurements from a 3′-diameter aperture from the COSMOS2015 catalog (Laigle et al. 2016) and converted these to total fluxes with the appropriate offsets. We refer to the photometric flux in the $i$th filter as $F_{i}^{\text{phot}}$ and the corresponding central wavelength as $\lambda_{i}$. We then also compute the “pseudo” broad- and intermediate-band fluxes based on the VIMOS spectra in the same filter passbands using the filter transmission curves (see Figure 5). We refer to the fluxes measured on the input spectra using the $i$th filter curve as $F_{i}^{\text{spec}}$. The flux ratio $R_{i}^{\text{ph}} = F_{i}^{\text{spec}} / F_{i}^{\text{phot}}$ is therefore a measure of the slit loss at the different wavelengths, modulo the effects of observational noise in both the imaging and spectral measurements. $R_{i}^{\text{ph}}$ is calculated for all filters, regardless of their rest-frame wavelength.
We first need to derive the shape of the common $\lambda$-dependence, $\xi(\lambda)$. We define $Y_i$ by dividing each $R_i^{\text{spec}}/F_i$ to remove the overall scaling and tilt as follows:

$$Y_i = \log R_i^{\text{spec}}/F_i - (a + b \log \lambda_i)$$  \hfill (9)

where the term $(a + b \log \lambda_i)$ is a linear fit to $\log \lambda_i - \log R_i^{\text{spec}}/F_i$. We then compile the $Y_i$ of all the individual spectra to derive the $\xi(\lambda)$ function.

Figure 5 shows the average $\langle Y_i \rangle$ as a function of wavelength. The symbols indicate median values in the filters at their corresponding central wavelengths, and the black solid and dashed lines indicate the 16–84th and 5–95th percentiles of the range of $Y_i$. To compute these medians and percentiles, we limited the spectra to those with $S/N \geq 5$ in $F_i^{\text{phot}}$, while imposing a quite relaxed limit ($S/N \geq 1$) on $F_i^{\text{spec}}$ to avoid biasing the spectra towards those with smaller flux losses. The average $\langle Y_i \rangle$ shows a moderately curved shape decreasing (i.e., representing increasing spectral losses) at both extremities of the spectral window. This median trend in $\langle Y_i \rangle$ is well described by a third-order polynomial function of $\log \lambda$ (red curve in the figure). This overall trend is then adopted as our $\xi(\lambda)$ function. To avoid any confusion, we note that $\xi(\lambda)$ is not the average because it appears as with a multiplicative term in Equation (8).

Given $\xi(\lambda)$, we can then determine the $p_1$, $p_2$, and $p_3$ in Equation (8) for each spectrum, and correct the individual spectra by dividing by the resulting $\log R_i^{\text{spec}}/F_i$. Figure 6 shows that the pseudo broad- and intermediate-band fluxes recomputed in the flux-corrected spectra are now in excellent agreement with the photometric fluxes. The median values of the corrected $F_i^{\text{spec}}/F_i^{\text{phot}}$ ratios in each band are all within $\pm 0.012$ dex, presumably reflecting small residual errors in the photometric calibration of the photometry. The scatter at a given wavelength is 0.01–0.05 dex and is larger, relatively, in the intermediate bands because of their generally lower $S/N$.

The lower panel of Figure 6 shows the same data but now shifted to the rest-frame wavelength. There is no systematic trend in the corrected flux ratios as a function of the rest-frame wavelength. The running medians with a window size of 200 Å are all within 0.01 dex over the entire wavelength range of interest, and, in particular, they are quite close to zero (i.e., corrected $F_i^{\text{spec}}/F_i^{\text{phot}} = 1$) around the rest-frame wavelength of the UV bump (2175 Å). Simply as a reference, we show on this lower panel the excess absorption due to the UV bump that will be observed in the stacked spectrum of the entire sample (Section 3.6). This comparison simply shows that the accuracy of the spectro-photometric flux (re-)calibration is, by a good margin, sufficient to detect the UV bump signature, or equivalently that any resid-

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**Figure 5.** Altered flux ratios $Y_i$ defined as Equation (9). The circles indicate the median values of $Y_i$ from 4972 spectra at the central wavelength of each filter, whose transmission curve is shown in the bottom part of the panel with the corresponding color. The black solid and dashed lined indicate, respectively, the 16–84th and 5–95th percentiles. The red curve is the third-order polynomial fit to the median values.
Figure 6. Upper panel: Individual flux ratios, $F^\text{spec}/F^\text{phot}$, after correction for the sample of 505 galaxies. Symbols for each single spectrum are connected by a line. Different spectra are colored by different gradation colors for visual purposes. The red solid, dashed, and dotted lines indicate, respectively, the median values, the 16–84th percentiles, and the 5–95th percentiles. Lower panel: the same flux ratios, but as a function of rest-frame wavelength. The red solid and dashed lines indicate running medians and 16–84th percentiles with a window size of 200 Å. The horizontal and vertical lines indicate $F^\text{spec}/F^\text{phot} = 1$ and the center wavelength of the UV bump (2175 Å), respectively. The dot-dashed curve indicates the typical level of flux absorption caused by the UV bump feature measured in the stack of the whole sample (see Section 3.6).

Figure 7. The $\beta_b$ versus $\gamma_{34}$ diagrams for model spectra. Upper panel: color symbols indicate $\beta_b$ and $\gamma_{34}$ computed from representative Bruzual & Charlot (2003) models (a delayed SFH with $\tau = 1$ Gyr, age of 0.50 Gyr, and two stellar metallicities) in steps of $\Delta E(B-V) = 0.05$. The symbol size increases with $E(B-V)$. Different colors and symbols correspond to different dust extinction/attenuation laws and different line types are for different metallicities of the stellar synthesis models (see legend). Grey lines are for models within plausible ranges of star-formation history and age, which indicate the expected scatters of the $\beta_b$–$\gamma_{34}$ relations due to the galaxy stellar populations for each extinction law. Lower panel: $\beta_b$ versus $\gamma_{34}$ for attenuation laws which consist of the baseline Calzetti et al. (2000) law and the bump excess of different peak amplitudes ($0 \leq B_k \leq 2$, in steps of 0.05). The Bruzual & Charlot (2003) model with a delayed SFH with $\tau = 1$ Gyr, age of 0.50 Gyr, and $Z = 0.008$ is used as a representative. Circles mark $E(B-V)$ in steps of 0.05.

3.5. Characterization of the UV continua

In this subsection, we characterize the UV continua of the galaxy spectra in the region of the 2175 Å feature. We follow the parameterization introduced by Noll &...
Pierini (2005) and used in their subsequent papers (Noll et al. 2007, 2009b). The first parameter $\gamma_{34}$ represents the difference ($\gamma_3 - \gamma_4$) between the power-law slopes $\gamma_3$ and $\gamma_4$ measured in the wavelength ranges 1900–2175 Å and 2175–2500 Å, respectively. Thus, the parameter $\gamma_{34}$ is a measure of the strength of the 2175 Å feature: a larger negative $\gamma_{34}$ corresponds to a stronger feature. The second observational parameter is the overall slope $\beta_b$, an indicator of reddening of the UV continuum, measured across the UV bump using the rest-frame wavelength interval 1750–2600 Å but excluding 1950–2400 Å. In measuring these from the actual observed spectra, we exclude any strong narrow spectral features.

These two parameters, $\gamma_{34}$ and $\beta_b$, will vary together as a function of reddening following a relation that is determined by the dust extinction/attenuation law. We simulated these quantities using a range of Bruzual & Charlot (2003) stellar synthesis templates with typical ranges of star-formation histories and ages and for two metallicities ($Z = 0.004$ and 0.008). We modified these artificial spectra by applying dust attenuation with four different dust extinction/attenuation laws: the Calzetti et al. (2000) law, which is used in our SED fitting (Section 3.2), the MW extinction law from Fitzpatrick & Massa (2007), the LMC2 supershell curve, and the SMC one (Gordon et al. 2003).

Figure 7 shows that the relationship between $\beta_b$ and $\gamma_{34}$ depends significantly on the dust attenuation law, with some scatter caused by the variation in the input intrinsic UV continuum spectra, as shown by the thin grey lines. The $\beta_b - \gamma_{34}$ relations show variations of $\Delta \gamma_{34} \lesssim 0.5$ and $\Delta \beta_b \lesssim \pm 0.2$ at fixed $E(B-V)$. For reference, we highlight the loci for the intrinsic UV continuum spectra of a delayed SFH with $\tau = 1$ Gyr at an age of 0.50 Gyr for each constant stellar metallicity.

Figure 7 demonstrates that the presence of the 2175 Å feature could in principle be determined by measuring any $\gamma_{34} \lesssim -1$. The figure also shows that, if all galaxies in a given sample follow a single universal attenuation law, then measurements of ($\beta_b, \gamma_{34}$) for the sample enable us to constrain the strength of the 2175 Å feature.

Similarly, we simulated $\gamma_{34}$ and $\beta_b$ by applying synthetic attenuation laws that consist of the Calzetti et al. (2000) curve as a baseline, to which is added a bump component with different amplitudes (Equation 3; the Drude profile width parameter $\gamma$ is fixed to 0.64 μm$^{-1}$). The lower panel of Figure 7 shows that the gradient of the $\beta_b - \gamma_{34}$ relation becomes steeper for higher $B_k$, as expected. The relations of $B_k = 1.2$ yield a $\beta_b - \gamma_{34}$ relation which is similar to the prediction for the empirical LMC2 supershell extinction law.

### 3.6. Stacking analysis and detection of the 2175 Å bump feature

To accurately determine the shape of the 2175 Å bump, we rely on a stacking analysis of subsamples of galaxies selected by various intrinsic properties, specifically stellar mass and SFR. We stacked the observed VIMOS spectra as well as the best-fit Bruzual & Charlot (2003) templates derived from SED fitting as follows. We first transform all the individual VIMOS spectra and best-fit templates to the rest-frame wavelength based on their spectroscopic redshift. Both the spectra and templates are resampled to a common wavelength grid with a spacing of 2.0 Å/pixel. Each spectrum is then normalized by the average flux density within the rest-frame wavelength range of 1550–2200 Å region. The composite stacked spectra are then produced by taking the median value of the individual spectra at each wavelength grid while ignoring any spectral regions that are missing and/or contaminated by, for example, zeroth order contamination.

Figure 8 shows the composite stacked spectrum (middle panel) of the whole sample. Some prominent narrow spectral features are clearly identified in the stacked spectra as marked by vertical lines. Note that, given the redshift range of our sample, the rest-frame wavelength range of 1550–2400 Å is covered by nearly all the sources, while shorter and longer wavelengths are less fully represented within the sample. The top panel of the figure shows the number of spectra that have contributed to the stack at each wavelength. This begins to decrease at $\lambda > 2000$ Å because of the removal of a significant number of spectra that are contaminated at a given wavelength grid by sky lines that fall in the red side of the observing window (see Section 2.1).

The stacked template spectrum is in good agreement with the SED template at both the blue and red ends of the spectrum, either side of the wavelength interval of the bump feature ($\sim 1900$–2500 Å). This is a consequence of the precise flux calibration constructed in Section 3.4. Conversely, however, there is a clear gap between the stacked VIMOS spectrum and the stacked template spectrum across $\lambda \sim 1900$–2400 Å. Recalling that the latter was constructed using a featureless Calzetti et al. (2000) attenuation law, we can conclude that this gap is the result of a broad absorption excess that is attributed to the usual UV bump feature.

The absolute excess absorption, $A_{\text{bump}}(\lambda)$, can be measured as

$$A_{\text{bump}}(\lambda) = 2.5 \log \left( \frac{f_{\lambda}^{\text{BC03}}(\lambda)}{f_{\lambda}^{\text{obs}}(\lambda)} \right), \quad (10)$$

where $f_{\lambda}^{\text{obs}}$ and $f_{\lambda}^{\text{BC03}}$ are, respectively, the observed and the best-fit template spectrum constructed using the fea-
Figure 8. Composite VIMOS spectrum of the entire sample of 505 galaxies at $1.3 \leq z \leq 1.8$. Top panel: the number of spectra that have been stacked at each wavelength grid. Middle panel: the stacked spectrum (black line), in which some prominent absorption and emission features are identified as marked by color-coded labels: interstellar absorption features (orange), nebular emission lines (green), fluorescence Fe$^{+}$ lines (purple). The spectral region of the Rix et al. (2004) 1978 Å index is marked by dashed triplicate-dotted lines. The blue line indicates the composite of the best-fit templates obtained from SED fitting in which dust extinction following the bump-free Calzetti et al. (2000) attenuation law is applied. The grey line indicates the noise in the composite spectrum. Bottom panel: the 2175 Å bump feature in the attenuation curve. The black line indicates the stack of the individual $k_{\text{bump}}(\lambda)$ computed by Equation 11 for the whole sample. The red line indicates the best-fit Drude profile fit of the bump component shown.
correlated with $M_\star$. The positive correlation between $M_\star$ and $\beta_b$ is a reflection of the correlation between $M_\star$ and the reddening as already reported in the literature (e.g., Pannella et al. 2015). The interpretation of $\gamma_{34}$ is more complicated because the excess attenuation due to the UV bump depends both on the bump strength implemented in the attenuation curve and the absolute level of attenuation. Figure 9 shows that $\gamma_{34}$ decreases with $M_\star$, but the correlation becomes unclear at $\log M_\star/M_\odot \gtrsim 10.5$ with possible increase of the scatter. The correlation appears also to vanish at lower masses ($\log M_\star/M_\odot \lesssim 9.4$) as $\gamma_{34}$ gets close to the upper limit corresponding to the zero attenuation.

Figure 10 shows $\beta_b$ versus $\gamma_{34}$ together with the simulated relations for different extinction and attenuation laws (see Figure 7). We here show as reference a stellar population model with $Z = 0.008$ and adopting a delayed SFH with $\tau = 1$ Gyr at an age of 0.50 Gyr, which is the representative case shown by solid lines in Figure 7. The majority of the sample are located in-between the ones for the bump-free (i.e., the Calzetti et al. (2000) and SMC) dust laws and for the LMC2 supershell extinction curve, with some outliers that are presumably due to measurement errors. The location occupied by the sample is very consistent with that found by Noll et al. (2009b, see their Figures 3 and 5).

There is a clear correlation between $\beta_b$ and $\gamma$. A linear fit to the relatively secure data points ($\sigma(\gamma_{34}) < 1.0$) yields

$$\gamma_{34} = -2.19\beta_b - 4.16.$$ (12)

The best-fit relation passes closely the location of zero attenuation. The slope of the fit is between the relations for the SMC and LMC2 supershell extinction curves. Thus, we can state that, to first order, the dust attenuation of the sample can be represented by an attenuation curve with a moderate UV bump that can nearly reproduce the best-fit $\beta_b-\gamma_{34}$ relation. However, the substantial scatter remains (rms $\approx 1.15$ in $\gamma_{34}$) after accounting for the measurement errors, which clearly indicates the presence of intrinsic variations in the attenuation curves across the sample.

Given the threshold of $\gamma_{34} = -2$ adopted by Noll et al. (2009b), we find that the fraction of the sample hav-
ing a nominal $\gamma_{34} < -2$ to be 30% (27% if limiting to those with $\sigma(\gamma_{34}) < 1.0$). This fraction is in very good agreement with that found by Noll et al. (2009b) at $1 < z < 2.5$. Note that this fraction is for a somewhat conservative threshold chosen for a robust detection of the bump feature, and not the fraction of galaxies whose attenuation curve really has a detectable bump. The latter fraction would be $\sim 1$ because we almost always detect a bump feature in the stacked spectra in bins of galaxy properties, as shown in the following subsections.

### 4.2. The UV bump profiles in stacked spectra

In this subsection, we show the direct measurements of the UV bump profiles based on different stacked spectra. As already demonstrated in Figure 8, we found that the stacked $k_{\text{bump}}(\lambda)$ of the entire sample of 505 galaxies is well described by a Drude profile. The UV bump parameters of the fit that minimize the $\chi^2$ value are given in Table 1. The amplitude is found to be $B_k = 0.577 \pm 0.013$, which corresponds to a fractional bump absorption of $f_{\text{bump}} = B_k/(B_k + k_{\text{Dr}}(2175 \, \text{Å})) = 0.064$. The width $\gamma = 0.536 \pm 0.023 \, \mu\text{m}^{-1}$ (or $254 \pm 10 \, \text{Å}$) is very consistent with that measured for $1 < z < 2.5$ galaxies with a similar approach by Noll et al. (2009b). The fiducial results have been obtained by fixing the central wavelength $\lambda_0$ to 2175 Å. If it is treated as a free parameter, we found $\lambda_0 = 2165 \pm 3 \, \text{Å}$ while that the amplitude $B_k$ and width $\gamma$ change very little.

We show in Figure 11 the stacked spectra and $k_{\text{bump}}(\lambda)$ in bins of the nominal value of $\gamma_{34}$. As expected, the stacked spectra appear to be more bent at larger negative $\gamma_{34}$. The right panels show that the amplitude of the UV bump, $B_k$, decreases with increasing $\gamma_{34}$. The best-fit Drude parameters are given in Table 1. If $x_0 = 1/\lambda_0$ is treated as a free parameter, we found highly consistent values ($\Delta \lambda_0 = |\lambda_0 - 2175 \, \text{Å}| < 10 \, \text{Å}$) when the bump is strong as in the upper panels of Figure 11, while a slightly shorter $\lambda_0$, but still $\Delta \lambda_0 \lesssim 30 \, \text{Å}$ was obtained as the bump becomes weaker. The amplitude $B_k$ and the width $\gamma$ depend hardly on whether or not the peak wavelength is fixed. Note that, in the lowest $\gamma_{34}$ bin, we measured the width parameter $\gamma$ to be much larger than the rest, with a large error. This is presumably due to noise and the low $B_k$, rather than reflecting such a real extremely wide bump. Though, the bump amplitude, $B_k$, itself is more or less accurate under the assumption of $\lambda_0 = 2175 \, \text{Å}$. Among these subsample, the median $M_*$ decreases weakly with $\gamma_{34}$ and the median sSFR hardly varies (see Table 1). This means that the galaxies in a single $\gamma_{34}$ bin have a range of $M_*$ and sSFR. Even at a given $\gamma_{34}$, the variations in the intrinsic galaxy properties may bring a variation in the bump amplitude. We will see this later in Section 4.3.

Figure 12 indicates a tight negative correlation between $B_k$ and $\gamma_{34}$. The bump amplitude reaches to $B_k \approx 0.8$ in the lowest $\gamma_{34}$ bin. A concern with this approach, however, is that stacking those binned by the observed $\gamma_{34}$ may induce an artificial magnification of the bump strength, since we are constructing the stack on the basis of the quantity of interest and possibly thereby. We thus repeated the analysis excluding those spectra with larger uncertainties in $\gamma_{34}$. We attempted two thresholds of $\sigma(\gamma_{34}) = 0.5$ and 1.0 while adopting the same binning grid as the original one: the numbers of galaxies in the bins are thus no longer equal. The results are shown together in Figure 12, demonstrating that the measurements of $B_k$ appear to converge in all but the lowest $\gamma_{34}$-bin where the exclusion of lower-quality measurements result in a slightly lower $B_k$. The presence of a tight $\gamma_{34}$–$B_k$ correlation is robust. Our result thus confirms the result of Noll et al. (2009b, see their Figure 8), whose $\gamma_{34}$–$B_k$ data points are plotted in the figure, and strengthens their statement that the more negative $\gamma_{34}$ could be associated with more prominent UV bump in the attenuation curves.

We next measure the bump strengths as a function of $\beta_b$ and $\gamma_{34}$ by stacking galaxies at grid points in the $\beta_b$–$\gamma_{34}$ plane in steps of 0.1 and 0.25, respectively, in $\Delta \beta_b$ and $\Delta \gamma_{34}$. Note that the size of the elliptic bin ($\Delta \beta_b = 0.2$ and $\Delta \gamma_{34} = 0.5$ in each radius) is larger than the grid separations to achieve a reasonable S/N in the stacked spectra. The left panel of Figure 13 shows a clear trend of the stacked $B_k$ which is similar to the simulations that are shown in the lower panel of Figure 7.

We also show in Figure 13 (middle panel) the observed amplitudes of the absolute excess absorption, $B_A$. The excess absorption reaches $\sim 0.3$ mag at 2175 Å in the population of lowest $\gamma_{34}$ and highest $\beta_b$. The observed trend $B_A$ increase with the distance from the locus that corresponds to $E(B - V) = 0$ in the upper left corner. Lastly, the right panel of Figure 13 shows the mean best-fit $E_{\text{best}}(B - V)$ in the corresponding bins. As expected, the mean $E_{\text{best}}(B - V)$ is tightly correlated with $\beta_b$, but almost independent of $\gamma_{34}$. Thus, we can conclude that the variations in $\gamma_{34}$ at a given $\beta_b$ reflect a real diversity of the bump strengths in the attenuation curves rather than a variation in the amount of overall reddening of the spectra.

### 4.3. UV bump strength versus galaxy stellar mass and sSFR
In this subsection, we correlate the amplitude of $k_{bump}(\lambda)$ with galaxy properties. We first look at the global trend along the main sequence by stacking the individual spectra in six bins of the nominal stellar mass of the galaxies. Table 1 summarizes the bump parameters obtained from the fits and Figure 14 shows the measured $B_k$ as a function of $M_*$. We found a tight positive correlation across $9.8 \lesssim \log M_*/M_\odot \lesssim 10.5$, though the correlation may not hold at the lowest and highest mass ends.

We next focus on both stellar mass and specific SFR (sSFR). In order to understand the dependence of the bump strength on $M_*$ and sSFR separately, we measure the $k_{bump}(\lambda)$ in stacked spectra of galaxies constructed at grid points in the log $M_*$–log sSFR plane in steps of 0.1 dex in $M_*$ and 0.05 dex in sSFR. At each grid point, objects within an elliptic bin of $\Delta \log M_* = 0.2$ dex
and $\Delta \log \text{sSFR} = 0.1$ dex in each radius were stacked. Therefore the adjacent grid points partially share the same galaxies, and thus the measurements will be correlated. We limited bins to those containing $\geq 20$ galaxies so as to achieve a reasonable S/N in the stacked spectra.

Figure 15 shows in the top row the stacked $B_k$ as a function of $M_*$ and sSFR. Across the accessible range, $B_k$ depends on both $M_*$ and sSFR with a stronger dependence on sSFR. We find that $\log B_k$ can be expressed by a linear function of $\log M_*$ and $\log \text{sSFR}$. The best fit is given by

$$
\log <B_k> = -0.163 + 0.139 \log (M_* / 10^{10} M_\odot) - 0.432 \log (\text{sSFR}/\text{Gyr}^{-1}),
$$

(13)

which is shown in the middle panel in the top row. The rms of residuals in $B_k$ from this fitted surface is 0.0372 (right panel). The result indicates that $B_k$ decreases with increasing sSFR at fixed $M_*$ and increases weakly with $M_*$ at fixed sSFR. Note that this empirical functional form has been obtained from a limited region in the $M_*$ vs sSFR space, and thus that extrapolation of this fitted relation for galaxies lying outside the region may not be justified.

Figures 15 also shows in the middle row the amplitude of the absolute excess absorption, $B_A$, in the same stacking bins. The amplitude $B_A$ ranges from $\approx 0.07$ to $0.26$ mag and increases with increasing $M_*$ and decreases with sSFR. A linear fit to $\log B_A$ yields

$$
\log <B_A> = -0.825 + 0.420 \log (M_* / 10^{10} M_\odot) - 0.296 \log (\text{sSFR}/\text{Gyr}^{-1}),
$$

(14)

with the rms residual of $B_A$ of 0.0103 mag.

The bottom panels of Figure 15 show that the mean $E_{\text{best}}(B-V)$ increases with both $M_*$ and sSFR. A linear fit yields

$$
\log <E_{\text{best}}(B-V)> = -0.650 + 0.285 \log (M_* / 10^{10} M_\odot) + 0.145 \log (\text{sSFR}/\text{Gyr}^{-1}),
$$

(15)

with the rms residual of $E_{\text{best}}(B-V)$ is 0.0075. The both positive coefficients on $M_*$ and sSFR indicate that the $E_{\text{best}}(B-V)$ is rather correlated with the absolute SFR. The presence of a tight positive correlation between the reddening and SFR (or the UV luminosity) is consistent with those found at $z \sim 2–3$ in previous studies (e.g., Meurer et al. 1999; Bouwens et al. 2009).

It may be noted that the dependence of $B_A$ (Equation 14) can be reproduced trivially from a combination of those of $B_k$ and $E(B-V)$ (Equations 13 and 15) and vice versa as expected from the definition.

5. DISCUSSION

Table 1. UV bump parameters$^a$

| Sample | $N$ | $\langle \gamma_{\lambda_0} \rangle_{\text{med}}$ | $\langle M_* \rangle_{\text{med}}$ | $\langle \text{sSFR} \rangle_{\text{med}}$ | $\langle E_{\text{best}}(B-V) \rangle_{\text{med}}$ | $\gamma$ | $w_\lambda$ | $B_k$ | $B_A$ |
|-------|----|-----------------|-----------------|-----------------|-----------------|-------|-------|-------|-------|
| all   | 505| -1.020          | 0.285           | 10.177          | -8.782          | 0.536 ± 0.023 | 254 ± 10 | 0.577 ± 0.013 | 0.156 ± 0.004 |
| $\gamma_{\lambda_0}$-bin-1 | 84 | -3.389          | 10.499          | -8.838          | 0.361           | 0.482 ± 0.017 | 228 ± 8  | 0.847 ± 0.016 | 0.300 ± 0.006 |
| $\gamma_{\lambda_0}$-bin-2 | 84 | -2.234          | 10.300          | -8.783          | 0.309           | 0.518 ± 0.020 | 245 ± 9  | 0.734 ± 0.016 | 0.227 ± 0.005 |
| $\gamma_{\lambda_0}$-bin-3 | 84 | -1.407          | 10.248          | -8.791          | 0.286           | 0.498 ± 0.023 | 236 ± 10 | 0.642 ± 0.016 | 0.180 ± 0.004 |
| $\gamma_{\lambda_0}$-bin-4 | 84 | -0.678          | 10.121          | -8.744          | 0.263           | 0.512 ± 0.032 | 243 ± 15 | 0.534 ± 0.018 | 0.134 ± 0.005 |
| $\gamma_{\lambda_0}$-bin-5 | 84 | 0.047           | 9.984           | -8.783          | 0.237           | 0.567 ± 0.047 | 269 ± 22 | 0.419 ± 0.018 | 0.095 ± 0.004 |
| $\gamma_{\lambda_0}$-bin-6 | 85 | 0.918           | 10.019          | -8.745          | 0.256           | 1.264 ± 0.182 | 609 ± 90 | 0.254 ± 0.017 | 0.060 ± 0.004 |

$^a$ The central wavelength ($\lambda_0 = 1/z_0$) was fixed to 2175 Å ($z_0 = 4.598 \mu$m$^{-1}$).

$^b$ Median values of $\gamma_{\lambda_0}$.

$^c$ Median values of $\log (M_* / M_\odot)$.

$^d$ Median values of $\log (\text{sSFR}/\text{Gyr}^{-1})$.

$^e$ The mean of the best-fit $E(B-V)$ derive from SED fitting.

$^f$ The full-width at half-maximum in wavelength ($w_\lambda \approx \gamma \lambda_0$).
5.1. Comparison with local starbursts

We have detected the broad excess absorption due to the UV bump in the attenuation curve of $1.3 \leq z \leq 1.8$ galaxies and mapped the dependence of this on $M_*$ and sSFR, within the accessible region. The impact of the UV bump on the spectra is intermediate between that of the LMC2 supershell extinction law and that of a featureless attenuation law, like the Calzetti et al. (2000) curve or the SMC extinction law, without a bump. Our result is thus at face value different to what has been found for local starburst galaxies in the series of papers which led to the so-called Calzetti law (Calzetti et al. 1994; Calzetti 1997; Calzetti et al. 2000). We therefore here attempt to directly compare our high-$z$ sample of main-sequence galaxies and the local starbursts from which the featureless attenuation curve has been derived. We refer back to Section 2.3 for the selection of the local starbursts.

The measurements of the absolute excess attenuation due to the UV bump are available for 23 starbursts (for 17 of them, the estimates of $M_*$ and sSFR are also available) in Calzetti et al. (1994), and thus can be compared with our $B_A$ measurements, or $B_k$ by dividing by the reddening measurements of the sources, although there are some methodological differences in detail\footnote{Calzetti et al. (1994) parametrized the absorbed flux as $\eta \equiv \Delta \log f_\lambda$ at $\lambda_{rest} = 2175$ \AA. This can be converted to our $B_A$ as $B_A = -2.5\eta$.}. An absorption excess, i.e., a positive bump amplitude, has been measured for 14/23 of the galaxies, or 9/17 if limiting those with the available $M_*$ and SFR. For the remaining a negative amplitude has been obtained presumably due to uncertainties in the spectral data.

In Figure 16, we show the positions of the local starburst galaxies in the $M_*$ vs. sSFR diagram, relative to the region in which our stacked spectra have yielded $B_k$ measurements. As noted earlier, the local “starburst” sources have sSFRs that are on average $\sim 0.5$ dex lower than our high-$z$ main-sequence galaxy sample, while spanning a wider range of stellar mass of $8 \lesssim \log M_*/M_\odot \lesssim 11$. The dependence of $B_k$ that we have observed within our high-redshift sample indicates that lower sSFR galaxies tend to have a stronger bump in the attenuation curves and the extrapolation of this observed trend would clearly predict that the local sources should generally have much larger UV bumps. Since the majority of the local sample are located below the dashed line in Figure 16, we would definitely expect that the $B_k$ of the local sample should exceed the value observed in the stacked spectrum of our entire sample ($B_k = 0.577$). Considering the then-current data quality, it should have been easy to detect such a bump signature in the average attenuation law (see e.g., Figure 20 of Calzetti et al. 1994).

The local starbursts, however, shows on average much weaker bump strengths with the median amplitude $(B_k)_{med} = 0.20$ ($(B_A)_{med} = 0.028$ mag) for the entire 23 local sources, and $(B_k)_{med} = 0.06$ ($(B_A)_{med} = 0.025$ mag) for the plotted 17 sources. These average excess absorptions are very significantly smaller than the $B_k = 0.577$ ($B_A = 0.156$ mag) measured for our stack of the entire sample.

It is clear from the color-coding of Figure 16 that the $B_k$ of the local starbursts are completely inconsistent with the trend established by the higher redshift sample. We can thus conclude that local starbursts, or at least those used in the Calzetti et al. papers, have an attenuation curve in which the UV bump is on average substantially weaker than what is seen in $1.3 \leq z \leq 1.8$ star-forming galaxies, despite the latter’s higher sSFR.

We here recall that, however, the local “starbursts” are, as their name implies, almost certainly undergoing a substantial, recent and short-lived elevation of their...
Figure 13. Left panel: stacked measurements of $B_k$ as a function of $\beta_b$ and $\gamma_M$. The ellipse at the lower-left corner indicates the bin size. The grey lines indicate the predictions for a representative model ($Z = 0.008$, delayed SFH with $\tau = 1$ Gyr, and age of 0.50 Gyr) and the purple dot-dashed line indicates the linear fit to the individual measurements (Equation 12; same as in Figure 10). Middle panel: stacked measurements of $B_A$ in the same stacking bins. Right panel: mean $E_{\text{best}}(B-V)$ in the same stacking bins.

Figure 14. Top panel: $B_k$ versus median $M_*$ in six bins of the individual $M_*$ estimates. The horizontal error bars present the 16–84th percentiles in $M_*$. Lower panel: mean best-fit $E_{\text{best}}(B-V)$ in the same bins as above. The vertical error bars present the 16–84th percentiles in $E_{\text{best}}(B-V)$.

SFR. In contrast, the galaxies in the higher redshift sample are close to the Main Sequence and have probably been forming stars at a more or less steady rate.

To gain further insights into how the bump feature depends on the star formation activity, we now compare the high-$z$ sample and the local starbursts by re-normalizing their sSFR to that of the Main Sequence at the appropriate epoch, i.e., we consider the $\Delta \log \text{sSFR} = \log(\text{sSFR}/\langle \text{sSFR}\rangle_{\text{MS}})$ relative to the appropriate Main Sequence. We utilize the main-sequence relation combining the Speagle et al. (2014) relation at $z = 0.01$ ($M_* \geq 10^{9.66} M_\odot$) and the one from Renzini & Peng (2015) ($< 10^{9.66} M_\odot$) for the local sources (see Figure 4). We then rebin our sample in the log $M_*$ vs. $\Delta \log \text{sSFR}$ plane in steps of, respectively, 0.1 and 0.05 dex using elliptic apertures with radii of 0.2 and 0.1 dex in each axis.

Figure 17 summarizes the new bump measurements, $B_k$ and $B_A$, and the reddening $E_{\text{best}}(B-V)$ for our high-$z$ main-sequence galaxies, together with the local starbursts, in the log $M_*$ vs. $\Delta \log \text{sSFR}$ plane. Our sample covers $\pm 0.3$ dex with respect to the main sequence. It may be worth providing the empirical fits to these measurements as a function of $M_*$ and $\Delta \log \text{sSFR}$. The best linear fits for our sample are given as follows:

$$\log \langle B_k \rangle = -0.271 + 0.198 \log(M_* / 10^{10} M_\odot) - 0.422 \Delta \log \text{sSFR},$$

$$\log \langle B_A \rangle = -0.898 + 0.454 \log(M_* / 10^{10} M_\odot) - 0.260 \Delta \log \text{sSFR},$$

$$\log \langle E_{\text{best}}(B-V) \rangle = -0.614 + 0.259 \log(M_* / 10^{10} M_\odot) + 0.167 \Delta \log \text{sSFR}.$$  

The rms residuals in $B_k$, $B_A$, and $E(B-V)$ are, respectively, 0.0357, 0.0101, and 0.0072.

It is obvious in the top panel of Figure 17 that the majority of the local starbursts differ from the local main sequence, lying well above the commonly-used threshold of $\Delta \log \text{sSFR} > 4$ (0.6 dex) for starbursts. Interestingly, the observed UV bump strengths, $B_k$, in the local starbursts are now in much better agreement, at least qualitatively, with the extrapolation of the trends in our high-$z$ sample which predicts weaker bumps for higher $\Delta \log \text{sSFR}$. This suggests that the weak or ab-
sent UV bump in the local starbursts is linked to their large positive offset from the main sequence, i.e., their ∆ log sSFR, rather than the their absolute SFRs, or sSFRs. In the following subsection, we will come back to this point in interpreting the observed behavior of the bump feature.

5.2. Interpretation of the dependence of $B_k$

The identification of carriers of the UV bump is a long-standing object of controversy (see Draine 1989 for a review). Carbonaceous grains containing sp$^2$-bonded structures are the most widely accepted materials because these materials exhibit a broad excess in the absorption cross-section at $\lambda \sim 2200$ Å due to resonant absorption in the Rayleigh limit (i.e., grain size $a \lesssim 0.01$ μm $\ll \lambda$; e.g., Gilra 1971). Multiple possible forms of the carbonaceous bump carrier candidates have been considered, including (partially) graphitized particles, a random assembly of microscopic sp$^2$ carbon chips (Papoular & Papoular 2009), and polycyclic aromatic hydrocarbons (PAHs; e.g., Mathis 1994; Steglich et al. 2010; Hirashita & Murga 2020). In the following discussion, we assume that the UV bump is attributed to small ($a \sim 0.01$ μm) carbonaceous grains whatever their form. We will, however, come back to a particular caveat to this assumption at the end of the section.

We here attempt to connect the observed dependence of $B_k$ to possible processes relevant to the evolution of
Figure 16. The bump amplitude, $B_k$ of the local starbursts from the Calzetti et al. papers (Section 2.3) in the $M_*$ versus sSFR plane, compared with our results (colored tiles). The filled diamonds indicate the local starbursts and are color-coded by the bump amplitude, but the black filled diamonds correspond to the negative measurements of the bump. The white diamonds indicate the local sources for which no individual bump measurements are available. The color-scale has been changed from Figure 15 to cover the measurements of the local sources down to zero. The dashed line indicates Equation (13) at $B_k = 0.577$, which is obtained for our stack of the entire sample. Note that, a single red diamond has $B_k = 3.96$ as labeled, which is largely exceeding the upper limit of the color range.

dust grains. These physical processes governing the total amount of dust and the distribution of grain sizes include dust production by type-II supernovae (SNe) and Asymptotic Giant Branch (AGB) stars (Gall et al. 2011), the shattering and coagulation processes resulting from grain collisions (Ormel et al. 2009; Yan et al. 2004), the growth of small grains through metal accretion (Dwek 1998; Inoue 2011) and dust destruction by SN-driven shocks (Dwek & Scalo 1980; McKee 1989). These processes all act differently under various size regimes (e.g., Hirashita 2015). The stellar sources of dust are predicted to supply large grains ($a \gtrsim 0.1 \mu$m). These grains are converted into smaller grains through the shattering process, while the coagulation process converts small grains into large grains. The grain growth through metal accretion predominates on smaller grains ($a \lesssim 0.03 \mu$m), which have larger surface-to-volume ratios. Dust destruction by sputtering in hot gas may more efficiently work on smaller grains because it is a surface process, although the net effect is more complicated because larger grains are converted into smaller grains through the destruction process.

Among the MW, LMC, and SMC, there is a trend that the more massive and/or the more higher metallicity the galaxy, the stronger the bump. The metallicity dependence is also reported at high redshifts (Shivaei et al. 2020). It is known that the abundance of PAHs, estimated from the mid-IR luminosity, depends strongly on the metallicity of the galaxies, which may likely be linked to the possible metallicity dependence of
the bump strength given PAHs being a plausible candidate of the bump carrier (e.g., Engelbracht et al. 2005; Galliano et al. 2008; Shivaei et al. 2017). Theoretical models can successfully explain the metallicity dependence if considering the shattering efficiency increasing with the dust (and metal) abundance (Seok et al. 2014; Rau et al. 2019). A recent study, however, shows that there is no correlation between gas-phase metallicity and bump strength, while the bump strength may be anticorrelated with stellar mass for main-sequence galaxies at $z \sim 0.1$ with a typical strength one-third that of the MW bump (Salim et al. 2018). The correlation with $M_*$ and with metallicity, which will be linked through the mass–metallicity relation, and its cosmic evolution remain subject to controversy.

To first order, the observed $M_*-B_k$ correlation (Figure 14) appears to be consistent with the correlation between the bump strength and stellar mass, or metallicity, seen in the Local Group, given the metallicity being tightly correlated with $M_*$ up to high redshifts (e.g., Zahid et al. 2014; Kashino et al. 2017). On the other hand, our results, obtained from binning the sample onto the $M_*-$sSFR plane, indicates that the $M_*$ dependence is only weak when fixing sSFR, implying that an apparently stronger $M_*$ dependence may be derived if measuring $B_k$ only along the $M_*$ axis due to the anticorrelation between $M_*$ and sSFR as well as between $B_k$ and sSFR within a representative sample of main sequence galaxies. As the dependence on $M_*$ is very moderate when fixing sSFR, from now on we focus on the dependence of $B_k$ on sSFR at fixed $M_*$ and its interpretation.

The strength of the bump feature will reflect the destruction and creation of the bump carriers. The destruction of small-sized ($a \lesssim 0.01$ $\mu$m) grains that may be able to giving rise to the bump feature, whatever the chemical composition, is accelerated by an enhanced frequency of SNe and/or by intense hard radiation fields (Gordon & Clayton 1998; Sloan et al. 2008). Harder and more intense radiation fields may arise due to the lower metallicity in less massive and/or higher sSFR galaxies (e.g., Zahid et al. 2014; Sanders et al. 2018) and these may more efficiently destroy small grains (Sloan et al. 2008).

The production rate of small grains is also a factor. It is thought that dust grains of size $a \sim 0.1$ $\mu$m are produced by SNe and AGB stars. Although the fraction of the ejected metals that are condensed into dust is still uncertain in both cases, it is expected that AGB stars dominate the dust production, followed by type-II SNe, while type-Ia SNe make a negligible contribution. Carbonaceous grains that could be the precursors of bump carriers would thus be attributed mainly to carbon-rich AGB stars. On the other hand, AGB stars in the oxygen-rich phase are thought to produce silicate grains that do not cause the absorption excess at 2175 Å (e.g., Höfner & Olofsson 2018). Because only moderate mass stars ($\lesssim 3 M_\odot$) can be carbon stars (Renzini & Voli 1981), the dust production in the AGB phase achieves its peak efficiency $\sim 1$ Gyr (the lifetime of $\sim 2 M_\odot$ stars) after star formation (Zhukovska et al. 2008). Contrarily, the time delays in the appearance in SNe II and oxygen-rich AGB stars, whose progenitor masses are $> 8 M_\odot$ and $\sim (3-8) M_\odot$ respectively, are significantly shorter than 1 Gyr. The ejected carbonaceous grains then need to shattered into small grains, and, if amorphous, need to be at least partially graphitized and/or aromatized to be bump carriers. The timescales of these processes, however, are both thought to be shorter ($\sim 100$ Myr) than the time delay in the appearance of the carbon-rich AGB stars (Sorrell 1990; Hirashita 2015). The supply of the bump carriers is thus likely to reflect the star formation history $\sim 1$ Gyr ago, but not the recent SFR, as averaged over the last $\sim 10^7-8$ yr, that is traced by the UV luminosity.

This all suggests that a key quantity in the balance between production and destruction of the bump carriers may be the recent SFR as measured on $\sim 10^7-8$ yr compared with the SFR of order 1 Gyr ago. We may for simplicity denote, following Wang & Lilly (2020), the ratio of the current instantaneous SFR (measured on $\sim 10^7-8$ yr timescales) to that 1 Gyr ago, as SF$_{79}$. It should be noted that this definition is actually slightly different from that in Wang & Lilly (2020) who defined SF$_{79}$ to be the ratio of the instantaneous SFR to that averaged over the previous 1 Gyr.

We may then look at the behaviour of SF$_{79}$ in two idealized cases. First, for galaxies with a constant sSFR, both the stellar mass$^5$ and the SFR increase exponentially with an $e$-folding timescale given by the inverse sSFR$^{-1}$. The change in SFR will therefore depend on the sSFR multiplied by the time interval of interest, which in this case is of order 1 Gyr:

$$\ln \text{SF}_{79} \sim \text{sSFR} \times 1 \text{ Gyr}. \quad (19)$$

It is then easy to see that different galaxies with different constant sSFR will have different SF$_{79}$. We can approximately write these in terms of some average fidu-

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$^5$ Here we are referring to an sSFR computed using the stellar mass as the integral of the past star formation history, so that the sSFR$^{-1}$ is the mass doubling timescale. This is different from the definition of the stellar masses estimated for the individual galaxies in our sample, which denote the mass in stars that have survived to the time of observation.
where $sSFR_{\text{Gyr}} = \text{sSFR} \times 1 \text{ Gyr}$, i.e., the sSFR in units of Gyr$^{-1}$. When the inverse sSFR$^{-1}$ timescale becomes comparable to the Gyr timescales of interest, i.e., $sSFR_{\text{Gyr}} \sim$ unity, as is certainly the case at high redshift $z \sim 2$, variations in the (steady) sSFR will cause significant variations in $SF_{79}$, with a consequent effect on the amplitude of the absorption bump. This effect alone could conceivably account for the observed trend of decreasing bump strength with sSFR that is seen within our high redshift sample of main-sequence galaxies. Note, however, that at low redshift, where sSFR $\ll 1$ Gyr$^{-1}$, it can be seen that variations in the steady sSFR will have a much smaller effect on SF$_{79}$.

However, a potentially much larger effect on SF$_{79}$ will be produced by any rapid temporal changes in the sSFR. In particular, even at low redshift when most galaxies have sSFR $\ll 1$ Gyr$^{-1}$, a short sharp increase in the SFR, as in a “starburst”, could lead to a corresponding increase in SF$_{79}$. If the burst is of short duration, much less than 1 Gyr, then it simply follows (independent of the value of the fiducial sSFR) that

$$\Delta \log SF_{79} \sim \Delta \log \text{sSFR}. \quad (21)$$

This second effect is almost certainly the one that is relevant for the low-redshift sample of starburst galaxies. Remarkably, it can be seen that Equations (20) and (21) have exactly the same form if Equation (20) is evaluated in the regime where sSFR $\sim 1$ Gyr$^{-1}$, i.e., at $z \sim 2$.

This undoubtedly simplified picture therefore provides a natural explanation of the effects in Figure 17, in which high redshift Main Sequence galaxies and local starburst galaxies are combined: high-redshift main-sequence galaxies in a quasi-steady state and local starburst galaxies undergoing a short temporal elevation in their sSFR happen to display the same relation when the amplitude of the bump feature is plotted against the $\Delta \log \text{sSFR}$ relative to the appropriate Main Sequence, but quite different relations when plotted against the sSFR.

It should be noted that a prediction of this very simplified picture is that we would expect to see a very much weaker or absent trend of bump strength with $\Delta \log \text{sSFR}$ for Main Sequence galaxies at low redshift, since, at low redshift, $sSFR_{\text{Gyr}} \ll 1$ and so the dependence on $\Delta \log \text{sSFR}$ in Equation (20) is correspondingly much smaller.

The success of this simple approach in explaining the observations presented in this paper adds support to the idea that the abundance of the carrier grains of the 2175 Å excess absorption is strongly linked to variations in the recent star formation history of the galaxies over the last billion years or so.

Lastly, however, we have to mention a caveat in the assumption that is a base of our interpretation. Here the bump carriers are assumed to be small carbonaceous grains that were initially supplied by carbon-rich AGB stars and then processes in the ISM to be able to give rise to the bump feature. Although many theoretical models employ this general picture (e.g., Zhukovska et al. 2008; Asano et al. 2013; Hirashita & Murga 2020), on the other hand, there is a known paradoxical problem that the bump strength appears to be anticorrelated with the abundance ratio of carbon-rich to oxygen-rich stars (the C/M ratio): the SMC (with no bump) presents the highest C/M while the MW (with strong bump) the lowest among the Local Group objects (e.g., Cook et al. 1986; Groenewegen 1999; Monleine & Lanchon 2003). This established observational fact appears to disfavor carbonaceous grains being the bump carriers, or at least scenarios in which the supply of the bump carriers is owed to carbon-rich AGB stars. There thus remains a tension between physical arguments favoring carbon grains and astrophysical arguments disfavoring them. Nevertheless, the success of our interpretation suggests a time delay in the appearance of the bump carriers, regardless of the materials, substantially longer than the typical timescale of a single episodic starbursting phenomenon.

5.3. The assumed baseline attenuation curve

In this work, we adopted the Calzetti et al. (2000) law as the baseline of the attenuation curves for all galaxies in the sample, which is the same approach as employed by Noll et al. (2009b). The evolution of the dust population, however, implies that, not only the bump profile, but also the overall shape of the attenuation curve, may be different at high redshift, as it is the case locally. The global shape of the attenuation curve also depends on the geometrical configuration of dust and stars (Witt & Gordon 2000).

For a given UV continuum, the measurement of $B_k$ depends on the overall slope of the baseline attenuation curve. Application of a baseline curve that has a steeper rise towards the far-UV results in a lower $E(B-V)$ for a given observed UV slope, and thus a higher $B_k$ for a given level of absolute excess absorption due to the UV bump. Possible variations in the underlying attenuation curve has also impacts on the SFR derived from the UV luminosity. Applying a steeper attenuation curve will lead to a lower level of dust attenuation and thus a lower SFR for a given UV continuum.
Scoville et al. (2015) found that star-forming galaxies at $2 < z < 6.5$ have an average attenuation curve that is very similar to the Calzetti et al. (2000) curve in the overall shape and present a moderate UV bump feature. On the other hand, there have been several claims that $z \sim 2$ star-forming galaxies have an attenuation curve that is steeper than the Calzetti et al. (2000) curve (Buat et al. 2012; Salmon et al. 2016; Salim et al. 2018; Reddy et al. 2018; Battisti et al. 2020). For example, Buat et al. (2012) found an average $\langle B_k \rangle = 1.6$ and $\langle \delta \rangle = -0.27$ for galaxies at $1 \lesssim z \lesssim 2$ applying a "modified" Calzetti et al. (2000) curve:

$$k_{mod}(\lambda) = \frac{R_V}{4.05} k_{Cal}(\lambda) \left( \frac{\lambda}{5500 \text{Å}} \right)^{\delta} + k_{bump}(\lambda), \quad (22)$$

where $\delta$ modifies the slope. Their $\langle B_k \rangle = 1.6$ is higher than our measurements at face value. If we adopted the modified baseline curve using their average value of $\delta = -0.27$, however, then we obtained $B_k \approx 1.7$ from the stack of the entire sample, which is in agreement with the average value of Buat et al. (2012).

Observational constraints on the relation between the overall shape of the attenuation curve and galaxy properties remain very limited (e.g., Salmon et al. 2016; Salim et al. 2018). If all galaxies in the sample can be assumed to follow a common baseline attenuation, whatever the slope, then the dependence of $B_k$ that we found would qualitatively still hold. On the other hand, there are some claims that lower sSFR galaxies tend to have a steeper attenuation curve (Kriek & Conroy 2013; Battisti et al. 2020). If this is true, then our analysis may have underestimated $B_k$ and overestimated SFR in lower sSFR galaxies and vice versa. Subsequently, we may have artificially narrowed both the range in sSFR (or the main sequence, i.e., the range of $\Delta \log$ sSFR) and the range in $B_k$, and thus the effects on the coefficients in Equations 13 and 17 would be small.

Though the conversion to the amplitude in $k(\lambda)$ depends on the assumption, we stress that the presence of the UV bump in the attenuation curves has been robustly confirmed through the pure observables such as $B_A$ and $\gamma_{34}$ for our sample. Attenuation curves without a UV bump cannot explain the shape of the stacked spectra that are bent at $\lambda \approx 2175$ Å. The observed trend in $B_A$ (Figures 13, 15 and 16) therefore is essentially independent of the assumption of the shape of the baseline attenuation curve, and is thus useful for predict the absolute excess absorption for galaxies at similar redshifts.

The shape of the attenuation curve potentially has significant impacts on the SED of galaxies and thus derived fundamental quantities such as SFR as mentioned above. In particular, the potential variations in the FUV slope of the attenuation curves also implies that the attenuation of the Lyman continuum photons may even largely vary from galaxy to galaxy. This, for instance, may have a significant impact in estimating SFR from the Hα flux (or whatever the recombination line flux) since dust absorption in Lyman continuum reduces the number of produced Hα photons (Puglisi et al. 2016). Variations in the Lyman continuum absorption may also affect the measurements of the ionizing photon escape fraction of galaxies. Accurate determination of the overall shape of the attenuation curve is thus essential for better understanding the evolution of galaxies.

6. SUMMARY

We have investigated the strength of the 2175 Å UV bump feature in the attenuation curves of a sample of 505 star-forming galaxies at $1.3 \leq z \leq 1.8$ in the zCOSMOS-deep survey. Approximately 30% of the galaxies exhibit a robust signature of the UV bump ($\gamma_{34} < -2$) in their individual spectra (Section 4.1) and it may be that almost all galaxies have this feature. Significant intrinsic scatter in the observed $\gamma_{34}$ at a given UV slope clearly indicates the presence of a real diversity in the bump strength in the attenuation curves across the sample (see Section 4.1).

To increase the signal-to-noise ratio, we have also measured the UV bump profiles in stacked spectra representing the whole sample, and in sub-samples of galaxies selected in $(\gamma_{34}, \beta_h)$ space, and in stellar mass and sSFR. The attenuation profiles are all well described by Drude profiles with the center wavelength of 2175 Å but varying amplitudes. The derived bump amplitudes vary across the range $B_k \approx 0.3-0.8$ (Section 4.2) with an inverse correlation with $\gamma_{34}$. Using the stacks in $M_\ast$ bins, we found a tight positive $M_\ast-B_k$ correlation across $9.8 \lesssim \log M_\ast/M_\odot \lesssim 10.5$ along the Main Sequence, though the correlation may not hold at the low and high mass ends (Figure 14).

Binning the sample in the $M_\ast$–sSFR plane, we found that there is a strong negative trend between $B_k$ and sSFR at fixed $M_\ast$ while $B_k$ increases moderately with $M_\ast$ at fixed sSFR (Section 4.3). This correlation with sSFR in the high-redshift sample is strikingly counter to the observed absence of the UV bump in the average attenuation curve of local starburst galaxies, since these local sources actually have lower sSFR than our high-$z$ main-sequence sample. We found, however, that the two samples empirically come into much better agreement if we plot the bump strength against the $\Delta \log$ sSFR, relative to the evolving main sequence at the appropriate epoch, rather than against the sSFR itself (see Figure 17).
We have interpreted these findings in terms of the recent star formation history of the galaxies. The bump strength is determined by the balance between the destruction and production of the bump carriers. The former may be accelerated by a higher frequency of SNe and/or more intense radiation fields in galaxies with higher instantaneous sSFR, whereas the latter only reflects the star formation history 1 Gyr before, but not the current SFR, for the time delay in the appearance of carbon-rich AGB stars (which are here assumed to be main suppliers of precursor carbonaceous grains of the bump carriers) from the onset of star formation. This suggests that the bump strength should be largely determined by the ratio of the current SFR measured on order 10^{7–8} yr timescales to that of order 1 Gyr ago, which we denote as SF_{79} (Section 5.2).

We therefore explored how the SF_{79} would be expected to vary with the sSFR of a galaxy in two different regimes: (i) that of a quasi-constant sSFR and (ii) that of a short-lived rapid increase in the SFR. This reveals an interesting effect. High-redshift main-sequence galaxies with quasi-constant sSFRs of order of sSFR ∼ 1 Gyr^{-1} (appropriate for the high redshift sample at z ∼ 2), and local starburst galaxies that are undergoing a short-lived sharp increase in SFR, should both exhibit the same relations between SF_{79} and ∆sSFR, but quite different relations between SF_{79} and sSFR.

The fact that the bump strength is observed to behave in this same way therefore adds weight to the idea that the variation in SFR over the last roughly 1 Gyr, as parameterized by SF_{79}, that is responsible for the observed variations in the bump strength through the creation and destruction of the carrier grains responsible for the bump. A prediction of this no doubt oversimplified picture is that main-sequence galaxies at low redshift should show a very much weaker trend of bump strength with Δ log sSFR than their high-redshift counterparts.

In the future, next generation multi-object spectrographs, such as VLT/MOONS and Subaru/Prime Focus Spectrograph (PFS) will provide us with rest-frame UV spectra of order 10^{5–6} galaxies at high redshifts. This will enable us to investigate the attenuation curves and the bump feature against various galaxy properties using both individual spectra and stacks, and thus to understand much better the nature of dust through cosmic time.

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APPENDIX

A. RE-ANALYSIS WITH THE UV+IR-BASED SFRS

In our main analysis, we used total SFRs that were estimated from the UV luminosity with appropriate correction for dust absorption (see Section 3.3). However, for a non-negligible fraction of the galaxies, the dust correction becomes quite large (attenuation at rest-frame 1600 Å, $A_{1600} \gtrsim 2.5$) and thus the dust-corrected UV luminosity may be uncertain. Another concern is that the rest-frame UV emission does not trace highly dust-obscured star formation (Puglisi et al. 2017) and thus dusty starburst galaxies could be included in our sample as normal star-forming galaxies. Therefore we here re-estimate total SFRs of our sample galaxies by incorporating the rest-frame far-IR-to-millimeter photometry and present the results from reanalysis using the new SFR estimates.

A.1. SFR from IR luminosity

We utilized a “super-deblended” far-IR to millimeter photometric catalog presented by Jin et al. (2018). This catalog contains point spread function fitting photometry at fixed prior positions including 88,008 galaxies detected either in VLA 1.4 GHz, 3 GHz, and/or MIPS 24 µm images. To derive the total IR luminosity, we use the available photometry in the five Herschel PACS (100 µm and 160 µm) and SPIRE (250 µm, 350 µm, and 500 µm), complemented with JCMT/SCUBA2 850 µm, ASTE/AzTEC 1.1 mm, and IRAM/MAMBO 1.2 mm. We fit these photometric fluxes with a coupled modified blackbody plus mid-IR truncated power-law component using the prescription given in Casey (2012). The total IR luminosity, $L_{\text{IR}}$, is then taken from the rest-frame 8 to 1000 µm, and converted to the IR-based SFR by employing a relation in Madau & Dickinson (2014) converted to a Chabrier (2003) IMF:

$$\text{SFR}_{\text{IR}} (M_\odot \, \text{yr}^{-1}) = 2.64 \times 10^{-44} L_{\text{IR}} (\text{erg s}^{-1}).$$  \hspace{1cm} (A1)

The total SFR is then computed as SFR$_{\text{UV+IR}} = $ SFR$_{\text{UV}} + $ SFR$_{\text{IR}}$ where SFR$_{\text{UV}}$ is computed from the observed UV luminosity not corrected for dust absorption.

A.2. The bump strength as a function of $M_*$ and sSFR

Cross-matching our sample with the far-IR catalog, we found a counterpart for 429 among our sample of 505 galaxies. For 70 of these, we measured $L_{\text{IR}}$ at S/N $\geq 3.0$, ranging across log $L_{\text{IR}}/L_\odot \sim 11.5$–12.5. In Figure 18, we compare the new SFR$_{\text{UV+IR}}$ with the fiducial SFR$_{\text{UV,corr}}$ for these 70 galaxies. The data points are color-coded by the dust attenuation at rest-frame 1600 Å, $A_{1600}$. Although these two SFRs are in broad agreement with each other, there is a substantial scatter. Particularly, there are some objects having relatively low $A_{1600}$ whose SFR$_{\text{UV+IR}}$ exceeds SFR$_{\text{UV,corr}}$ by $\gtrsim 0.4$ dex, suggesting that these galaxies contain star-forming regions which contribute largely to the total SFR but are heavily dust-obscured, and thus their total SFR is not fully recovered in SFR$_{\text{UV,corr}}$ even by applying dust absorption correction. In contrast, a con-
ple of sources are located well below the one-to-one relation with relatively large $A_{1600}$, suggesting that their SFR$_{UV,\text{corr}}$ may be overestimated due to over-correction for dust. This implies that SFR$_{UV,\text{corr}}$ could in general be largely uncertain than the nominal error bars for larger $A_{1600}$.

For the reanalysis, we replaced the fiducial SFR$_{UV,\text{corr}}$ with the total SFR$_{UV+IR}$ for these 70 objects. For the remaining, we adopted SFR$_{UV,\text{corr}}$ if they have $A_{1600} < 2.5$ mag (see Equation 5), but exclude other 74 sources with $A_{1600} \geq 2.5$ mag from the sample. The final sample here contains 431 galaxies. In the lower panel of Figure 18, we show the sample in the $M_*$ vs sSFR plane. After replacing SFR$_{UV,\text{corr}}$ with SFR$_{UV+IR}$, the sample remains largely consistent with the same main sequence, with only a handful of objects are located well above the main sequence ($\Delta \log \text{sSFR} \gtrsim 0.5$ dex). These objects could be heavily-obscured starburst galaxies. In this paper, we do not specifically treat this type of galaxies because of their minor contribution to the whole sample and thus to the conclusions.

Using this sample, we carried out the same analysis described in Section 4.3. An exception is that we stacked galaxies at each grid point in the $M_*$ vs sSFR plane within a radius of 0.2 dex in both axes, instead of 0.1 dex in the sSFR-axis, because the number density of the data points in the $M_*$ vs sSFR plane is reduced (but this does not change the results anyway). Figure 19 shows the results. The linear fits are given as

$$
\log \langle B_k \rangle = -0.163 + 0.177 \log \left( M_*/10^{10} M_\odot \right) - 0.466 \log \left( \text{sSFR/yr}^{-1} \right), \quad (A2)
$$

$$
\log \langle B_A \rangle = -0.828 + 0.397 \log \left( M_*/10^{10} M_\odot \right) - 0.342 \log \left( \text{sSFR/yr}^{-1} \right), \quad (A3)
$$

$$
\log \langle E_{\text{best}}(B-V) \rangle = -0.656 + 0.228 \log \left( M_*/10^{10} M_\odot \right) + 0.126 \log \left( \text{sSFR/yr}^{-1} \right). \quad (A4)
$$

The rms residuals in $B_k$, $B_A$, and $E(B-V)$ are, respectively, 0.0371, 0.0090, 0.0074. The dependence of the bump amplitude $B_k$ appears to be very similar to what is seen in Figure 15: $B_k$ is in a tight negative correlation with sSFR, while moderately increasing with $M_*$. This is also the case for $B_A$ and the mean $E_{\text{best}}(B-V)$, as compared with the corresponding panels in Figure 15. The consistent result from the reanalysis makes our statements in this paper further robust.

Figure 19. Same as the right panels in Figure 15, but showing the results from the reanalysis using SFR$_{UV+IR}$ as described in the text. The ranges of the color bars are the same as in Figure 15.