The MOSDEF-LRIS Survey: The Interplay Between Massive Stars and Ionized Gas in High-Redshift Star-Forming Galaxies

Michael W. Topping, Alice E. Shapley, Naveen A. Reddy, Ryan L. Sanders, Alison L. Coil, Mariska Kriek, Bahram Mobasher, Brian Siana

ABSTRACT

We present a joint analysis of rest-UV and rest-optical spectra obtained using Keck/LRIS and Keck/MOSFIRE for a sample of 62 star-forming galaxies at $z \sim 2.3$. We divide our sample into two bins based on their location in the [OIII]5007/Hβ vs. [NI]6584/Hα BPT diagram, and perform the first differential study of the rest-UV properties of massive ionizing stars as a function of rest-optical emission-line ratios. Fitting BPASS stellar population synthesis models, including nebular continuum emission, to our rest-UV spectra, we find that high-redshift galaxies offset towards higher [OIII]5007/Hβ and [NI]6584/Hα have younger ages ($\log(Age/yr) = 7.20^{+0.57}_{-0.30}$) and lower stellar metallicities ($Z = 0.0010^{+0.0011}_{-0.0003}$) resulting in a harder ionizing spectrum, compared to the galaxies in our sample that lie on the local BPT star-forming sequence ($\log(Age/yr) = 8.57^{+0.88}_{-0.84}$, $Z = 0.0019^{+0.0006}_{-0.0005}$). Additionally, we find that the offset galaxies have an ionization parameter of $log(U) = -3.04^{+0.06}_{-0.11}$ and nebular metallicity of $(12 + log(O/H)) = 8.40^{+0.06}_{-0.07}$, and the non-offset galaxies have an ionization parameter of $log(U) = -3.11^{+0.08}_{-0.09}$ and nebular metallicity of $(12 + log(O/H)) = 8.30^{+0.06}_{-0.05}$. The stellar and nebular metallicities derived for our sample imply that the galaxies offset from the local BPT relation are more $\alpha$-enhanced $(7.28^{+3.07}_{-2.82} O/Fe)$ compared to those consistent with the local sequence $(3.04^{+0.95}_{-0.54} O/Fe)$. However, even galaxies that are entirely consistent with the local nebular excitation sequence appear to be $\alpha$-enhanced – in contrast with typical local systems. Such differences must be considered when estimating gas-phase oxygen abundances at high redshift based on strong emission-line ratios. Specifically, a similarity in the location of high-redshift and local galaxies in the BPT diagram may not be indicative of a similarity in their physical properties.

1 INTRODUCTION

Rest-optical spectroscopy is a powerful tool that can be used to determine a wealth of information on the physical conditions within the interstellar medium (ISM) of galaxies. Measurements of optical nebular emission lines from local star-forming galaxies demonstrate that they trace a tight sequence of increasing [NI]6584/Hα and decreasing [OIII]5007/Hβ emission-line ratios (e.g., Veilleux & Osterbrock 1987; Kauffmann et al. 2003). The observed variation in emission-line ratios along the star-forming sequence reflects the increasing oxygen abundance and stellar mass and decreasing HII-region excitation of its constituent galaxies (Masters et al. 2016). Early observations with Keck/NIRSPEC suggested possible differences in the emission-line properties of high-redshift galaxies in the [OIII]5007/Hβ vs. [NI]6584/Hα “BPT” diagram (Baldwin et al. 1981; Shapley et al. 2005; Erb et al. 2006; Liu et al. 2008). New, statistical samples from the MOSFIRE Deep Evolution Field (MOSDEF; Kriek et al. 2015) sur-
survey and the Keck Baryonic Structure Survey (KBSS; Steidel et al. 2014) show that typical high-redshift galaxies are offset towards higher [OIII]4950/Hβ and/or [NII]6584/Hα on average relative to local galaxies.

There are many possible causes for this observed difference between local and $z \sim 2$ galaxies, including higher ionization parameters, harder ionizing spectra at fixed nebular metallicity, higher densities, variations in gas-phase abundance patterns, and enhanced contributions from AGNs and shocks at high redshift (see e.g., Kewley et al. 2013, for a review). Early results from the MOSDEF survey suggested that the offset of high-redshift galaxies on the BPT diagram is caused in part by the order-of-magnitude higher physical density in $z \sim 2$ star-forming regions, but is primarily a result of an enhanced N/O ratio abundance at fixed oxygen abundance in offset $z \sim 2$ star-forming galaxies relative to local systems (Masters et al. 2014; Shapley et al. 2015; Sanders et al. 2016b). Furthermore, there is evidence that the BPT offset is strongest among low-mass, young galaxies (Shapley et al. 2015; Strom et al. 2017). Results from KBSS were used to argue instead that the observed offset is more likely driven by a harder stellar ionizing spectrum at fixed nebular metallicity, which can also explain at least some of the observed emission-line patterns (Steidel et al. 2016; Strom et al. 2017). Recently, updated results from the MOSDEF survey corroborate these results favoring a harder stellar ionizing spectrum at fixed nebular metallicity (Sanders et al. 2019; Shapley et al. 2019). A harder ionizing spectrum at fixed nebular metallicity arises naturally due to the super-solar O/Fe values of the massive ionizing stars that excite the HII regions in these $z \sim 2$ star-forming galaxies. Such an-enhancement would naturally exist in high-redshift galaxies due to rapid formation timescales, and are therefore enriched by a larger fraction of Type II relative to Type Ia supernova explosions.

In star-forming galaxies, massive stars are the predominant sources of ionizing radiation driving the nebular emission lines included in the BPT diagram. As such, studying the properties of massive stars enables us to address the origin of the observed rest-optical spectroscopic differences between local and high-redshift galaxies. The formation and evolution of massive stars is intimately linked with the evolving properties of the ionized ISM. Specifically, the formation of massive stars is driven by the accretion of gas onto galaxies, and, in turn, massive stars regulate the chemical enrichment of the ISM by driving galaxy-scale outflows, and polluting the ISM when they explode as core-collapse supernovae. Additionally, due to the short-lived nature of these stars, they provide a probe of star-forming galaxies on timescales shorter to or equal to the typical dynamical timescale. One avenue for studying the properties of the massive star populations in high-redshift galaxies is directly observing their light using rest-UV spectroscopy.

Rest-UV spectra of star-forming galaxies contain many features tracing the massive, young stars that supply the ionizing luminosity exciting the gas in star-forming regions. These features, such as the CIV14548, 1550 (Crowther et al. 2006; Leitherer et al. 2001) and HeII1640 (Brinchmann et al. 2008) stellar wind lines, and a host of stellar photospheric features (Rix et al. 2004), provide information on the population of massive stars. In particular, using a given set of model assumptions, these features can be used to establish the form of the initial mass function (IMF), the abundance of Wolf-Rayet (WR) stars, and the nature of the ionizing spectrum in star-forming regions. The features of rest-UV spectra have also been used to estimate stellar abundances (i.e., Fe/H) in high-redshift galaxies. Halliday et al. (2008) used the FeII-sensitive 1978Å index defined by Rix et al. (2004) to measure a stellar metallicity of $Z_\ast/Z_\odot = 0.267$ in a composite spectrum of 75 $z \sim 2$ star-forming galaxies. Sommariva et al. (2012) employed a similar approach, and investigated new photospheric absorption line indicators suitable as calibrations of the stellar metallicity in high-redshift galaxies. They applied these calibrations to the rest-UV spectra of nine $z \sim 3.3$ individual galaxies, and one composite spectrum to construct the $Z \sim 2.5 M_\ast Z_\odot$ relation. Compared to the previously mentioned works, Cullen et al. (2019) instead fit models to the full rest-UV spectrum, an approach that uses all of the stellar-metallicity sensitive spectral features simultaneously. They applied this method to composite spectra to constrain the stellar metallicity of star-forming galaxies spanning a redshift range of $2.5 < z < 5.0$ and a stellar mass range of $8.5 < \log(M_\ast/M_\odot) < 10.2$.

Expanding on previous work, recent studies have made use of rest-UV spectra in combination with rest-optical spectra of high-redshift galaxies (Steidel et al. 2016; Chisholm et al. 2019). Using composite rest-UV and rest-optical spectra of 30 star-forming galaxies at $z \sim 2.4$, Steidel et al. (2016) found that the observed properties constrained by their composite spectra can be reproduced only by models that include binary stars, have low stellar metallicities ($Z_\ast/Z_\odot \sim 0.1$) and moderate nebular metallicities ($Z_{\text{neb}}/Z_\odot \sim 0.5$). These results indicate an-enhancement for the $z \sim 2$ galaxies in Steidel et al. (2016) relative to the solar abundance pattern, given that $Z_\ast$ is primarily tracing Fe/H and $Z_{\text{neb}}$ is tracing O/H. By analyzing a single composite rest-UV spectrum, Steidel et al. (2016) only probed average properties of their high-redshift galaxy sample. With single rest-UV and rest-optical composite spectra it is not possible to probe the average rest-UV spectral properties as a function of the location in the BPT diagram. In this paper we expand upon the important initial work of Steidel et al. (2016) by utilizing combined rest-UV and rest-optical spectra of 62 $z \sim 2.3$ galaxies spanning a broad range of physical properties. With this large sample, we investigate how the rest-UV spectral properties of the massive star population, including the inferred ionizing radiation field, vary for galaxies with different rest-optical emission-line properties in order to uncover the origin of differences between high-redshift and local galaxies in the BPT diagram.

The organization of this paper is as follows: Section 2 describes our observations, data reduction, and methods. Section 3 presents the results of our analysis, and Section 4 provides a summary and discussion of our key results. Throughout this paper we assume a cosmology with $\Omega_m = 0.3$, $\Omega_{\Lambda} = 0.7$, $H_0 = 70 \text{km s}^{-1} \text{Mpc}^{-1}$, and adopt solar abundances from Asplund et al. (2009).
Figure 1. Left: Redshift histogram for all objects with redshifts measured from LRIS spectra (black), totalling 188 galaxies. The blue redshift histogram comprises all objects within $2.09 \leq z \leq 2.55$ ($z_{\text{med}} = 2.28$) with all four BPT lines ($\text{H}\beta$, [OIII], $\text{H}\alpha$, [NII], $\lambda 6584$) detected at $\geq 3\sigma$ in MOSFIRE spectra from the MOSDEF survey, totalling 62 galaxies. Right: SFR calculated from the dust-corrected Balmer lines vs. $M_*$ for all objects with LRIS redshifts at $2.0 \leq z \leq 2.7$. The dashed line shows the SFR-$M_*$ relation of $z \sim 2.3$ galaxies from the MOSDEF survey calculated by Sanders et al. (2018).

2 METHODS AND OBSERVATIONS

2.1 Rest-Optical Spectra and the MOSDEF survey

Our analysis utilizes rest-optical spectroscopy of $z \sim 2.3$ galaxies from the MOSDEF survey (Kriek et al. 2015). The MOSDEF survey consists of moderate resolution ($R \sim 3500$) near-infrared spectra of $\sim 1500$ $H$-band selected galaxies observed over 48.5 nights during 2012–2016 in three distinct redshift intervals near the epoch of peak star formation ($1.4 \leq z \leq 3.8$) using the Multi-Object Spectrometer for Infra-Red Exploration (MOSFIRE; McLean et al. 2012). Additionally, the MOSDEF survey targeted galaxies in the Hubble Space Telescope extragalactic legacy fields in regions covered by the CANDELS (Grogin et al. 2011) and 3D-HST (Momcheva et al. 2016) surveys, which have assembled extensive ancillary multi-wavelength datasets. MOSDEF spectra were used to measure fluxes and redshifts of all rest-optical emission lines detected within the $Y$, $J$, $H$, and $K$ bands, the strongest of which are: [OII]$\lambda 3727$, $\text{H}\beta$, [OIII]$\lambda\lambda 4959, 5007$, $\text{H}\alpha$, [NII]$\lambda 6584$, and [SII]$\lambda\lambda 6717, 6731$.

2.2 LRIS Observations and Data

In order to characterize how galaxy properties vary across the BPT diagram, we selected a subset of MOSDEF galaxies for rest-UV spectroscopic followup based on the following criterion. We prioritized selecting galaxies drawn from the MOSDEF survey for which all four BPT emission lines ($\text{H}\beta$, [OIII], $\text{H}\alpha$, [NII]) were detected. Next highest priority was given to objects where $\text{H}\alpha$, $\text{H}\beta$, and [OIII] were detected, and an upper limit on [NII] was available. Finally, in order of decreasing priority, the remaining targets were selected based on: availability of spectroscopic redshift measurement from MOSDEF (with higher priorities given to those objects at $2.0 \leq z \leq 2.7$ than those at $1.4 \leq z \leq 1.7$ or $2.95 \leq z \leq 3.8$), objects observed as part of the MOSDEF survey without successful redshift measurements, and objects not observed on MOSDEF masks but contained within the 3D-HST survey catalog (Momcheva et al. 2016) and lying within the MOSDEF target photometric redshift and apparent magnitude range. These targets comprise $\sim 260$ observed galaxies with redshifts $1.4 \leq z \leq 3.8$, which is large and diverse enough to create bins across multiple galaxy properties (e.g., location in the BPT diagram, stellar mass, SFR). For this analysis, we do not include the small fraction of objects identified as AGN based on their X-ray and rest-IR properties. Figure 1 displays the redshift histogram and distributions of SFR and $M_*$ of the objects in our sample.

A detailed description of the LRIS data acquisition and data reduction procedures will be presented elsewhere, however a brief summary is provided here. The data were obtained using the Low-Resolution Imaging Spectrograph (LRIS; Oke et al. 1995) during five observing runs totalling ten nights between January 2017 and June 2018. We observed 9 multi-object slit masks with 1"/2 slits in the COSMOS, AEGIS, GOODS-S, and GOODS-N fields targeting 259 distinct galaxies. We used the d500 dichroic, the 400 lines mm$^{-1}$ grism blazed at 3400Å on the blue side, and the 600 lines mm$^{-1}$ grating blazed at 5000Å on the red side. This setup provided continuous wavelength coverage from the atmospheric cut-off at 3100Å up to a typical red wavelength limit of 7650Å. The blue side yielded a resolution of $R \sim 800$, and the red side yielded a resolution of $R \sim 1300$. The median exposure time was 7.5 hours, but ranged from 6–11 hours on different masks. One night was lost completely due to weather. On 6/9 of the remaining nights the conditions were clear, and on 3/9 of the remaining nights there were some clouds, although we collected data on all three of those nights. The seeing ranged from 0"76 to 1"2 with typical values of 0"8. Details of the observations are listed in Table 1.
Figure 2. Ten continuum-normalized individual rest-UV spectra from our sample ordered by redshift. These spectra have the highest continuum signal-to-noise ratio (SNR) from our sample with median $SNR_{\text{pixel}} = 7$ ($4.5 \leq SNR_{\text{pixel}} \leq 12$), measured over the wavelength range $1425\text{Å} \leq \lambda \leq 1500\text{Å}$. Labels on the top of the figure indicate several spectral features including stellar absorption lines (solid red lines), nebular emission lines (dashed dark blue lines), and fine structure lines (dotted green lines). At these redshifts, the dichroic cutoff between the red- and blue-side spectra occurs at a typical rest-frame wavelength of $\sim 1500\text{Å}$. The $1\sigma$ error spectrum is depicted by the shaded region surrounding each spectrum.
We reduced the data from the LRIS red and blue detectors using custom *iraf*, *idl*, and *python* scripts. We first fit polynomials to the traces of each slit edge, and rectified each slit accordingly, straightening the slit-edge traces. For blue-side images, we then flat-fielded each frame using twilight sky flats, and dome flats for the red side. We cut out the slitlet for each object in all flat-fielded exposures. Following this step we used slightly different methods to reduce the red- and blue-side images. For each object, the blue-side slitlets were first cleaned of cosmic rays. Then, slitlets from each individual blue frame were background subtracted, registered and combined to create a stacked two-dimensional spectrum. We then performed a second-pass background subtraction on the stacked two-dimensional spectrum of each object while excluding the traces of objects in the slits in order to avoid over-subtraction of the background (Shapley et al. 2006). For the red-side images, we first background subtracted the individual frames, and cut out the slitlet for each object in all images. These individual slitlets were then registered and median combined using minmax rejection to remove cosmic rays. Because the red-side slitlets are more significantly affected by cosmic rays, the individual slitlets were registered and median combined using minmax rejection to remove cosmic rays. We then used the stacked two-dimensional spectra to measure the traces of objects in each slit. The abundance of sky lines in the red-side images prevented us from achieving an accurate second-pass background subtraction on the stacked two-dimensional spectra. Therefore, we masked out the spectral traces in the individual red side slitlets, and recalculated the background subtraction on the individual slitlets. These individual, background subtracted slitlets were re-registered and median combined with rejection again to create the final stacked image.

Following these steps, we extracted and wavelength calibrated the blue and red side 1D spectrum of each object. The wavelength solution was calculated by fitting a 4th-order polynomial to the red and blue arc lamp spectra, resulting in typical residuals of $\sim 0.035\AA$ and $\sim 0.3\AA$ for the red and blue side spectra, respectively. We repeated this reduction procedure a second time without background subtraction and measured the centroid of several known sky lines. We shifted the wavelength solution zeropoint so that the sky lines appear at their correct wavelength values, and found the median required shift had a magnitude of $\sim 4\AA$ in either direction. To apply the flux calibration, we used a first pass calibration based on spectrophotometric standard star observations obtained through a long slit during each observing run. We performed a final, absolute flux cal-

| Field   | Mask Name | R.A.    | decl. Blue | $t_{gap}^{Blue}$ [s] | $t_{gap}^{Red}$ [s] | $N_{object}$ |
|---------|-----------|---------|------------|----------------------|---------------------|--------------|
| COSMOS  | co$_{J1}$ | 10:00:22:142 | +02:14:25:623 | 25200 | 24080 | 33 |
| COSMOS  | co$_{J2}$ | 10:00:22:886 | +02:24:45:096 | 24300 | 22716 | 31 |
| COSMOS  | co$_{J5}$ | 10:00:29:608 | +02:14:33:037 | 21492 | 20736 | 27 |
| COSMOS  | co$_{J6}$ | 10:00:39:965 | +02:17:28:409 | 25020 | 23264 | 26 |
| GOODS-S | gs$_{J1}$ | 03:32:23:178 | -27:43:08:900 | 39312 | 38664 | 30 |
| GOODS-S | gn$_{J1}$ | 12:37:13:178 | +62:15:09:647 | 27000 | 22968 | 30 |
| GOODS-N | gn$_{J3}$ | 12:36:54:841 | +62:15:32:920 | 32400 | 31500 | 27 |
| AEGIS   | ae$_{J1}$ | 14:19:14:858 | +52:48:02:128 | 28188 | 26964 | 31 |
| AEGIS   | ae$_{J3}$ | 14:19:35:219 | +52:54:52:570 | 34056 | 33120 | 25 |

Figure 3. Stacked spectrum composed of all galaxies with a redshift measured from LRIS and in the interval $2.09 \leq z \leq 2.55$, totalling 62 galaxies. The magnitude of the 1σ error spectrum is depicted by the thin black line. Spectral features are identified using the same labeling scheme as in Figure 2, with the addition of the Lyman series marked by dashed-dotted purple lines.

Table 1. Summary of LRIS observations.
ibration for each galaxy by comparing 3D-HST photometric measurements with spectrophotometric measurements calculated from our spectra, and normalized our spectra so that our calculated magnitudes matched the 3D-HST values. After this absolute calibration, we checked that the continuum levels of the red and blue side spectra matched on either side of the dichroic cut-off at 5000Å. Figure 2 shows some examples of reduced high-SNR continuum normalized spectra. Several strong absorption features are commonly visible, including Si\textsc{ii} $\lambda$1260, O\textsc{i} $\lambda$1302 + Si\textsc{ii} $\lambda$1304, C\textsc{ii} $\lambda$1334, Si\textsc{ii} $\lambda$1526, Fe\textsc{ii} $\lambda$1608, and Al\textsc{ii} $\lambda$1670. Figure 3 displays the median-combined spectral stack of the 188 galaxies in our sample where a redshift could be measured based on the LRIS spectrum.

2.3 Redshift Measurements

We measured a redshift for each object based on the Ly\textsc{$\alpha$} emission line, as well as low-ionization interstellar (LIS) absorption lines, namely, Si\textsc{ii} $\lambda$1260, O\textsc{i} $\lambda$1302 + Si\textsc{ii} $\lambda$1304, C\textsc{ii} $\lambda$1334, Si\textsc{ii} $\lambda$1526, Fe\textsc{i} $\lambda$1608, and Al\textsc{ii} $\lambda$1670, where available. Due to the presence of galaxy-scale outflows, the Ly\textsc{$\alpha$} emission and interstellar absorption lines are commonly Doppler shifted away from the systemic redshift, $z_{\text{sys}}$. Therefore, we defined two different redshift measurements, $z_{\text{Ly} \alpha}$, and $z_{\text{LIS}}$. We used the systemic redshift measured from nebular emission lines as part of the MOSDEF survey, when available, as an initial guess for $z_{\text{Ly} \alpha}$, and $z_{\text{LIS}}$. If no redshift was present for an object in the MOSDEF survey, we manually inspected the LRIS spectrum and measured the redshift based on any available features. This manually measured redshift was then used as an initial guess for our redshift measurement analysis. We measured the centroid of each line by simultaneously fitting the local continuum and spectral line with a quadratic function and a single Gaussian respectively. We restricted the amplitude of the Gaussian to be $\geq 0$ for the Ly$\alpha$ emission line, and $\leq 0$ for the absorption lines. We repeated this fitting process 100 times for each line, and with every iteration we perturbed the spectrum by its corresponding error spectrum. The average and standard deviation of the centroids from the 100 trials became the measured redshift and uncertainty for each spectral line. We manually inspected the fits to each line, and excluded that line if the fits were poor. We calculated the final $z_{\text{LIS}}$ using the available interstellar absorption lines for each galaxy by giving priority to absorption lines that provide a more accu-

Figure 4. Zoomed-in regions around the C\textsc{iv} $\lambda\lambda$1548, 1550 profile for several of the BPASS+Cloudy models of different stellar metallicities and ages used in our analysis. The blueshifted wing of the broad wind absorption, and the redshifted wind emission feature of the C\textsc{iv} $\lambda\lambda$1548, 1550 profile are highlighted in blue and orange respectively, showing how the overall C\textsc{iv} $\lambda\lambda$1548, 1550 profile varies with age and metallicity. Both the absorption (blue) and emission (orange) increase with strength toward higher stellar metallicity and younger age. Both of these shaded regions are outside of the range where interstellar absorption is important and which we mask for our stellar population fitting analysis.
MNRAS 000, 1–77 (0000)

Figure 5. [O III]/Hβ vs. [N II]/Hα BPT diagram for z = 2.3 galaxies in our sample (blue points) as well as local SDSS galaxies (grey; Abazajian et al. 2009). We split the region of the BPT diagram most densely covered by our sample into two bins, one consisting of galaxies along the locus of z = 0 galaxies (red shaded region; low sample), and one bin of galaxies toward higher [O III]/Hβ and [N II]/Hα (blue shaded region; high sample). The median [OIII]/Hβ vs. [N II]/Hα values of galaxies in each bin are depicted as diamond-shaped symbols. For reference, the ‘maximum starburst’ model of Kewley et al. (2001) (dotted curve) and star-formation/AGN boundary from Kauffmann et al. (2003) (solid curve) are plotted. A median error bar for the z = 2.3 sample is shown in the bottom left.

In order to determine the physical properties of the stars within our target galaxies we compared their observed spectra to a grid of stellar population models created with varying parameters. We used the Binary Population And Spectral Synthesis (BPASS) v2.2.1 models (Eldridge et al. 2017; Stanway & Eldridge 2018) because, relative to other recent models, they more accurately incorporate many key processes in the evolution of massive stars, including the addition of binary stars, rotational mixing, and Quasi-Homogeneous Evolution (QHE), resulting in longer main sequence lifetimes. We considered BPASS stellar population models with all available stellar metallicities (10^{-5} ≤ Z ≤ 0.04), which primarily trace Fe/H (Steidel et al. 2016; Strom et al. 2018), and ages between 10^{7.5}yr and 10^{9.8}yr in steps of 0.4 dex. The upper limit in age for this grid was chosen to include the age of the universe at the lowest redshift in our sample. We used the stellar population models that assume a Chabrier (2003) IMF, and have a high-mass cutoff of 100M_☉. By default, BPASS provides models of an instantaneous burst of star formation. We constructed models assuming a constant star-formation history, by summing up the burst models, weighted by their ages.

In order to accurately compare our models with our observed spectra, we must include contributions from the nebular continuum. To model the nebular continuum component of the UV spectrum we used the radiative transfer code Cloudy v17.01 (Ferland et al. 2017). For each individual BPASS stellar population of a given age and stellar metallicity, we ran a grid of Cloudy models with a range of nebular metallicities (i.e., gas-phase O/H) and ionization parameters. Our Cloudy grids include a range of nebular metallicities of \(-2.0 ≤ \log(Z_{\text{neb}}/Z_☉) ≤ 0.4\) in 0.2 dex steps, and ionization parameters of \(-4.0 ≤ \log(U) ≤ -1.0\) in 0.4 dex steps. All models were run assuming an electron density typical of galaxies at this redshift of n_e = 250 cm^{-3} (Sanders et al. 2016a; Strom et al. 2017). We set the abundance of nitrogen in the models using the log(N/O) vs. log(O/H) relation from Pilyugin et al. (2012). When using the stellar population models we added the contribution from the nebular continuum calculated assuming parameters typical of galaxies at this redshift (\log(U) = -2.5, \log(Z_{\text{neb}}/Z_☉) = -0.2; Sanders et al. 2016a). Adjusting these parameters does not affect the nebular continuum significantly enough to alter the results of our model fitting. Figure 4 shows the differences in the C iv1550, 1550 profile for a subset of age and stellar metallicity models used in our analysis. Two key features are highlighted in blue and red, both of which are located within regions of the C iv1550, 1550 profile that are not strongly affected by contamination from interstellar absorption. Both of these features increase in strength towards higher stellar metallicity and younger ages. While the strengths of these features do not necessarily represent a unique combination of age and stellar metallicity, this degeneracy is broken by considering the full rest-UV spectrum.

2.5 Spectra fitting

We fit the combined stellar population plus nebular continuum models to our observed spectra in order to determine which stellar population parameters produce a spectrum that most closely matches our observed spectra. We first continuum normalized the observed and model spectra. In fitting the continuum level, we only considered the rest-frame spectral region at 1270Å ≤ λ ≤ 2000Å to avoid the Lyα feature on the blue end, and a decrease in the qual-
ity of our spectra redwards of 2000 Å. To define an accurate continuum, we used spectral windows in regions of the spectrum relatively unaffected by stellar or nebular features, as defined by Rix et al. (2004). We averaged the flux in each of the windows and fit a cubic spline through the windows to obtain the continuum level.

The models that we used consist of stellar and nebular continuum components only, so we masked out regions of the spectrum that contain other features, such as interstellar absorption. For this purpose, we adopted ‘Mask 1’ from Steidel et al. (2016) in the wavelength range 1270 Å − 2000 Å.

To determine the best-fit age and metallicity, we first interpolated the model onto the wavelength scale of our observed spectrum, and then calculated the \( \chi^2 \) for each model in our grid:

\[
\chi^2 = \sum_i \left( \frac{f_{\text{spec},i} - f_{\text{model},i}}{\sigma_i^2} \right)^2,
\]

where \( f_{\text{spec},i} \), \( f_{\text{model},i} \), and \( \sigma_i^2 \) are the individual pixel values of the masked, continuum-normalized observed spectrum, masked, continuum-normalized model spectrum, and variance in the spectrum, respectively. We did not smooth either the models or the observed spectra as their resolutions were comparable. This sum was typically carried out over \( \sim 1000 \) wavelength elements, and resulted in a \( \chi^2 \) surface in the log(Age/yr)-Z plane, which we interpolated using a 2D cubic spline and minimized to find the best-fit parameters. To calculate the uncertainties in these parameters, we perturbed the spectrum and repeated this process 1000 times to produce a distribution of best-fit values. We then defined the boundaries of the 1σ confidence interval at the 16th and 84th percentiles of this distribution.

In addition to fitting individual spectra, we applied our method to fit composite spectra. To construct a composite spectrum, we first interpolated continuum-normalized individual spectra to a common wavelength grid with the sampling of the typical blue-side spectra (i.e., the lower resolution side), resulting in a typical sampling of \( \sim 0.6 \) Å/pixel in the rest frame. We then median combined the interpolated spectra to produce the final composite spectrum. We constructed the composite error spectrum using a bootstrap resampling method. For a composite spectrum composed of a given number of galaxy spectra, we first selected an equal number of spectra from the composite sample with replacement. We perturbed the selected spectra by their corresponding error spectra, and median combined them to create a composite spectrum. This process was repeated 1000 times to assemble an array of composite spectra. Finally, the composite error spectrum was determined as the standard deviation of the distribution of flux values of the perturbed composite spectra at each wavelength element.

3 RESULTS

To determine how galaxy properties vary across the BPT diagram, we create two stacks of galaxies with roughly comparable oxygen abundance based on their similar [NII]/Hα values, but characterized by different rest-optical line ratios relative to the \( z = 0 \) BPT excitation sequence. Figure 5 shows the regions we use to define our stacks. We label the stack of galaxies consistent with the \( z = 0 \) BPT locus as the
massive stars and ionized gas at high redshift

Figure 7. Best-fit $Z$ and log(Age/yr) for our two stacked spectra, and the five highest continuum SNR individual spectra from each stack, ranging from $4.5 \leq$ SNR/pixel $\leq 12$, measured in the wavelength range, 1425 $\leq A \leq 1500$. The remaining galaxies do not have high enough SNR (SNR/pixel $\leq 4$) for our fitting procedure to produce reliable results without stacking. The large square points show results from the two stacks, and the small individual points are for individual galaxy measurements. Points corresponding to the high (22 galaxies) stack are indicated in blue, those from the low (19 galaxies) stack are colored red. The results from fitting individual galaxy spectra are predominantly consistent with the stacked results, however one galaxy from the high stack has an age older than the stack. Two galaxies from the high stack had 1$\sigma$ uncertainties at the edge of our grid, so they are represented as upper limits here. The high sample is characterized by a younger age and lower stellar metallicity compared to the low stack.

low stack, and the stack of galaxies at higher [NII]/H$\alpha$ and [OII]/H$\beta$ as the high stack. The two stacks contain a majority of the galaxies in our LRIS-BPT sample, with the low and high stacks comprising 19 and 22 galaxies respectively. Despite being composed of a large number of galaxies, each stack covers a small enough area on the BPT diagram to sample galaxies with similar emission line properties. Figure 6 shows the stacked, continuum-normalized spectra of galaxies in the high and low stacks in blue (top) and red (bottom) respectively.

In order to estimate the average physical properties of galaxies in our two stacks, we fit models to our stacked spectra using the procedure described above. To measure uncertainties in these properties, we repeated the fitting process 1000 times, during each of which we recreated the stack using galaxy spectra randomly chosen from the original stack with replacement and perturbed by their corresponding error spectrum. Figure 7 shows the best-fit stellar parameters that we determined for our two stacks. Also shown are the results from applying our fitting procedure to the five individual galaxies with the highest SNR spectra in each bin. We find a stellar metallicity of $Z = 0.0019^{+0.0006}_{-0.0006}$ for the low stack. Both of these metallicities are consistent with each other within 1$\sigma$. We find a best-fit stellar age for the low stack of log(Age/yr) = 8.57$^{+0.88}_{-0.84}$. At this age, the number of O-stars, and therefore the FUV spectrum, has largely equilibrated in a stellar population with a constant star-formation history, which results in the large error bars (Eldridge & Stanway 2012). We find log(Age/yr) = 7.20$^{+0.57}_{-0.20}$ for the high stack. This result suggests that the galaxies consistent with the high stack typically have younger stellar populations compared to those in the low stack.

We check the properties for the galaxies in each stack estimated by comparing their broadband SEDs to stellar population synthesis models. Briefly, this analysis uses the fitting code FAST (Kriek et al. 2009) to fit stellar population models from Conroy et al. (2009), assuming a Chabrier (2003) IMF and the Calzetti et al. (2000) dust reddening curve. The models also assume a “delayed-$\tau$” star-formation history of the form: SFR $\propto t \exp(-t/\tau)$, where $t$ is the time since the onset of star formation, and $\tau$ is the characteristic star formation timescale. For a full description of the SED fitting procedure see Kriek et al. (2015). Based on the SED fitting, we find median ages of log(Age/yr) = 10.05 $\pm$ 0.43 and log(Age/yr) = 10.12 $\pm$ 0.32 for galaxies in the high and low stacks respectively. Also, we find median SFR of log(SFR$_{SED}$/(M$_\odot$/yr)) = 1.33 $\pm$ 0.42 and log(SFR$_{SED}$/(M$_\odot$/yr)) = 1.38 $\pm$ 0.34 for the galaxies in the high and low stacks respectively. Therefore, both stacks comprise galaxies that are well matched in SFR and $M_*$. Additionally, the median SED-based age for galaxies in the high stack (log(Age/yr) = 8.5 $\pm$ 0.4) is younger than the median SED-based age in the low stack (log(Age/yr) = 8.6 $\pm$ 0.3). This result from the broadband SED fitting agrees qualitatively with the younger age we find for the high stack based on the full rest-UV fitting, but is less significant.

In addition, the results from fitting model spectra to the high-SNR individual galaxy spectra are largely consistent with the results from using the stacked spectra. Four out of five individual galaxies from the high stack that we fit had stellar properties (age, stellar metallicity) consistent with stacked spectrum results, two of which were upper limits on the age. The remaining galaxy had a best fit age that was substantially older than the stack. All five individual galaxies in the low stack are consistent with an older population, and all but one object showed consistent metallicities with the stack. The best-fit parameters of the stacked spectra have larger uncertainties compared to the individual spectra, which suggests that our bootstrap resampling method is capturing galaxy-to-galaxy variations of age and Z, in our sample.

In addition to our global rest-UV fitting procedure, which covers the full FUV spectrum at 1270$\AA \leq A \leq 2000$A, evidence for a difference in age between our two stacks is visible in the wind lines produced by massive stars: CIV(λ1548, 1550) and HeII(λ1640) . Figure 8 shows these features for both of our stacks. The high stack has stronger CIV(λ1548, 1550) emission (1552A $\sim$ 1555A), as well as stronger stellar wind absorption (1536A $\sim$ 1545A) when compared to the low stack. This result is confirmed qualitatively by looking at the CIV(λ1548, 1550) profiles produced by stellar population models, which predict stronger CIV(λ1548, 1550) emission for younger stellar populations.
Figure 8. Zoomed-in regions around the C iv λλ 1548, 1550 (left) and He ii λ 1640 (right) features for our high (blue) and low (red) stacked spectra. The high stacked spectrum has stronger He ii λ 1640 and C iv λλ 1548, 1550 emission. Both features are signatures of massive stars, and are more prominent in younger populations. The 1σ composite error spectrum is depicted by the shaded region surrounding each spectrum. Figure 4 shows the age dependence of the C iv λλ 1548, 1550 line in the BPASS models.

(Figure 4). In addition, the high stack shows a significant He ii λ 1640 emission line, whereas the low stack has none visible. Both of these features confirm the results of our fitting analysis suggesting that the stack of high galaxies shows evidence for stellar youth.

Using the best-fit stellar population parameters, we can examine the ionizing spectrum predicted by the BPASS models. Figure 9 shows the predicted ionizing spectrum for both the high and low stacks. The most massive stars, which are responsible for producing the ionizing radiation, have lifetimes much shorter than the ages of most of our models. Due to the assumed constant star-formation history in our models, the number of these massive stars equilibrates quickly (\( \sim 10 \) Myr), and remains constant through most of our parameter space. As a result, the ionizing spectrum is similar between the two best-fit models to our observed spectra, however the model corresponding to the high stack has a harder ionizing spectrum due to its lower stellar metallicity. Specifically, the ionizing flux normalized at 900 Å, and integrated over the range 200 Å ≤ λ ≤ 912 Å, is \( \sim 7\% \) higher in the high stack compared to the low stack.

Using the predicted ionizing spectrum from our fitting analysis, we infer the nebular line fluxes expected for a given set of nebular parameters using Cloudy. We place our grid of Cloudy models on the [OIII]/Hβ vs. [NII]/Hα BPT diagram for the best-fit stellar spectrum of each of our stacks (Figure 10). We linearly interpolate the grid of [NII]/Hα and [OIII]/Hβ values produced by the Cloudy models to determine which \( Z_{\text{neb}} \) and \( \log(U) \) best match the median observed line ratios of each stack. To estimate the uncertainty, we perturb the median observed [NII]/Hα and [OIII]/Hβ of the stacks by their uncertainties, and repeat the pro-
cess 1000 times to create a distribution of values. Figure 11 (bottom row) displays the distributions of nebular metallicity and ionization parameter obtained from this analysis. We find an ionization parameter of $\log(U) = -3.04^{+0.06}_{-0.11}$ and nebular metallicity of $12 + \log(O/H) = 8.46^{+0.08}_{-0.07}$ for the high stack. For the low stack, we find an ionization parameter of $\log(U) = -3.11^{+0.08}_{-0.08}$ and nebular metallicity of $12 + \log(O/H) = 8.30^{+0.05}_{-0.06}$. These differences are small given the dynamic range of ionization parameter in high-redshift star-forming galaxies, and systematic uncertainties in nebular metallicities, but they have a measurable effect on the rest-optical emission ratios for the high and low stacks. Both of our stacks have $Z_{\text{neb}}$ and $U$ consistent with the range found for local HII regions (Pérez-Montero 2014). Table 2 summarizes the best-fit physical parameters we find for the high and low stacks.

4 DISCUSSION

Sensitive multiplexed spectroscopic instruments on large telescopes have enabled the study of rest-optical spectra for statistical samples of galaxies at high-redshift. These studies have established an offset of high-redshift star-forming galaxies towards higher $[\text{O III}]/H\beta$ and $[\text{N II}]/H\alpha$ compared to local galaxies. Several contributing factors have been proposed as the source of this offset, including varying abundance patterns, changes in the ionizing spectra, stellar and nebular metallicities, different ages of the stellar populations, and a different ionization parameter (Shapley et al. 2005; Erb et al. 2006; Liu et al. 2008; Kewley et al. 2013).

One essential aspect of understanding these differences in high-redshift galaxies is a robust constraint on the ionizing spectrum produced by massive stars. Rest-UV spectroscopy of star-forming galaxies traces the properties of the massive star populations, and (given a set of stellar population synthesis modeling assumptions) provides constraints on the ionizing radiation field. In turn, photoionization modeling enables us to connect the ionizing spectrum and massive star population, with rest-optical nebular line ratios including those in the BPT diagram.

Currently, studies utilizing this combined rest-UV and rest-optical analysis have focused on average properties of the high-redshift population. By dividing our sample into two bins based on their location on the BPT diagram, we investigated how stellar population properties change as galaxies move away from the local BPT sequence. We found that the stack of galaxies above the local BPT sequence have younger ages, and lower stellar metallicities compared to galaxies along the local sequence at $z \sim 2$. Additionally, we find that galaxies above the local BPT sequence have harder ionizing spectra compared to their low stack counterparts. In our models, which assume a constant star-formation history, the most massive star population equilibrates on timescales $\sim 10 \text{ Myr}$. Therefore, the difference in ionizing spectrum is not due to the age difference between our two stacks, but instead the lower stellar metallicity (i.e., Fe/H) in those galaxies that are offset.

While the most notable difference between our low and high stacks is a factor of $\sim 2$ lower stellar metallicity in the high stack, our photoionization modelling reveals small differences in the additional nebular parameters $U$ and $Z_{\text{neb}}$. All three of these parameters contribute to the observed rest-optical emission line ratios of the high and low stacks. Using photoionization modelling to measure $Z_{\text{neb}}$ (nebular O/H), and using rest-UV spectral fitting to measure $Z$ (stellar Fe/H), we find that both stacks have super-solar O/Fe, with our high and low stacks having values of $3.04^{+0.06}_{-0.07} \text{O}/\text{Fe}$ and $7.28^{+0.20}_{-0.22} \text{O}/\text{Fe}$ respectively. While α-enhancement has previously been presented as an explanation for the offset of $z \sim 2$ galaxies in the BPT diagram, we stress that even galaxies that are entirely consistent with the local excitation sequence in the $[\text{O III}]$ vs. $[\text{NII}]$ vs. $[\text{H}\alpha]$ diagram (i.e., the low stack) appear to have α-enhanced – in contrast with local systems. Such differences must be considered in order to accurately model the properties of these galaxies and to infer gas-phase oxygen abundances based on strong emission-line ratios. The O/Fe value for the high stack is above the $\sim 5.5 \times \text{O}/\text{Fe}$ theoretical limit assuming a Salpeter IMF and high-mass cutoff of $50 M_{\odot}$ (Nomoto et al. 2006), but is still consistent within 1σ. However, the exact value of this theoretical limit is dependent on supernova yield models, which are not well constrained (Kobayashi et al. 2006). Kriek et al. (2016) found comparable α-enhancement in a massive quiescent galaxy at $z = 2.1$, reporting a Mg/Fe = $3.9 \times \text{Mg}/\text{Fe}$. The assumed nitrogen abundance at fixed O/H affects where photoionization model grids fall in the BPT diagram, such that increasing N/O increases [NII]/Hα while keeping all other parameters fixed. Consequently, if our assumed N/O-O/H relation does not hold for typical $z \sim 2$ galaxies, then our inferred oxygen abundances will be systematically biased. An underestimate in N/O leads to an overestimate of O/H, and vice versa. Therefore, the high α-enhancement inferred in our offset galaxy stack could be due in part to differences in N/O at fixed O/H, perhaps due to the timescale of nitrogen enrichment in stellar populations (Berg et al. 2019). However, in order for the high and low stacks to each have solar O/Fe, an enhancement of N/O by $\sim 1$ dex and $\sim 0.5$ dex respectively at fixed O/H would be required. Given the age of both stacks, and the timescale of Fe enrichment from Type Ia supernovae ($\sim 1 \text{ Gyrr}$), the absence of α-enhancement in either stack is unlikely. Another question is whether the difference in inferred α-enhancement for the two stacks can be explained by different N/O vs. O/H relations. For O/Fe to match between the high and low stacks, we would need to assume an N/O higher by $\sim 0.6$ dex for the high stack. For consistency at the 1σ level, the assumed N/O would need to be $\sim 0.2$ dex higher for the high stack. Additionally, an O/Fe exceeding the theoretical limit of Nomoto et al. (2006) could be explained by a top-heavy IMF, or by increasing the high-mass cutoff of the stellar population. Investigating these possible differences in stellar populations is an avenue for future analysis.

An intriguing question is if the high-redshift galaxies that lie along the local sequence (i.e., the low sample) can be interpreted as descendants of the offset galaxies (i.e., the high sample). Qualitatively, it is suggestive that this may be the case based on the age dependence of α-enhancement seen in galactic bulge stars (Matteucci et al. 2016). However, chemical evolution models that incorporate realistic timescale differences between core collapse and Type Ia supernovae predict that significant evolution of O/Fe will only occur on
timescales of \( \sim 1 \) Gyr, assuming smooth star-formation histories (Weinberg et al. 2017), which is significantly longer than the age difference inferred between the high and low rest-UV composite spectra. In contrast, in the models of Weinberg et al. (2017), a sudden burst of star formation could temporarily boost O/Fe by \( \sim 0.3 \) dex. Accordingly, galaxies in the high stack may show the evidence of recent bursts of star formation, and follow systematically different star-formation histories from those in the low stack. More detailed modelling will be required to see if this proposed explanation is applicable.

5 SUMMARY & CONCLUSIONS

We have obtained rest-UV spectra for a sample of 259 galaxies at \( 1.4 \leq z \leq 3.8 \) that were observed as part of the MOSDEF survey, enabling a combined analysis of rest-UV probes of massive stars and rest-optical probes of ionized gas. Of these galaxies, 62 are at \( z \sim 2.3 \) (\( 2.09 \leq z \leq 2.55 \)), and have all four BPT emission lines (H\( \beta \), [OIII]\( \lambda5007 \), H\( \alpha \), [NII]\( \lambda6584 \)) detected at \( \geq 3\sigma \). We constructed two composite rest-UV spectra of a subset of these 62 galaxy spectra based on their location on the BPT diagram. We tested how galaxy properties, including the age, stellar metallicity, nebular metallicity, and ionization parameter vary for galaxies on and off the local sequence. To derive these properties, we first fit a grid of Cloudy+BPASS stellar population synthesis models to constrain the age and stellar metallicity of the massive star population, therefore fixing the intrinsic ionizing spectrum. With the ionizing spectrum established, we then computed optical emission line flux ratios using Cloudy for a grid of nebular metallicities and ionization parameters. Finally, we set the nebular metallicity and ionization parameter for our spectra based on the models that best reproduced the observed rest-optical emission line ratios. We summarize our main results and conclusions below.

(i) Using Cloudy+BPASS stellar population synthesis models we investigated how the age and stellar metallicity varies for high-redshift galaxies that lie on the local BPT sequence compared to those that are offset toward higher [OIII]/H\( \beta \) and [NII]/H\( \alpha \). We found that the offset galaxies have younger ages (log(Age/yr) = 7.20\(^{+0.57}_{-0.20} \)) compared to the galaxies in our sample that lie on the local sequence (log(Age/yr) = 8.57\(^{+0.88}_{-0.84} \)). Additionally, we found that the offset galaxies had overall lower stellar metallicities (\( Z_\ast = 0.0016^{+0.0011}_{-0.0003} \)) compared to the non-offset galaxies (\( Z_\ast = 0.0019^{+0.0006}_{-0.0006} \)). These results are displayed in Figure 7.

(ii) We investigated how the ionizing spectrum of the best-fit stellar population synthesis models varies across the BPT diagram, and found that the galaxies that are offset from the local BPT sequence have a harder ionizing spectrum compared to those that are not offset (Figure 9). This difference is due to the lower stellar metallicity in the offset galaxies. Inferred ages for both composites are old enough such that in constant star-formation models, the number of O-stars has reached an equilibrium, and the age of the population no longer has a significant effect on the ionizing spectrum.

(iii) Using the ionizing spectrum inferred for each stack from the rest-UV spectral fitting, we computed the result-

![Figure 10. Predicted [OIII]/H\( \beta \) and [NII]/H\( \alpha \) emission-line ratios corresponding to the Cloudy+BPASS model grid of 12 + log(O/H) and log(U) for a given ionizing spectrum. The center of each point is color-coded by log(U), increasing from yellow to orange, while the border of each point is color-coded by 12 + log(O/H), increasing from light to dark green. The scale for each parameter is indicated by the color bars to the right of the panels. The median value and uncertainty in the observed [OIII]/H\( \alpha \) border of each point is color-coded by 12 + log(O/H).](image)

| log(Age/yr) | \( Z_\ast \) | log(U) | 12 + log(O/H) |
|-------------|-------------|--------|---------------|
| high stack  | 7.20\(^{+0.57}_{-0.20} \) | 0.0010\(^{+0.0011}_{-0.0003} \) | 3.04\(^{+0.06}_{-0.11} \) | 8.40\(^{+0.06}_{-0.07} \) |
| low stack   | 8.57\(^{+0.88}_{-0.84} \) | 0.0019\(^{+0.0006}_{-0.0006} \) | 3.11\(^{+0.08}_{-0.08} \) | 8.30\(^{+0.05}_{-0.06} \) |

Table 2. Best-fit physical parameters for the high and low stacks.
Figure 11. Distributions of best-fit age, stellar metallicity (Z), ionization parameter (U), and nebular metallicity (O/H) for our two stacks. The parameter distributions of age and stellar metallicity are produced by fitting a grid of Cloudy+BPASS stellar population models to a bootstrap resampled composite spectrum 1000 times. The parameter distributions of ionization parameter and nebular metallicity for each galaxy sample are produced by perturbing the sample median [O III]/Hβ and [N II]/Hα values by their uncertainties 1000 times and comparing the perturbed values to the inferred line ratios from our grid of Cloudy+BPASS models. All panels display parameter distributions for the high and low stacks in blue and red, respectively. Top Left: Distribution of best-fit ages. We find the high stack is younger (log(Age/yr) = 7.20^{+0.57}_{-0.20}) compared to the low stack (log(Age/yr) = 8.57^{+0.84}_{-0.45}). Top Right: Distribution of best-fit stellar metallicities. We find that the high stack has an overall lower stellar metallicity (Z = 0.0010^{+0.0011}_{-0.0003}) compared to the low stack (Z = 0.0019^{+0.0006}_{-0.0008}). Bottom Left: Distributions of best-fit ionization parameters. We obtain values of log(U) = -3.04^{+0.06}_{-0.11} for the high stack, and log(U) = -3.11^{+0.08}_{-0.06} for the high stack. Bottom Right: Distributions of best-fit nebular metallicities. We find best-fit values of 12 + log(O/H) = 8.40^{+0.06}_{-0.07} for the high stack, and 12 + log(O/H) = 8.30^{+0.05}_{-0.06} for the low stack.

Understanding the observed differences between local and high-redshift galaxies in terms of their physical properties is required for a complete galaxy evolution model. Thus far, these differences have mainly been probed in a sample-averaged sense, therefore variations across the high-redshift galaxy population cannot be determined. By stacking our sample based on BPT location we observed which differences were enhanced in high-redshift galaxies that are most offset from the local sequence. We found that high-redshift galaxies had several factors contributing to the offset, namely that the most offset galaxies have younger ages, lower stellar metallicities, higher ionization parameters, and higher nebular oxygen abundances. Notably, the offset galaxies are more α-enhanced compared to high-redshift galaxies that lie along the local sequence. Any photoionization modelling of z ~ 2.3 galaxies that do not take these differences into account, instead using local properties, will yield biased results. While α-enhancement was found to be heightened in the most offset galaxies, some level of enhancement is present throughout the high-redshift sample—even those coincident with the local sample. Therefore, interpreting the agreement between the location local galaxies and some high-redshift galaxies (i.e., our low sample) on the BPT diagram as a sim-
ilarity of physical properties is an oversimplification. While our method of inferring $Z_\ast$ from rest-UV spectral fitting, and $Z_{	ext{neb}}$ from photoionization modelling has not been applied to local galaxies, joint studies of the local stellar and gas-phase mass-metallicity relations suggest that $\sim L_\ast$ star-forming galaxies in the local universe are not $\alpha$-enhanced (Zahid et al. 2017).

While we have refined the results of previous studies by measuring variations in high-redshift galaxy properties on and off the local sequence, a further refinement of composite spectra, or large numbers of high-SNR individual galaxies is still required. In addition, during this analysis we made several assumptions about the stellar populations of these galaxies, namely constant star-formation histories, and a single IMF. Future investigations will need to examine more general star-formation histories and variations in the IMF in order to more accurately constrain galaxy properties at high redshift.

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REFERENCES

Abazajian K. N., et al., 2009, ApJS, 182, 543
Asplund M., Grevesse N., Sauval A. J., Scott P., 2009, ARA&A, 47, 481
Baldwin J. A., Phillips M. M., Terlevich R., 1981, PASP, 93, 5
Berg D. A., Erb D. K., Henry R. B. C., Skillman E. D., McQuinn K. B. W., 2019, ApJ, 874, 93
Brinchmann J., Pettini M., Charlot S., 2008, MNRAS, 385, 769
Calzetti D., Armus L., Bohlin R. C., Kinney A. L., Koornneef J., Storchi-Bergmann T., 2000, ApJ, 533, 682
Chabrier G., 2003, PASP, 115, 763
Chisholm J., Rigby J. R., Bayliss M., Berg D. A., Dahlé H., Gladders M. D., Sharon K., 2019, ApJ, 882, 182
Conroy C., Gunn J. E., White M., 2009, ApJ, 699, 486
Crowther P. A., Prinja R. K., Pettini M., Steidel C. C., 2006, MNRAS, 368, 895
Cullen F., et al., 2019, MNRAS, 487, 2038
Eldridge J. J., Stanway E. R., 2012, MNRAS, 419, 479
Eldridge J. J., Stanway E. R., Xiao L., McClelland L. A. S., Taylor G., Ng M., Greis S. M. L., Bray J. C., 2017, Publ. Astron. Soc. Australia, 34, 0058
Erb D. K., Shapley A. E., Pettini M., Steidel C. C., Reddy N. A., Adelberger K. L., 2006, ApJ, 644, 813
Ferland G. J., et al., 2017, Revista Mexicana de Astronomía y Astrofísica, 53, 385
Grogin N. A., et al., 2011, ApJS, 197, 35
Halkiadakis C., et al., 2008, A&A, 479, 417
Kauffmann G., et al., 2003, MNRAS, 346, 1055
Kewley L. J., Dopita M. A., Sutherland R. S., Heisler C. A., Trevena J., 2001, ApJ, 556, 121
Kewley L. J., Dopita M. A., Leitherer C., Davé R., Yuan T., Allen M., Groves B., Sutherland R., 2013, ApJ, 774, 100
Kobayashi C., Umeda H., Nomoto K., Tominaga N., Ohkubo T., 2006, ApJ, 653, 1145
Kriek M., van Dokkum P. G., Labbé I., Franx M., Illingworth G. D., Marchesini D., Quadri R. F., 2009, ApJ, 700, 221
Kriek M., et al., 2015, ApJS, 218, 15
Kriek M., et al., 2016, Nature, 540, 248
Leitherer C., Leão J. R. S., Heckman T. M., Lennon D. J., Pettini M., Robert C., 2001, ApJ, 550, 724
Liu X., Shapley A. E., Coil A. L., Brinchmann J., Ma C.-P., 2008, ApJ, 678, 758
Masters D., et al., 2014, ApJ, 785, 153
Masters D., Faisst A., Capak P., 2016, ApJ, 826, 18
Matteucci F., Spitoni E., Romano D., Rojas Arriagada A., 2016, in Frontier Research in Astrophysics II (FRAPWS2016), p. 27
McLean I. S., et al., 2012, in Ground-based and Airborne Instrumentation for Astronomy IV. p. 84460J, doi:10.1117/12.924794
Momcheva I. G., et al., 2016, ApJS, 225, 27
Nomoto K., Tominaga N., Umeda H., Kobayashi C., Maeda K., 2006, Nuclear Physics A, 777, 424
Oke J. B., et al., 1995, PASP, 107, 375
Pérez-Montero E., 2014, MNRAS, 441, 2663
Pilyugin L. S., Vílchez J. M., Mattsson L., Thuan T. X., 2012, MNRAS, 421, 1624
Rix S. A., Pettini M., Leitherer C., Bresolin F., Kodzitski R.-P., Steidel C. C., 2004, ApJ, 615, 98
Sanders R. L., et al., 2016a, ApJ, 816, 23
Sanders R. L., et al., 2016b, ApJ, 816, 23
Sanders R. L., et al., 2018, ApJ, 858, 99
Sanders R. L., et al., 2019, MNRAS, p. 2653
Shapley A. E., Steidel C. C., Pettini M., Adelberger K. L., 2003, ApJ, 588, 65
Shapley A. E., Coil A. L., Ma C.-P., Bundy K., 2005, ApJ, 635, 1006
Shapley A. E., Steidel C. C., Pettini M., Adelberger K. L., Erb D. K., 2006, ApJ, 651, 688
Shapley A. E., et al., 2015, ApJ, 801, 88
Shapley A. E., et al., 2019, ApJ, 881, L35
Sommariva V., Mannucci F., Cresci G., Maiolino R., Marconi A., Nagao T., Baroni A., Grazian A., 2012, A&A, 539, A136
Stanway E. R., Eldridge J. J., 2018, MNRAS, 479, 75
Steidel C. C., et al., 2014, ApJ, 795, 165
Steidel C. C., Strom A. L., Pettini M., Rudie G. C., Reddy N. A., Trainor R. F., 2016, ApJ, 826, 159
Strom A. L., Steidel C. C., Rudie G. C., Trainor R. F., Pettini M., Reddy N. A., 2017, ApJ, 836, 164
Strom A. L., Steidel C. C., Rudie G. C., Trainor R. F., Pettini M., 2018, ApJ, 868, 117
Veilleux S., Osterbrock D. E., 1987, ApJS, 63, 295
Weinberg D. H., Andrews B. H., Freudenburg J., 2017, ApJ, 837, 183
Zahid H. J., Kudritzki R.-P., Conroy C., Andrews B., Ho I. T., 2017, ApJ, 847, 18

MNRAS 000, 1–77 (0000)