THE RELATIONSHIP BETWEEN STELLAR MASS, GAS METALLICITY, AND STAR FORMATION RATE FOR 
Hα-SELECTED GALAXIES AT z ≈ 0.8 FROM THE NEWHα SURVEY

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ABSTRACT

Using a sample of 299 Hα-selected galaxies at z ≈ 0.8, we study the relationship between galaxy stellar mass, gas-phase metallicity, and star formation rate (SFR), and compare to previous results. We use deep optical spectra obtained with the IMACS spectrograph at the Magellan telescope to measure strong oxygen lines. We combine these spectra and metallicities with (1) rest-frame UV-to-optical imaging, which allows us to determine stellar masses and dust attenuation corrections, and (2) Hα narrowband imaging, which provides a robust measurement of the instantaneous SFR. Our sample spans stellar masses of ~10^9.6–10^11 M☉, SFRs of 0.4–270 M☉ yr^-1, and metal abundances of 12 + log (O/H) ≈ 8.3–9.1 (≈0.4–2.6 Z☉). The correlations that we find between the Hα-based SFR and stellar mass (i.e., the star-forming “main sequence”) and between the stellar mass and metallicity are both consistent with previous z ≈ 1 studies of star-forming galaxies. We then study the relationship between the three properties using various plane-fitting techniques and a curve-fitting projection. In all cases, we exclude strong dependence of the M*–Z relation on SFR, but are unable to distinguish between moderate and no dependence. Our results are consistent with previous mass–metallicity–SFR studies. We check whether data set limitations may obscure a strong dependence on the SFR by using mock samples drawn from the Sloan Digital Sky Survey. These experiments reveal that the adopted signal-to-noise ratio cuts may have a significant effect on the measured dependence. Further work is needed to investigate these results, and to test whether a “fundamental metallicity relation” or a “fundamental plane” describes star-forming galaxies across cosmic time.

Key words: galaxies: abundances – galaxies: evolution – galaxies: fundamental parameters – galaxies: ISM – galaxies: starburst

Supporting material: machine-readable and VO tables

1. INTRODUCTION

Studying the general relationships between the physical properties of galaxies— including stellar mass (M*), gas-phase metallicity (Z), and star formation rate (SFR) — provides clues about galaxy formation and evolution. Stellar mass is an estimate of the amount of gas converted into stars in a galaxy over time, whereas the SFR measures the current rate at which gas is consumed to form stars. In addition, the gas-phase metallicity reflects both the amount of gas reprocessed by stars and galactic interactions with the environment through the infall and outflow of gas.

Combinations of these three properties have been well studied. The mass–metallicity (M*–Z) relation is a nonlinear one in which Z increases with M* up to a stellar mass of about 3 × 10^10 M☉ and then plateaus (e.g., Tremonti et al. 2004, hereafter T04; Moustakas et al. 2011; Zahid et al. 2011; Andrews & Martini 2013). The relation has been shown to evolve toward lower metallicity at higher redshifts (Erb et al. 2006; Maiolino et al. 2008; Mannucci et al. 2009; Zahid et al. 2013), although the exact nature of this evolution is unclear, in part because high-z results are still significantly incomplete at low stellar masses. Similarly, the positive correlation between M* and SFR (SFR ∝ M*α, Salim & Lee 2012), called the “star formation sequence” (Salim et al. 2007) or the galaxy “main sequence” (Noeske et al. 2007), shows evolution with redshift toward higher SFRs at earlier times (e.g., Elbaz et al. 2007; Noeske et al. 2007; Whitaker et al. 2012).

Despite the tightness of the M*–Z relation, some intrinsic scatter remains (~0.1 dex). It has been suggested that part of this scatter can be accounted for by a secondary dependence on the SFR—at a given stellar mass, lower-metallicity galaxies tend to have higher SFRs (Ellison et al. 2008; Lara-López et al. 2010; Mannucci et al. 2010) and lower SFR galaxies tend to have higher metallicities (Ellison et al. 2008; Peebles et al. 2008). A relationship between all three properties was proposed (e.g., Mannucci et al. 2010, hereafter Man10).

The physical origin of such a M*–Z–SFR relation is thought to be a result of the way galaxies process gas. The oxygen-to-hydrogen gas ratio in a galaxy is regulated by its stellar mass, history of outflows, and gas mass. The amount of oxygen in the

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interstellar medium (ISM) is primarily set by the mass of oxygen the galaxy has produced in its lifetime (which is roughly proportional to its stellar mass), minus the oxygen mass residing in stars and/or lost in outflows (Peeples et al. 2014). The degree to which the ISM oxygen content is diluted is determined by the galaxy’s gas mass (Peeples & Shankar 2011), which is in turn regulated by a balance between star formation, accretion, and outflows (e.g., Davé et al. 2011; Lilly et al. 2013; Forbes et al. 2014).

Infall of metal-poor gas will initially dilute the metal abundance already present in the ISM while enhancing the SFR, leading to the observed trend of Z and SFR being inversely proportional at a given mass. However, as the enhanced star formation continues, the freshly produced metals can quickly erase the signature of fresh inflow, causing an increase in metallicity while the SFR is still relatively high (Torrey et al. 2012). Outflows driven by star formation must then be removing these freshly produced metals from the ISM in order for the galaxy to continue to have a low ISM abundance while having enhanced star formation. In this scenario, an observed $M_\star$–Z–SFR relation (and its assumed lack of evolution) is largely coincidental and a result of the tendency for galaxies to move toward an equilibrium between galactic inflows and outflows (Davé et al. 2011).

In this framework, if galaxies at different redshifts universally obey the same relation between stellar mass, gas mass, and gas metallicity, then this could imply something “fundamental” about how galaxies expel their metals through time. Measurements of H i masses are not currently feasible at redshifts beyond the local universe, so SFR has generally been used as a proxy for gas mass. Furthermore, a “fundamental” $M_\star$–Z–SFR relation would imply that the evolution of the $M_\star$–Z relation and the star formation sequence are simply consequences of preferentially observing higher SFRs at higher redshifts (Man10; Hunt et al. 2012).

However, the existence of a fundamental $M_\star$–Z–SFR relation remains controversial. While several works have found evidence of such a relation at local redshifts (see, e.g., Man10; Hunt et al. 2012; Yates et al. 2012, hereafter Yat12, Andrews & Martini 2013; Pérez-Montero et al. 2013), Sánchez et al. (2013) and Hughes et al. (2013) were unable to find a significant dependence of the $M_\star$–Z relation on the total SFR from integral field spectroscopy at local redshifts and suggested that previously reported results may be due to the impact of observational effects such as aperture bias on the SFR. At higher redshifts, uncertainty remains over the existence of the $M_\star$–Z–SFR relation and its evolution. Once again, several studies found evidence of a relation (e.g., Richard et al. 2011; Cresci et al. 2012; Belli et al. 2013; Henry et al. 2013a, 2013b, the results of which all agreed with the local $M_\star$–Z–SFR relation), but other studies were less conclusive. Yabe et al. (2012) and Yabe et al. (2014) found a $M_\star$–Z–SFR relation deviating slightly from that reported at local redshifts, while Zahid et al. (2014) found a weak dependence of the $M_\star$–Z relation on SFR that was significantly different from the local relation and concluded that this was a result of redshift evolution. In addition, Stott et al. (2013) stacked spectra and found evidence that star-forming galaxies at $z \sim 0.8$ and $z \sim 1.5$ have gas-phase metallicities that are consistent with the local $M_\star$–Z relation, in contrast with other high-$z$ studies. In most cases, samples are potentially subject to data set limitations.

Ideally, tracking $M_\star$, Z, and SFR in a consistent manner across a range of redshifts would provide a solid empirical basis from which to study their relationship and its evolution. At low-$z$, the $M_\star$–Z–SFR relation has largely been investigated using data from the Sloan Digital Sky Survey (SDSS; York et al. 2000), a sample consisting of over a hundred thousand galaxies that covers stellar masses from about $10^{2}$ to $10^{11.5}$ $M_\odot$, gas-phase metallicities from $12 + \log (O/H) = 8.5$ to 9 (0.6–2 $Z_\odot$), and SFRs from log (SFR/$M_\odot$ yr$^{-1}$) = −1.45 to 0.8 (Man10). The $M_\star$–Z–SFR relation has also been extended to low-mass galaxies, albeit with smaller sample sizes, down to $M_\star \sim 10^{7.3}$ $M_\odot$ with gamma-ray bursts (Mannucci et al. 2011) and $\sim 10^{6}$ $M_\odot$ with dwarf galaxies (Hunt et al. 2012).

Studies at higher redshifts generally have much smaller samples that cover more limited portions of parameter space. For $z = 0.4–1$, Man10 used a sample of 69 galaxies with masses of $10^{8.2}–10^{10.7}$ $M_\odot$ from Savaglio et al. (2005), while Lara-López et al. (2010) (hereafter Lar10) used 88 galaxies from Rodrigues et al. 2008 with masses of $10^{8}–10^{12.2}$ $M_\odot$. At $1 \leq z \lesssim 3$, the largest samples used are those of Erb et al. (2006), with 91 UV-selected galaxies at $z \sim 2.2$, and that of the Spectroscopic Imaging Survey (Fürster Schreiber et al. 2009), consisting of 62 galaxies at $z \sim 2$, both with mass ranges of $10^{7}–10^{11}$ $M_\odot$. Recent efforts have increased the sample size at $z \sim 1.5$. Zahid et al. (2014) used $\sim$150 star-forming galaxies from the COSMOS field at $z \sim 1.6$ and masses ranging from approximately $10^{9.5}$ to $10^{11}$ $M_\odot$. Yabe et al. (2012) and Yabe et al. (2014) conducted near-infrared fiber spectroscopy for 70–340 galaxies at $z \sim 1.4$, Stott et al. (2013) used 64 Hα-selected galaxies at $z \sim 1–1.5$, and Henry et al. (2013b) performed infrared grism spectroscopy for 83 galaxies at $z \sim 1.5–2.3$. However, at high-$z$, spectral stacking is predominantly used, and low-mass galaxies below $5 \times 10^{8}$ $M_\odot$ have yet to be studied extensively. There have been efforts to extend $z \sim 0.5–3$ studies toward lower stellar masses (Xia et al. 2012; Belli et al. 2013; Henry et al. 2013a, 2013b; Ly et al. 2014); however, sample sizes remain limited.

Thus, the $M_\star$–Z–SFR relation requires further study, particularly for redshifts above $z \sim 0.3$ (the maximum redshift for the SDSS sample). We aim to build upon previous work by using a sample of star-forming galaxies at $z = 0.8$ (when the universe was roughly $\sim$7 Gyr old or half of the Hubble time). We use methods of deriving $M_\star$, Z and SFR that are similar to those used by local studies. Deep rest-frame optical spectra obtained with the IMACS spectrograph at the Magellan 6.5 m telescope are used to measure gas-phase metallicities with oxygen strong-line calibrations. The spectra are used along with (1) rest-frame UV-to-optical imaging data, which allow us to determine stellar masses and dust attenuation corrections, and (2) our Hα narrowband imaging data, which provide a robust measure of SFR.

In Section 2, we describe the NewHα survey, sample selection, and spectroscopy. We also present the photometric properties and the spectroscopic emission-line fluxes of the galaxies used in this analysis. Section 3 discusses the calculation of our physical properties from (1) spectral energy distribution (SED) fitting spanning rest-frame 1400–7000 Å to estimate stellar masses, dust attenuation, and UV SFRs, (2) Hα luminosities to determine SFRs, and (3) several empirical and theoretical strong-line calibrations to estimate gas-phase metallicity. In Section 4, we use our data to produce a $M_\star$–Z relation and a $M_\star$–SFR relation, and compare them with
previous literature results. We also investigate the $M_{\ast}$–$Z$–SFR relation through different plane-fitting and three-dimensional curve-fitting approaches and compare with literature $M_{\ast}$–$Z$–SFR relations found at local redshifts. In Section 5, we discuss how limitations in (1) our data set, (2) plane-fitting techniques, and (3) the parameterization of the $M_{\ast}$–$Z$–SFR relation may affect our ability to fully constrain the existence or evolution of the $M_{\ast}$–$Z$–SFR relation. Finally, we summarize our work in Section 6.

Throughout this paper, we assume a ΛCDM cosmology with $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_M = 0.3$, and $\Omega_{\Lambda} = 0.7$ for distance-dependent calculations, which is similar to the 7 year WMAP results (Komatsu et al. 2011). Unless otherwise noted, a Chabrier (2003, hereafter Chabrier) initial mass function (IMF) is assumed, and all magnitudes are reported on the AB system (Oke 1974).

2. DATA

We present near-IR narrowband photometry and optical spectroscopy for a sample of 299 Hα-selected galaxies at $z \sim 0.8$ from the NOAO Extremely Wide-Field Infrared Imager (NEWFIRM) NewHα survey (Ly et al. 2011a; Lee et al. 2012). The galaxies are identified in the Subaru/XMM Deep Survey (SXDS) field (Furusawa et al. 2008), and deep follow-up spectroscopy was performed with the Inamori Magellan Areal Camera and Spectrograph (IMACS; Dressler et al. 2006) at the Magellan 6.5 m Baade telescope (Momcheva et al. 2013). Emission lines from [O II] $\lambda 3727$ to [O III] $\lambda 5007$ are observed in the spectra. In this section, we provide a brief overview of the NewHα survey, the sample selection, and the IMACS spectroscopy. We also describe multiwavelength broadband photometry used in SED fitting to derive galaxy stellar masses, dust attenuation, and a second measure of the dust-corrected SFR.

2.1. The NewHα Narrowband Survey: Selecting Emission-line Galaxies

The NewHα Survey is a program that has obtained emission-line selected samples at intermediate redshift (Lee et al. 2012). The program was designed to efficiently obtain statistical samples of both luminous (but rare) and faint emission-line galaxies. We do this by combining the near-IR imaging capabilities of NEWFIRM (Auty et al. 2003; Probst et al. 2008) at the KPNO/CTIO 4 m telescopes to cover large areas (field of view (FOV) of 27′6 × 27′6), and FourStar (FOV of 10′9 × 10′9; Persson et al. 2008) at the Magellan 6.5 m Baade telescope to probe luminosities that are about a factor of three deeper over smaller areas. For both cameras, we use a pair of custom 1% narrowband filters that fit within windows of high atmospheric transmission and low OH airglow at 1.18 and 2.09 μm. With these two filters, deep Hα-selected galaxy samples are obtained at $z = 0.8$ (near the beginning of the tenfold decline in the cosmic SFR density) and at $z = 2.2$ (near the peak of the cosmic SFR density; see, e.g., Reddy et al. 2008; Ly et al. 2009, 2011b).

The work presented in this paper focuses on Hα emitters at $z = 0.8$, which are detected in NEWFIRM narrowband 1.18μm (hereafter NB118) and J imaging of a 0.82 deg$^2$ region in the SXDS (see Figure 1). Here we summarize the NB118 observations, data reduction, and selection method used to produce samples of emission-line galaxy candidates that are then targeted for IMACS spectroscopy.

NEWFIRM at the KPNO 4 m was used to obtain observations over three pointings in the SXDS ($\alpha = 2^h 18^m, \delta = -5^o$) in 2007 December, 2008 September, and 2008 October. The positioning of these three fields relative to other observations are shown in Figure 1. The cumulative exposure times for each pointing ranged from 8.47 to 12.67 hours in NB118 and from 2.40 to 3.97 hours in J. The median seeing during our observations was 1′2, and varied between 1′0 and 1′9, so point sources are adequately sampled by NEWFIRM’s 0′4 pixels. Standard near-IR deep-field observing procedures and reduction techniques were used, and are discussed further in Ly et al. (2011a). The 3σ limiting magnitudes, in apertures (of diameters twice the FWHM) containing at least ~80% of the flux of a point source, range from 23.7 to 24.2 mag (23.4–24.1 mag) in NB118 (J).

Sources are selected as emission-line galaxy candidates if they show a J–NB118 color excess that is significant at the 3σ level and is greater than 0.2 mag. The minimum of 0.2 mag is based on the scatter in the color excess for bright point sources. Corrections for the continuum slope are applied based on the $z′$–$i′$ color (Ly et al. 2011a), using publicly available Subaru/Suprime-Cam $z′$ data where available (see Section 2.3 for further details). The overall procedure follows general selection techniques commonly used in narrowband surveys (Fujita et al. 2003; Ly et al. 2007; Shioya et al. 2008; Villar et al. 2008; Sobral et al. 2009). A total sample of 661 emission-line galaxy candidates meeting these criteria was obtained over the three NEWFIRM pointings. Follow-up spectroscopy was obtained for a subset of these galaxies, as described below. Using a combination of color-selection methods and spectroscopic confirmation, approximately half of these candidates are identified as Hα excess emitters at $z \sim 0.8$ (Ly et al. 2011a).

2.2. IMACS Spectroscopy

As discussed in Momcheva et al. (2013), deep follow-up spectroscopy of the NewHα NB118 emission-line galaxy candidate sample was performed in 2008–2009 with IMACS on the Magellan-I telescope. IMACS enables multi-object spectroscopy with slit masks over a 27′4 diameter area (well matched to NEWFIRM’s FOV), and has good sensitivity to ~9500 Å. These two characteristics make IMACS an ideal instrument for optical spectroscopic follow-up of NewHα NB118 excess sources, and in particular, Hα emitters at $z \sim 0.8$.

The chosen observational setup yields spectral coverage from 6300 to 9600 Å (corresponding to rest frame ~3500–5300 Å), and captures the strong rest-frame optical emission lines from [O II] $\lambda 3727$ (observed at ~6700 Å) to [O III] $\lambda 5007$ (observed at ~9000 Å) for galaxies at $z \approx 0.8$. Slit widths of 1″5 were chosen (~11 kpc at $z = 0.8$). The seeing during our observing runs was generally sub-arcsecond. The typical integration time was 4.5 hours; however, for about half of the Hα-emitting galaxies, deeper observations were acquired for a total of 7.75 hours (see Figure 1 of Momcheva et al. 2013) to improve the measurement of detected, but low signal-to-noise ratio (S/N) Balmer lines.

Of the 661 NB118 emission-line galaxy candidates in the SXDS, 386 were targeted with IMACS. Priority was given to sources likely to be intermediate redshift candidates based on their photometric redshifts (Furusawa et al. 2008), while
3. Multiwavelength Photometry

We use multiband photometry (NUV, u, B, V, R_C, i', z' and J) as constraints in the spectral energy distribution (SED) fitting, which is discussed later in Section 3.1. The NUV photometry are based on deep (46 ks) GALEX (Martin et al. 2005; Morrissey et al. 2007) imaging of the SXDS fields (PI: S. Salim, GI6-005). At z = 0.8, the NUV band (λ_c ≈ 2300 Å) samples the rest-frame far-UV. In addition to the dedicated “tilt” (1.2 deg circular GALEX pointing) from this program, our NEWFIRM observations in the SXDS also partially overlap three shallower archival GALEX tiles with exposure times of 26–30 ks (Figure 1). The mean 5σ depth for the combined NUV imaging in the NEWFIRM fields is 25.3 mag (exposure time ~80 ks), which is ~1 mag shallower than the deepest GALEX NUV imaging (the Extended Groth Strip (EGS) field; Salim et al. 2009), with integration time of ≈260 ks. 

Because sources are unresolved in GALEX at z ≈ 0.8 (the GALEX FWHM is ~5") we use point-spread function (PSF) source extraction and photometry based on u-band priors, which improves upon the NUV photometry used in Momcheva et al. (2013). The u-band photometry is based on a (1 deg)^2 pointing with Canada–France–Hawaii Telescope (CFHT) Megacam (Boulade et al. 2003) with a 3σ depth in 20'' aperture of 27.0 mag (S. Foucaud 2014, private communication). The prior-based photometry is performed using EMphot software (version 2.0; Vibert et al. 2009). Priors were limited to u ≤ 25 mag in order to match the GALEX depth. 

The optical photometry was obtained with Suprime-Cam (Miyazaki et al. 2002) as part of the Subaru Telescope Observatory Projects (Furusawa et al. 2008). The SXDS fields observed by NEWFIRM roughly correspond with the Suprime-Cam south, west, and north pointings (SXDS-S, SXDS-W, and SXDS-N; Figure 1). Subaru imaging is publicly available in five broadband filters to 3σ depths of B = 28.4, V = 27.8, R_C = 27.7, i' = 27.7, and z' = 26.6 mag. The Suprime-Cam data reduction and photometry are further described in Furusawa et al. (2008).

Based on publicly available CFHT/Megacam data: http://www1.cadc-ccda.hia-iha.nrc-cnrc.gc.ca/en/.
Table 1
NEWFIRM Photometry of Hα-selected z = 0.8 Galaxies

| ID          | R.A. (J2000) | Decl. (J2000) | z   | $m_b$ | $m_{NB18}$ | Line flux | NB EW | $[N\,\text{II}]/H\alpha$ | log ($L_{H\alpha}$) |
|-------------|--------------|---------------|-----|-------|------------|-----------|-------|-------------------------|-------------------|
| SXDSN-12615 | 2 17 17.7    | -4 45 18.9    | 0.796 | 21.46 ± 0.07 | 20.79 ± 0.05 | 19.6 ± 2.0 | 56 ± 17 | 0.27 | 41.660 |
| SXDSN-14848 | 2 18 09.7    | -4 42 25.1    | 0.805 | 22.96 ± 0.24 | 21.83 ± 0.09 | 10.6 ± 1.7 | 125 ± 94 | 0.40 | 41.364 |
| SXDSN-17153 | 2 17 29.1    | -4 47 11.4    | 0.797 | 20.56 ± 0.02 | 19.90 ± 0.01 | 41.5 ± 1.5 | 48 ± 5  | 0.38 | 41.953 |
| SXDSN-17287 | 2 18 11.5    | -4 47 01.0    | 0.805 | 22.75 ± 0.22 | 21.99 ± 0.13 | 7.2 ± 1.9  | 68 ± 62 | 0.35 | 41.213 |
| SXDSN-18372 | 2 18 11.6    | -4 46 17.3    | 0.804 | 21.52 ± 0.07 | 20.94 ± 0.05 | 14.8 ± 1.9 | 43 ± 16 | 0.31 | 41.537 |
| SXDSN-18825 | 2 17 24.3    | -4 45 55.8    | 0.797 | 22.70 ± 0.16 | 22.22 ± 0.12 | 3.5 ± 1.6  | 29 ± 33 | 0.31 | 40.908 |
| SXDSN-19419 | 2 18 20.1    | -4 36 46.9    | 0.806 | 21.14 ± 0.05 | 20.73 ± 0.04 | 13.2 ± 2.0 | 26 ± 10 | 0.41 | 41.459 |
| SXDSN-19725 | 2 18 18.3    | -4 36 28.1    | 0.805 | 21.16 ± 0.05 | 20.13 ± 0.02 | 48.2 ± 1.8 | 108 ± 17 | 0.33 | 42.044 |

Notes.
(1) ID from the NewHα survey catalog.
(2) Units of R.A. are hours, minutes, and seconds.
(3) Units of decl. are degrees, arcminutes, and arcseconds.
(4) IMACS spectroscopic redshift.
(5) J-band AB magnitude. The conversion from Vega to AB magnitudes is given by $m(AB) - m(Vega) = 0.87$ (Ly et al. 2011a).
(6) Narrowband AB magnitude. The conversion from Vega to AB magnitudes is given by $m(AB) - m(Vega) = 0.95$ (Ly et al. 2011a).
(7) Narrowband flux given in units of $10^{17}$ erg s$^{-1}$ cm$^{-2}$.
(8) Narrowband EW (rest-frame) given in Å.
(9) Estimated [N II]/Hα flux ratio, calculated using the narrowband EW (refer to Section 3.2 for further details). Here, [N II] refers to the doublet, 6548 and 6583 Å.
(10) Log of observed Hα luminosity given in units of erg s$^{-1}$. For both flux and luminosity, the amount of foreground extinction is negligible, so we excluded it in our calculations.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms.)

Table 2
NewHα Emission-line Fluxes from Magellan/IMACS

| ID          | [OIII]$^+$ | [OIII]λ4959 | [OIII]λ5007 | Hβ       | Hγ       | Hα       |
|-------------|-----------|-------------|-------------|----------|----------|----------|
|             | (2)       | (3)         | (4)         | (5)      | (6)      | (7)      |
| SXDSN-12615 | 4.23 ± 0.19 | 1.35 ± 0.45 | 2.61 ± 0.56 | 1.74 ± 0.28 | 1.73 ± 0.33 | 1.90 ± 0.36 |
| SXDSN-14848 | 6.02 ± 0.21 | 1.49 ± 0.42 | 4.83 ± 0.47 | 0.96 ± 0.79 | 1.41 ± 0.25 | 0.09 ± 0.26 |
| SXDSN-17153 | 3.83 ± 0.12 | 1.31 ± 0.36 | 3.81 ± 0.24 | 2.01 ± 0.24 | 0.63 ± 0.22 |       |
| SXDSN-17287 | 1.67 ± 0.12 | 1.39 ± 0.40 | 0.30 ± 0.31 | 0.83 ± 0.45 | 0.56 ± 0.18 | 0.08 ± 0.15 |
| SXDSN-18372 | 3.80 ± 0.15 | 1.66 ± 0.34 | 0.23 ± 0.29 | 3.79 ± 0.59 | 0.99 ± 0.17 | 0.23 ± 0.24 |
| SXDSN-18643 | 2.24 ± 0.09 | 1.82 ± 0.27 | 0.35 ± 0.18 | 2.82 ± 0.33 | 0.79 ± 0.11 |       |
| SXDSN-18689 | 1.65 ± 0.11 | 0.58 ± 0.33 | 0.61 ± 0.29 | 2.40 ± 0.47 | 0.90 ± 0.17 | 0.21 ± 0.18 |
| SXDSN-18825 | 4.46 ± 0.11 | 1.03 ± 0.30 | 2.90 ± 0.40 | 2.09 ± 0.20 | 1.26 ± 0.18 | 1.10 ± 0.19 |
| SXDSN-19419 | ...       | ...         | ...         | ...      | ...      | ...      |
| SXDSN-19725 | 15.14 ± 0.27 | ...         | ...         | ...      | ...      | 1.50 ± 0.29 |

Note. All line fluxes are in units of $10^{-17}$ erg s$^{-1}$ cm$^{-2}$.
$^+$ The sum of the 3726 and 3729 Å lines.

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms.)

3. STELLAR MASS, SFR, AND GAS-PHASE METALLICITY MEASUREMENTS

We now turn our attention to calculating physical properties for the galaxies in the sample from the data presented in Section 2.

3.1. Stellar Masses

Following the methodology of Salim et al. (2007), we derive stellar masses by fitting SEDs to the eight-band$^{14}$ photometry that span rest-frame UV and optical wavelengths, their photometric uncertainties, and spectroscopic redshift. Stellar masses have already been computed using SED fitting for this same sample for the nebular reddening analysis of Momcheva et al. (2013). The main improvement in the calculation performed here is the inclusion of $u$-band photometry, which in combination with the NUV photometry, provides more direct constraints on internal dust attenuation for galaxies at $z \sim 0.8$ via the rest-frame UV color. We give a brief summary of the modeling used, and refer readers to Salim et al. (2007, 2009) for further details.

We use total magnitudes determined within Kron apertures (MAG_Auto from SExtractor; Bertin & Arnouts 1996), except in the NUV band, where PSF extracted magnitudes are used as described above. The SEDs are fit with a library of

$^{14}$ Up to eight bands are available. Coverage in the $u$-band is available for 160 of 278 galaxies, or 57.6% of our sample (see Figure 1).
45,000 Bruzual & Charlot (2003) stellar population synthesis models. The model libraries are built with a wide range of SFHs and metallicities, as described in Salim et al. (2007), and updated in da Cunha et al. (2008). Only models with formation ages lower than 6.8 Gyr, corresponding to the age of the universe at $z = 0.8$, are allowed. Each model is attenuated according to the prescription of Charlot & Fall (2000), with randomly sampled values of both the total optical depth and the fraction of the total optical depth due to attenuation by the ambient ISM. The dust attenuation in the SED fitting is mainly constrained by the UV slope, which gets steeper with increasing attenuation (Calzetti et al. 1994). However, differences in the SFHs can produce significant scatter between the UV slope and dust attenuation (e.g., Kong et al. 2004). This is generally overcome in our modeling because the near-IR and optical data help to constrain the age. Intergalactic reddening is included via the prescription of Madau (1995), and a Chabrier IMF is assumed. The spectroscopic redshift provides the luminosity distance, which allows the apparent model quantities to be scaled to absolute values. We use 0.025 mag calibration errors in all bands, including the NUV photometry, yielding approximately unit Gaussian residuals with respect to the model photometry. An offset of +0.12 mag in $R_C$-band photometry is applied in order to correct the rest-frame 3700 Å discrepancy with the stellar synthesis models (Salim et al. 2009).

For each galaxy the observed fluxes are compared to those in the model library, and the goodness of fit ($\chi^2$) determines the probability weight of a given model. The average of the probability distribution of each fitted parameter is the nominal estimate of that parameter and its width is used to estimate the errors and confidence intervals. The majority of galaxies in the sample are well fit and the median $\chi^2$ per degree of freedom of the best-fitting SED models is close to unity. In the target redshift range (0.77 < $z$ < 0.83), 23 objects are excluded from the sample due to poor fits (i.e., if $\chi^2_{\nu}$ of the best-fitting model is >10), leaving 255. Another 118 non-AGN objects lack $u$-band (rest-frame FUV) photometry.

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**Table 3**

Stellar Mass, SFR, and AGN Classification

| ID         | Mass     | SFR$_{SED}$ | SFR$_{H\alpha,SED}$ | SFR$_{H\alpha, Balmer}$ | AGN |
|------------|----------|-------------|----------------------|-------------------------|-----|
| SXDSN-12615 | 10.23 ± 0.11 | 0.76 ± 0.10 | 0.68 ± 0.29 | −1.75 ± 0.75 | 0   |
| SXDSN-14848 | ... | ... | 0.01 ± 0.08 | ... | 0   |
| SXDSN-17153 | 11.15 ± 0.06 | 1.88 ± 0.05 | 1.73 ± 0.19 | 0.27 ± 0.38 | 0   |
| SXDSN-17287 | 9.93 ± 0.13 | 0.26 ± 0.30 | 0.89 ± 0.46 | ... | 0   |
| SXDSN-18372 | 10.01 ± 0.08 | 0.70 ± 0.09 | 0.81 ± 0.35 | 1.79 ± 0.64 | 0   |
| SXDSN-18643 | 10.81 | 1.81 | 1.55 ± 0.06 | 1.59 ± 0.46 | 0   |
| SXDSN-18689 | 10.48 ± 0.12 | 0.77 ± 0.33 | 1.32 ± 0.42 | 0.79 ± 0.74 | 0   |
| SXDSN-18825 | 9.52 ± 0.14 | 0.57 ± 0.20 | 0.03 ± 0.40 | −1.14 ± 0.49 | 0   |
| SXDSN-19419 | 10.60 ± 0.09 | 0.93 ± 0.22 | 0.59 ± 0.39 | ... | 0   |
| SXDSN-19725 | 10.16 ± 0.10 | 0.99 ± 0.18 | 1.05 ± 0.40 | ... | 0   |

Notes. (1) Ellipses indicate weak measurements. (2) Stellar mass determinations are described in Section 3.1. (3) SFR based on SED fitting. (4) $H\alpha$ SFR, dereddened using the prescription of Charlot & Fall (2000) and SED results. (5) $H\alpha$ SFR, dereddened using the Balmer decrement. (6) “1” denotes AGN, using diagnostics described in Section 2.2.

This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms.

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Figure 2. Top: distribution of stellar masses. Center: measurement error in stellar mass vs. stellar mass (filled points mark AGNs). Right: distribution of stellar mass uncertainties.

The stellar masses and their uncertainties are given in Table 3. The uncertainties include errors from input photometry and parameter degeneracy (e.g., with respect to SFH and dust). Additional systematic uncertainties may arise from the models themselves and the choice of IMF (e.g., Maraston 2005; Conroy et al. 2009; Taylor et al. 2011).

The distribution of derived stellar masses and their uncertainties are shown in Figure 2. AGNs are included in the stellar mass sample, but 25 sources (2 are AGNs) have poor SED fits and are thus excluded from the original sample size of 299, leaving 274 sources. The mean (median) of the sample is $10^{10.9}$ ($10^{9.8}$) $M_\odot$, with an average uncertainty of $\sigma = 0.11$ dex. There are a few galaxies with masses as low as $10^{8.9} M_\odot$, and as high as $10^{11.8} M_\odot$.

### 3.2. Star Formation Rates

The SFRs used in our analysis are measured using two independent methods that are sensitive to different timescales of star formation. First, as with stellar masses, we use the SED...
fitting to provide a measurement of the recent SFR. The rest-frame FUV continuum provides the main constraint on the SFR in the SED modeling, since it primarily originates from the photospheres of O- through late B-type stars in the SED modeling, since it primarily originates from the gas ionized by the most massive O- and early B-type stars. We follow this empirical approach since both the gas ionized by the most massive O- and early B-type stars and both the [O III] lines to be detected at a minimum of 3σ. This restriction limits the DR7 sample to 165,622 galaxies. We do not apply a restriction on [N II], as the line is intrinsically weak, so a required detection will bias the correction against metal-poor galaxies. We then use the Baldwin et al. (1981) “BPT” diagnostic diagram to exclude AGNs. Here we adopt the Kauffmann et al. (2003) selection for star-forming galaxies, which limits the sample further to 140,101 galaxies. We illustrate the [N II] λ6583/Hα and R23 ratios for these galaxies in Figure 4(a). It can be seen that the two ratios are well-correlated with [N II] λ6583/Hα reaching a maximum of ∼0.4. To correct for [N II]/Hα, we use the mean values, which are shown as solid filled squares in Figure 4(a). We also factor in the dispersion of this correlation, which is typically σ ≤ 0.1 dex. Since the [N II] λ6583 is the stronger of the two [N II] lines, we also assume λ6583/λ6548 = 3. For our sample, the [N II] correction is between log ([N II]/Hα) = −1.36 and −0.29, with an average of −0.55.

We note that for a subset of our galaxies (N = 168), the emission lines used for computing R23 are not well measured (<3σ). To correct these galaxies for their [N II] contamination, we follow previous efforts that use the Hα + [N II] equivalent width (EW). This method was first implemented by Villar et al. (2008). One problem with the previous calibration was the inclusion of AGNs and LINERs (Heckman 1980), which significantly biased the [N II] correction. Here, we therefore reproduce the relation of Villar et al. (2008) with only star-forming galaxies. We emphasize that the AGN contribution is low in our sample, and we have utilized various empirical methods to identify and remove AGNs from our sample (see Section 2.2). The EW correlation of [N II]/Hα is illustrated in Figure 4(b).

We find that both the R23- and EW-based methods yield fairly consistent [N II] corrections for the sample with R23 emission lines ([O II], [O III], and Hβ) detected at ≥3σ; the EW-based [N II] corrections are higher than the R23 [N II] corrections by ∼0.05 dex, with a dispersion of ∼0.03 dex. We also find that the EW approach suffers from greater dispersion. This is not a surprise since a tight correlation is not expected between the specific SFR (SFR per unit stellar mass; SFR/M*) of galaxies, as measured from the Hα EW, and their metallicity, as measured from [N II] λ6583/Hα. Since previous studies (e.g., Sobral et al. 2009) used the Villar et al. (2008) calibration, we note that their Hα measurements are underestimated due to a systematically larger correction for [N II].

We note that adopting local measurements to correct for [N II] contribution in the NB filter has its limitations, particularly since a few studies of strongly star-forming galaxies have seen nitrogen abundance enhancements relative to oxygen (Amorín et al. 2010; Masters et al. 2014). This result is not too surprising since nitrogen has a secondary production source. Given this recent evidence, it is therefore likely that we are underestimate the [N II] correction, and thus...
overestimating the H$\alpha$ flux. For the purpose of our analysis, we defer on this issue, but we plan to revisit it in future work.

Dust Attenuation. The H$\alpha$ emission-line luminosities are corrected for dust reddening in two ways: using the Balmer decrement (H$\gamma$/H$\beta$) from spectroscopy and the estimate of nebular attenuation from SED fitting. Since the H$\gamma$ line is intrinsically weak for much of our sample, the majority of the following analysis is based on SED-derived attenuation.

Finally, we use the prescription of Kennicutt (1998) to derive SFRs from H$\alpha$ luminosities. We divide by a factor of 1.8 to convert the SFRs from a Salpeter (1955) to a Chabrier IMF. The distribution of dust-corrected H$\alpha$-based SFR (corrected using SED results and the extinction formalism of Charlot & Fall 2000) is shown in Figure 5. AGNs are again included in this sample; however, 90 sources with $<3\sigma$ NB118 excess flux are removed along with 8 more sources without SED fits, leaving a sample size of 201. The mean (median) of the sample is $10^{0.72}$ ($10^{0.67}$) $M_\odot$ yr$^{-1}$, and the average uncertainty is $\sigma = 0.33$ dex. There are a few galaxies with SFRs as low as $10^{-0.4}$ $M_\odot$ yr$^{-1}$, and as high as $10^{2.6}$ $M_\odot$ yr$^{-1}$. SFRs based on the SED-fitting and H$\alpha$ luminosities are reported in Table 3.

3.3. Gas-phase Metallicities

Various metallicity calibrations have been developed for over two decades, yet the absolute metallicity scale is still uncertain, as demonstrated by Kewley & Ellison (2008). In general, oxygen abundance is used as a proxy for global gas-phase metallicity and expressed as a dimensionless quantity, $Z \equiv 12 + \log (O/H)$. On this scale, $Z_\odot = 8.76$ (Caffau et al. 2011).

The “direct” method of determining Z is to measure the ratio of the weak [O iii] $\lambda$4363 line to a lower excitation line, which gives an estimate of the electron temperature $T_e$ that is inversely related to the gas metallicity. While efforts have measured direct metal abundances (e.g., Kakazu et al. 2007; Brown et al. 2008; Hu et al. 2009; Berg et al. 2012; Ly et al. 2014), [O iii] $\lambda$4363 is very difficult to robustly detect. As a result, strong-line calibrations based on the empirical relationship between $T_e$-based metallicities and strong-line ratios (e.g., $R_{23}$) have been developed (e.g., Nagao et al. 2006). Other calibrations use population synthesis and photoionization models to calculate theoretical strong-line ratios for various input metallicities (e.g., McGaugh 1991; Zaritsky et al. 1994; Kobulnicky & Kewley 2004, hereafter M91, Z94 and KK04, respectively). Finally, Bayesian fitting has been used to find the photoionization model that best explains the observed fluxes of all the most prominent rest-frame optical emission lines (T04).

Metallicities determined from the direct and empirical methods based on $T_e$ have been shown to be systematically lower than those determined from the theoretical methods based on photoionization models (Kewley & Ellison 2008). While this discrepancy is unresolved, problems with photoionization models or temperature gradients/inhomogeneities may cause $T_e$ methods to underestimate true metallicities (Kewley & Ellison 2008). Also, recent efforts have suggested that non-Maxwellian energy distributions in the ISM may be the culprit for many systematic differences (Nicholls et al. 2012, 2013; Dopita et al. 2013). Regardless of what is responsible for the discrepancies, it is clear that a consistent use of a single metallicity calibration is required to obtain a self-consistent $M_*$–$Z$–SFR relation and to study its evolution.

For completeness and to aid direct comparisons in future work, we have determined metallicity using multiple calibrations. In Tables 4 and 5, we present these metallicities, calculated using the nebular emission lines reported in Table 2, with dust attenuation correction derived from the SED fitting and the Balmer decrement (H$\gamma$/H$\beta$), respectively. The transformation from observed line ratios to gas metallicity is summarized in the appendix of Kewley & Ellison (2008).

Note that several calibrations rely on the $R_{23}$ line ratio (Pagel et al. 1979). The M91 and KK04 calibrations also use the $O_{32}$ line ratio: $O_{32} \equiv [O iii] \lambda\lambda 4959, 5007/[O ii] \lambda\lambda 3726, 3729$, as an estimate of the ionization state of the gas. This measurement helps to resolve the degeneracy between ionization state and metallicity (see e.g., Figures 3 and 12 of KK04 and M91, respectively). For this reason, we choose to use the M91...
For the $M_* - Z$–SFR relation (Section 4.4), previous studies have used the T04 calibration rather than M91 (e.g., Lar10; Yat12). To aid in direct comparisons, we analyze the $M_* - Z$–SFR relation using metallicities scaled with respect to the photoionization models derived by T04; however, supplementary results using M91 metallicities are provided. When computing T04-based metallicities, we use the following empirical $R_{23}$–Z relation provided by T04:

$$12 + \log \left( \frac{O}{H} \right) = 9.185 - 0.313x - 0.264x^2 - 0.321x^3,$$

where $x \equiv \log (R_{23})$.

The relationship between $R_{23}$ and O/H is double-valued, and so a given value of $R_{23}$ may correspond to a low or high metallicity (“lower branch” and “upper branch,” respectively), and additional line ratios are needed to break the degeneracy. One such ratio is $[\text{NII}]_{6583}/\text{H}\alpha$ (Kewley & Ellison 2008); however, this requires medium-resolution infrared spectroscopy for our galaxies, which we currently do not have. An alternative line ratio that can distinguish between the upper and lower branch is the $O_{32}$ ratio (e.g., Nagao et al. 2006; Maiolino et al. 2008). We illustrate the dust-corrected $R_{23}$ and $O_{32}$ ratios in Figure 6, which demonstrates that the majority of our sources follow the upper $R_{23}$ branch. There are a few sources with line ratios such that the choice in upper or lower branch is ambiguous (shaded region in Figure 6). Adopting either branch does not impact the primary results of our $M_* - Z$–(SFR) analysis.

For this work with previous results (Section 4.3). For instances where a different metallicity calibration was used, we converted to M91-based metallicity using the relations defined in Table 3 of Kewley & Ellison (2008).

![Figure 5](image_url)

**Figure 5.** Top: distribution of dust-corrected Hα-based SFRs. Center: measurement error in SFR vs. SFR (filled points mark AGNs). Right: distribution of SFR uncertainties.

### Table 4

NewHα SED-corrected Metallicities

| ID       | M91 upper | M91 lower | Z94 | T04 | N06 | KK04 upper | KK04 lower |
|----------|-----------|-----------|-----|-----|-----|------------|------------|
| SXDSN-12615 | 8.661 ± 0.120 | 7.986 ± 0.179 | 8.768 ± 0.132 | 8.713 ± 0.119 | 8.700 | 8.828 | 8.177 |
| SXDSN-18825 | 8.568 ± 0.079 | 8.149 ± 0.092 | 8.672 ± 0.097 | 8.635 ± 0.068 | 8.601 | 8.734 | 8.302 |
| SXDSN-19922 | 8.944 ± 0.002 | 7.362 ± 0.006 | 9.102 ± 0.003 | 9.020 ± 0.003 | 9.066 | 9.049 | 7.680 |
| SXDSN-20554 | 8.956 ± 0.026 | 7.408 ± 0.069 | 9.122 ± 0.032 | 9.041 ± 0.033 | 9.094 | 9.066 | 7.701 |
| SXDSN-22048 | 8.295 ± 0.183 | 8.487 ± 0.202 | 8.358 ± 0.256 | 8.400 ± 0.172 | 8.410 | 8.574 |
| SXDSN-22245 | 8.519 ± 0.058 | 7.783 ± 0.116 | 8.973 ± 0.063 | 8.894 ± 0.058 | 8.911 | 8.985 | 7.992 |
| SXDSN-23784 | 8.814 ± 0.039 | 7.770 ± 0.100 | 8.962 ± 0.043 | 8.884 ± 0.039 | 8.899 | 8.977 | 7.988 |
| SXDSN-23860 | 8.903 ± 0.048 | 7.597 ± 0.116 | 9.065 ± 0.054 | 8.983 ± 0.052 | 9.019 | 9.043 | 7.843 |
| SXDSN-24371 | 8.948 ± 0.027 | 7.500 ± 0.099 | 9.118 ± 0.033 | 9.036 ± 0.030 | 9.088 | 9.072 | 7.759 |
| SXDSN-24458 | 8.830 ± 0.026 | 7.763 ± 0.054 | 8.985 ± 0.030 | 8.906 ± 0.028 | 8.924 | 8.993 | 7.975 |

**Note.** All metallicities are reported in form $Z = 12 + \log (O/H)$. “N06” refers to Nagao et al. (2006).

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms.)

### Table 5

NewHα Balmer-corrected Metallicities

| ID       | M91 upper | M91 lower | Z94 | T04 | N06 | KK04 upper | KK04 lower |
|----------|-----------|-----------|-----|-----|-----|------------|------------|
| SXDSN-12615 | 9.077 ± 0.009 | 6.776 ± 0.080 | 9.301 ± 0.017 | 9.218 ± 0.015 | 9.071 | 7.242 |
| SXDSN-18825 | 8.697 ± 0.079 | 7.820 ± 0.162 | 8.751 ± 0.116 | 8.699 ± 0.091 | 8.682 | 8.840 | 8.067 |
| SXDSN-19922 | 8.700 ± 0.066 | 7.986 ± 0.092 | 8.839 ± 0.080 | 8.773 ± 0.068 | 8.771 | 8.880 | 8.159 |
| SXDSN-20554 | 9.068 ± 0.021 | 7.048 ± 0.136 | 9.276 ± 0.041 | 9.196 ± 0.040 | 9.132 | 7.400 |
| SXDSN-22048 | 8.935 ± 0.060 | 7.490 ± 0.223 | 9.099 ± 0.079 | 9.017 ± 0.069 | 9.063 | 9.059 | 7.760 |
| SXDSN-23860 | 8.692 ± 0.122 | 8.064 ± 0.234 | 8.852 ± 0.145 | 8.785 ± 0.118 | 8.784 | 8.884 | 8.202 |
| SXDSN-24371 | 8.830 ± 0.026 | 7.763 ± 0.054 | 8.985 ± 0.030 | 8.906 ± 0.028 | 8.924 | 8.993 | 7.975 |
| SXDSN-24458 | 8.293 ± 0.130 | 8.413 ± 0.153 | 8.138 ± 0.193 | 8.250 ± 0.112 | 8.264 | 8.562 |

**Note.** All metallicities are reported in form $Z = 12 + \log (O/H)$. “N06” refers to Nagao et al. (2006).

(This table is available in its entirety in machine-readable and Virtual Observatory (VO) forms.)
Figure 6. Metallicity-sensitive \( R_{23} \) and ionization parameter-sensitive \( O_{32} \) emission-line ratios for the \( z = 0.8 \) NewH\( \alpha \) sample. We limit the sample to galaxies that are not AGNs, as well as galaxies that have reliable SED fits (i.e., these galaxies are later used to construct the \( M_\ast - Z \) relation). Filled points show the \( R_{23}(5\sigma) \) sample with additional sources from the \( R_{23}(3\sigma) \) sample as unfilled points. Brown circles indicate galaxies with high \( R_{23} \) values such that the upper branch metallicity is less than the lower branch metallicity. Photoionization models from M91 are overlaid in colors for metallicities \( \leq 0.8 \) NewH\( \alpha \) sample. We limit the sample to metallicities uncertainties. Only galaxies with \( \chi^2 < 10 \) with \( u \)-band photometry are included, leaving a sample size of 114.

In our analysis, we first compare the two measures of the SFRs computed above—those based upon the H\( \alpha \) flux and those derived from the SED modeling of rest-frame FUV to R-band photometry—as a check on the relative reliability of the methods (Section 4.1). We then compare the stellar mass, SFR, and metallicity measurements for the NewH\( \alpha \) sample to other measurements in the literature, as studied within the framework of the star formation sequence (Section 4.2) and the \( M_\ast - Z \) relation (Section 4.3). Finally, we combine these two relations to investigate the \( M_\ast - Z \)–SFR relation at \( z \approx 0.8 \) (Section 4.4).

In each analysis, we use various combinations of sample restrictions. For convenience, the sample cuts used and the subsample sizes are compiled in Table 6.

4. RESULTS AND ANALYSIS

4.1. Comparison of SFR Tracers

In order to compare SFR measurements from different tracers, we do not consider AGNs. From the remaining sample of 278 galaxies, only those with an NB118 excess line flux \( \geq 5\sigma \) and good SED fits \( (\chi^2 < 10) \) with \( u \)-band photometry are included, leaving a sample size of 114.

We illustrate the SED- and H\( \alpha \)-based SFRs in Figure 8. Since the SED modeling constrains the dust attenuation, we also correct the H\( \alpha \) measurements with the SED-based dust extinction estimates for each of our galaxies, \( A(H\alpha) = 0.96 \eta \). We find that the SED-based SFRs are higher than the H\( \alpha \)-based SFRs by \( \sim 0.09 \) dex in the median, well within the scatter of 0.24 dex. In addition, we find that there is no mass dependence of the residual, and that these two measurements even agree at high SFRs (\( \geq 100 \ M_\odot \ yr^{-1} \)). We note that similar results on the SFR comparison are found using Balmer decrements (\( H\gamma/H\beta \), obtained from spectroscopy; see Section 2.2) for dust attenuation. However, only 27 galaxies have deep enough spectra (\( H\gamma \ S/N \geq 10 \)) to yield individual decrements that are reliable at \( \Delta(E_{B-V}) = 0.2 \) mag.

These results are roughly consistent with other comparisons of SFR tracers at similar or lower redshifts. For example, Villar et al. (2011) compared H\( \alpha \)- and FUV-based SFRs at \( z \sim 0.84 \). While Villar et al. (2011) found that observed H\( \alpha \)-based SFRs were systematically higher than FUV-based SFRs, they also found that correcting for dust caused the two SFR tracers to agree at the level of 0.05 dex with a dispersion of \( \sim 0.2 \)–0.25 dex. Also, Ly et al. 2012 have compared SED-based SFRs against H\( \alpha \) SFRs in \( z = 0.4 \)–0.5 H\( \alpha \)-selected galaxies, and also find good agreement with low dispersion \( (\sim 0.2 \) dex) with corrections for dust attenuation based on estimates from SED fits.

Since the H\( \alpha \)-based SFRs are more robust to the effects of dust attenuation compared with the SED-based SFRs, we hereafter use H\( \alpha \) SFRs, corrected for dust attenuation determined from SED fitting.
4.2. The Star Formation Sequence

The relation between SFR and $M_\star$, commonly referred to as the “star-forming sequence” (Salim et al. 2007) or the “main sequence of star-forming galaxies” (Noeske et al. 2007), has been well studied at low (e.g., Brinchmann et al. 2004; Salim et al. 2007) and intermediate (e.g., Noeske et al. 2007; Villar et al. 2011; Whitaker et al. 2012) redshifts, with general agreement among different literature results. It manifests as a relatively tight ($\sigma \sim 0.3$ dex) relationship usually parameterized as SFR $\propto M_\star^{1.3}$, although some recent works have suggested that the $M_\star$–SFR relation is not a simple power law at high redshifts (Whitaker et al. 2014). The evolution of the form of the $M_\star$–SFR relation over cosmic time can provide constraints on the characteristic star formation history of galaxies and the significance of episodic bursts of activity in building up the stellar mass (e.g., Noeske et al. 2007). In this section, we compare our NewH$\alpha$ results with other studies at $z \sim 0.8$.

The top panel in Figure 9 plots the NewH$\alpha$ $M_\star$–SFR data and a least-squares linear fit to our 3$\sigma$ sample (i.e., NB118 excess flux $>3\sigma$). We find the resulting best-fit power law to be:

$$\log \left( \frac{\text{SFR}_{\text{H}\alpha}}{M_\odot \, \text{yr}^{-1}} \right) = (0.75 \pm 0.07) \log \left( \frac{M_\star}{M_\odot} \right) - (6.73 \pm 0.67). \tag{3}$$

The bottom panel compares this linear fit (red line with average measured scatter of 0.47 dex) against literature star formation sequences and estimated intrinsic scatters determined by Noeske et al. (2007) and Elbaz et al. (2007) (compiled by Dutton et al. 2010), as well as Villar et al. (2011) and Whitaker et al. (2012). The medians of the NewH$\alpha$ data binned by mass (black points) are provided in Table 7. When necessary, stellar masses and SFRs have been converted to a Chabrier IMF from a Salpeter (1955) IMF by dividing by 1.8 (e.g., González et al. 2010). The local star formation sequence (solid orange band, Salim et al. 2007; Salim & Lee 2012) has also been plotted for comparison.

Despite small variations, the NewH$\alpha$ $M_\star$–SFR relation and literature relations at similar redshift are all systematically higher than the local relation (Salim et al. 2007). This is consistent with studies that generally find that galaxies at higher redshift tend to have higher SFRs at fixed stellar mass compared to galaxies in the local universe.

As noted in Section 3.1, the NewH$\alpha$ survey covers a stellar mass range of $10^{8.8}$–$10^{11.8} M_\odot$ with an average mass of $10^{9.9} M_\odot$. At similar redshifts, Noeske et al. (2007) investigated a limited stellar mass range of $10^{10.0}$–$10^{11.3} M_\odot$, whereas Elbaz et al. (2007) covered a mass range of $10^{9.3}$–$10^{11.1} M_\odot$ and Whitaker et al. (2012) covered a mass range of $10^{9.5}$–$10^{11.0} M_\odot$. It is notable that despite varying mass ranges, sample selection methods, and SFR determinations, Noeske et al. (2007), Elbaz et al. (2007), and Whitaker et al. (2012) each find best-fit power-law relationships that are all fairly consistent with each other. The NewH$\alpha$ fit also agrees well with these relations, with some minor variations.

The Noeske et al. (2007) relation (green band horizontally cross-hatched) is $\log \left( \frac{\text{SFR}}{(M_\odot \, \text{yr}^{-1})} \right) = (0.67 \pm 0.08) \log \left( \frac{M_\star}{M_\odot} \right) - (5.96 \pm 0.78)$ (using the relation compiled by Dutton et al. 2010). It therefore has a shallower slope than the NewH$\alpha$ relation. However, the NewH$\alpha$ fit lies within the scatter of the Noeske et al. (2007) relation ($\sim0.3$ dex). The slope of the Elbaz et al. (2007) relation (blue band cross-hatched diagonally upward right) is 0.90, rising more steeply than our fit, but its intercept is much lower ($-8.17$, again using the relation compiled by Dutton et al. 2010). This could simply be due to the fact that Elbaz et al. (2007) study galaxies at a slightly higher median redshift and wider redshift range (0.80 < $z$ < 1.20). Despite this offset, the NewH$\alpha$ fit is within the scatter of the Elbaz et al. (2007) relation ($\sim0.3$ dex). On the other hand, the Whitaker et al. (2012) relation (pink band cross-hatched diagonally downward right) has a shallower slope, with a functional form of $\log \left( \frac{\text{SFR}}{(M_\odot \, \text{yr}^{-1})} \right) = 0.6 \log \left( \frac{M_\star}{M_\odot} \right) - 5.09$ at $z \sim 0.8$ (uncertainties not given). This is more likely due to incompleteness at masses below $10^{9.8} M_\odot$, as shown in Figure 1 of Whitaker et al. (2012). Above this mass-completeness limit, the NewH$\alpha$ relation is well within the scatter derived by Whitaker et al. (2012) ($\sim0.34$ dex).

Villar et al. (2011) use a narrowband selection similar to that used in the NewH$\alpha$ survey and study 153 H$\alpha$ emitters at $z \sim 0.84$ in the EGS and GOODS-North fields. This survey covered a mass range of $10^{10.0}$–$10^{11.5} M_\odot$. Villar et al. (2011) do not provide a functional form for their $M_\star$–SFR relation; however, when we calculated our own least-squares linear fit for the Villar et al. (2011) data points (light-blue band cross-hatched vertically), we found a fit of $\log \left( \frac{\text{SFR}}{(M_\odot \, \text{yr}^{-1})} \right) = (0.51 \pm 0.15) \log \left( \frac{M_\star}{M_\odot} \right) - (4.11 \pm 1.61)$. Although both

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Table 6: Sample Cuts and Subsamples Used in Analysis

| Sample Cut | $N$ (total) | $N$ (no AGN) | SFR Comparison | $M_\star$–SFR Relation (Section 4.1) | $M_\star$–Z Relation (Section 4.3) | $M_\star$–Z–SFR Relation (Section 4.4) |
|------------|-------------|-------------|---------------|-------------------------------------|----------------------------------|--------------------------------------|
| No restrictions | 299 | 278 | ... | ... | ... | ... |
| Good SED ($\chi^2 < 10$) | 274 | 255 | X | X | X | X |
| $u$-band photometry | 174 | 160 | X | ... | ... | ... |
| Narrowband S/N $>3\sigma$ | 209 | 202 | X | X | ... | ... |
| Metallicity cut$^a$ | 166 | 147 | ... | X | X | X |
| Total | ... | ... | 114 | 188 | 136 | 119 |

**Note.** Note that AGNs are removed for all four analyses listed. Also note that these sample cuts denote only the restrictions placed on data sets. Further restrictions (for linear or planar fits) are not listed here and are noted in the text and figures.

$^a$ The “metallicity cut” includes a $3\sigma$ restriction on [O ii], [O iii], and H$\beta$ (i.e., the $R_{23}(3\sigma)$ sample), as well as the removal of sources for which the calculated M91 upper-branch metallicity was lower than the M91 lower-branch metallicity.
the Villar et al. (2011) slope and intercept are systematically lower than the NewHα slope and intercept, the NewHα relation is consistent with the Villar et al. (2011) relation at overlapping mass bins (i.e., above $10^{10}M_\odot$).

Since our sample is selected by Hα emission, we expected our galaxies to be biased toward higher SFRs, which would result in a $M_\star$–SFR relation systematically higher than those found using mass- and luminosity-limited surveys. However, that is not the case, as demonstrated in Figure 9. This is because our Hα survey is reasonably deep with a 50% completeness limit that corresponds to an observed Hα SFR of 0.4 $M_\odot$ yr$^{-1}$ (Ly et al. 2011a). Our greater observational limitation is on the amount of excess flux (i.e., the Hα EW) that we can measure, which corresponds to the specific SFR. Previous Monte Carlo simulations suggest that the low-EW population that we are missing amounts to $\approx 20\%$ at high masses and increases to 50% near our sensitivity limits (Ly et al. 2011a). These selection limitations, however, do not appear to bias our sample any more than mass- and luminosity-limited surveys. We note that Henry et al. (2013b), who used a sample of emission-line
galaxies selected from grism spectroscopy, have also found good agreement with other \( M_\ast - \text{SFR} \) relation studies. We also note that despite the consistency between the NewH\( \alpha \) data with literature \( M_\ast - \text{SFR} \) relations, the upper panel of Figure 9 shows that a line does not perfectly fit the NewH\( \alpha \) \( M_\ast - \text{SFR} \) data. This may be evidence that the \( M_\ast - \text{SFR} \) relation is not a simple power law at higher redshifts, as recently suggested by Whitaker et al. (2014). However, the observed curvature in the \( M_\ast - \text{SFR} \) relation may be the result of selection bias (i.e., missing more dust-obscured galaxies) or because the dust attenuation correction is underestimated.

### 4.3. The Mass–Metallicity Relation

Several previous studies have examined the \( M_\ast - \text{Z} \) relation at \( z \sim 0.8 \). However, these studies used samples with different ranges of stellar mass and metallicity, as well as different treatments of systematic effects like dust extinction (for some analysis, see Moustakas et al. 2011; Zahid et al. 2011). We therefore aim to supplement and compare previous results with our large spectroscopically selected NewH\( \alpha \) sample.

As before, we fit the NewH\( \alpha \) data with a linear relation using a least-squares fit. We plot both \( R_{23}(3\sigma) \) and \( R_{23}(5\sigma) \) metallicity detections, but for the linear fit, we use the \( R_{23}(5\sigma) \) sample. Using the \( 5\sigma \) cut did not significantly bias the sample, as the top panel of Figure 10 shows. We also remove 9 sources for which the calculated upper-branch metallicity is lower than the lower-branch metallicity, leaving a \( \sigma \) sample size of 98. Using the M91 metallicity calibration, we find the resulting linear relation to be

\[
12 + \log(O/H) = (0.25 \pm 0.03) \log \left( \frac{M_\ast}{M_\odot} \right) + (6.23 \pm 0.33),
\]

with an intrinsic scatter of 0.16 dex.

The top plot in Figure 10 shows this linear relation, while the bottom plot compares this linear fit to other \( M_\ast - \text{Z} \) relation determinations at similar redshifts. The means of the NewH\( \alpha \) data binned by mass are also plotted, and their values are provided in Table 7. All stellar masses are converted to be consistent with a Chabrier IMF, and all metallicities are made to be consistent with the M91 upper-branch calibration using the conversions in Kewley & Ellison (2008).

We find that the NewH\( \alpha \) \( M_\ast - \text{Z} \) relation is generally consistent with literature relations, and all these relations at higher redshifts are systematically lower than the local \( M_\ast - \text{Z} \) relation of T04 (dark blue solid curved line), once it has been converted to the same metallicity calibration. This result is consistent with previous studies of metallicity evolution with redshift.

Savaglio et al. (2005) used galaxies from the Gemini Deep Deep Survey and the Canada France Redshift Survey to investigate the \( M_\ast - \text{Z} \) relation at \( 0.4 \sim 0.98 \). A final sample of 56 galaxies was selected by the existence of rest-frame optical emission lines with a \( 3\sigma \) detection limit of \( (0.6-3.2)(10^{-18})\text{erg s}^{-1}\text{cm}^{-2} \). Metallicities were calculated using the \( R_{23} \) line flux ratio and KK04 calibration. The pink dashed-triple dotted line in Figure 10 marks the Savaglio et al. (2005) linear bisector fit, which does not agree with the NewH\( \alpha \) data (nor other higher redshift studies). However, the small sample size, lack of selection criteria (i.e., no color selection, no S/N threshold for the \( R_{23} \) emission lines), and different fitting method for the Savaglio et al. (2005) data all prevent us from directly comparing the two relations.

Lamareille et al. (2009) examined two subsets of \( \sim 3000 \) \( z = 0.7-0.9 \) galaxies from the VIMOS VLT Deep Survey—a wide-shallow sample (6.1 deg\(^2\) and 17.5 \( \leq I_{AB} \leq 22.5 \)) and a narrow-deep sample (0.61 deg\(^2\) and 17.5 \( \leq I \leq 24 \)), green dotted–dashed line in Figure 10). Metallicities were calculated from rest-frame optical emission lines using the \( R_{23} \) line flux ratio and the T04 metallicity calibration. Because the wide sample has shallower magnitude limits and is biased toward massive galaxies, we choose to compare the NewH\( \alpha \) \( M_\ast - \text{Z} \) relation against the deep sample (\( N \sim 40 \) for \( 0.7 < z < 0.9 \)). Figure 10 shows that this sample is well within the intrinsic scatter of the NewH\( \alpha \) relation. Lamareille et al. (2009) observed that the \( M_\ast - \text{Z} \) relation evolves toward lower overall metallicities more quickly for more massive galaxies. However, low spectral resolution \( (R_s \sim 230) \) or a large error domain on

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18 These nine galaxies have \( R_{23} \) values that are higher than the limit of many of these metallicity calibrations (see Section 3.3 and Figure 6). Zahid et al. (2011) removed such galaxies as well, believing them to be AGNs.

19 Again, we use the Kewley & Ellison (2008) relation to transform to M91-based metallicities.
AGN classification could also have an effect on both the Lamareille et al. (2009) samples; in particular, contamination from AGNs would falsely lower metallicity results, since photoionization by AGNs can produce rest-frame optical emission-line ratios that appear similar to metal-poor star-forming galaxies (Moustakas et al. 2011).

Cowie & Barger (2008) used a sample of 154 galaxies from the 145 arcmin² GOODS-N field, selected by rest-frame NIR bolometric flux (the limiting flux corresponding roughly to an NIR magnitude of $K_s = 23.4$). Metallicities were calculated using the $R_{23}$ line ratio with both the KK04 and T04 calibrations, although EWs were used rather than emission-line fluxes. Zahid et al. (2011) noted a systematic error in the Cowie & Barger (2008) relation as a result of the fitting procedure used—the $R_{23}$ metallicity diagnostic is less sensitive at the $R_{23}$ local maximum at $12 + \log (O/H) \sim 8.4$, which leads to asymmetric metallicity errors that influence the least-squares fit. We therefore follow the example of Zahid et al. (2011) and plot the median metallicities (red triangles in Figure 10) rather than the functional form prescribed by the mean metallicities. The median metallicities are within the scatter of the NewHα relation.

Zahid et al. (2011) studied galaxies from the DEEP2 survey (Davis et al. 2003), which covers a fairly large field of 3.5 deg². Out of 31,656 objects in the DEEP2 survey with well-measured redshifts, only sources with spectra covering the wavelength range of 3720–5020 Å (rectangular the rest-frame optical emission lines required for $R_{23}$, see Section 3.3) and emission lines that could be fit were considered in analysis. Further sample cuts included thresholds on Hβ/S/N, H/β EW, combined $R_{23}$ errors, continuum fits, and the removal of sources with $\log R_{23} > 1$ (considered AGNs), leaving a final sample size of ≈1600. As in Cowie & Barger (2008), metallicities were calculated with the $R_{23}$ ratio formula, using emission line EWs and the KK04 calibration. Insufficient sample cuts for AGN, color contamination from red non-SF galaxies, and a lack of S/N cut on [O ii] and [O iii] lines would all tend to underestimate metallicity, but we find that the Zahid et al. (2011) relation (light blue dashed line in Figure 10) is very consistent with the NewHα data at overlapping mass bins.

Finally, Moustakas et al. (2011) used a large (~3000 galaxies) sample from the AGN and Galaxy Evolution Survey, which covers 7.9 deg². The survey is magnitude-limited ($I_{AB} < 20.45$), and emission-line galaxies were selected with the criteria that Hβ line flux is above $3 \times 10^{-17}$ erg s⁻¹ cm⁻² and $\log ([O \text{ ii}] /H\beta) > 0.3$. Metallicities are computed using the EW formulas for the line ratios $R_{23}$ and $O_{32}$ and the M91, KK04, and T04 calibrations. The Moustakas et al. (2011) and NewHα samples are complementary: the former is mass incomplete below $10^{10.7} M_\odot$ at $z \sim 0.8$ as a result of the survey flux limit, while the NewHα mass completeness drops off below $10^{10.5} M_\odot$ because our data are emission-line selected. Therefore, disregarding the NewHα data above an upper mass-complete limit ($\sim 10^{10.5} M_\odot$), the Moustakas et al. (2011) $M_\star$–Z relation (orange diamonds in Figure 10) appears to be a smooth extension of the NewHα relation to higher masses.

4.4. The Mass–Metallicity–SFR Relation

Combining the stellar mass, metallicity, and SFR measurements for the NewHα sample, we now consider the correlation between all three derived properties. As discussed in the introduction, residuals from the $M_\star$–Z relation have been found to correlate with the SFR in local galaxy samples. We aim to test whether a similar secondary dependence on the SFR also exists in galaxies at $z \sim 0.8$ as sampled by the NewHα data set.

The NewHα survey is one of the first surveys to offer both spectroscopic measurements of the strong oxygen emission lines and Hα narrowband fluxes at intermediate redshifts, enabling more robust constraints on the nebular abundances and instantaneous SFRs. These measurement methods are also commonly used at local redshifts, and allow a more self-consistent test of whether the $M_\star$–Z–SFR relation remains the same over cosmic time. To investigate the $M_\star$–Z–SFR relation, we first remove all AGNs, sources with poor SED fits ($\chi^2 > 10$), sources with an NB118 excess flux below $3\sigma$, and limit the data set to the $R_{23}(3\sigma)$ sample. These restrictions remove 180 galaxies from the sample, leaving 119 galaxies for the following analysis. We note that the $R_{23}(3\sigma)$ cut removed the majority of galaxies ($N = 120$).

Different parameterizations have been used to describe the local $M_\star$–Z–SFR relation (see e.g., Man10; Lar10). Some studies (Lar13; Hunt et al. 2012) have assumed that this relation can be accurately described by a plane. In particular, Lar13 argued that this may in fact be the best functional representation of the $M_\star$–Z–SFR relation, and refer to it as a “fundamental plane.” In contrast, Man10 used a higher order parameterization (dubbed the “fundamental metallicity relation”), which is motivated by the flattening at high stellar masses in the $M_\star$–Z relation (e.g., T04; Moustakas et al. 2011). In addition, many studies (e.g., Richard et al. 2011; Xia et al. 2012; Belli et al. 2013; Henry et al. 2013a, 2013b; Stott et al. 2013; Zahid et al. 2014; Ly et al. 2014; Yabe et al. 2014) have compared their samples against the fundamental metallicity relation to determine whether it holds at higher redshifts.

To enable direct comparison to Lar10 and Lar13, we begin by assuming that our relation can be accurately described by a plane. Since commonly adopted methods for determining the best-fit plane may lead to different results and interpretation, we use multiple techniques as described below: (1) principal component analysis (PCA), (2) two-parameter regression, and (3) three-dimensional $\chi^2$ minimization.

We then explore a higher order parameterization of the data following the methodology of Man10. We later compare our analyses with previous works in Section 5, and revisit the assumed plane parameterization in Section 5.3 and discuss possible implications.

We note that all the results that follow are based on metallicities determined using the T04 calibration, in order to facilitate direct comparison with previous studies. Another metallicity calibration (M91 as used previously for the $M_\star$–Z relation) has been used, and we find that to first order, the $M_\star$–Z–SFR relation does not significantly differ. The results of our planar fits with different metallicity calibrations (T04 and M91) are summarized in Tables 8–10.

4.4.1. Principal Component Analysis

First, we conduct a PCA for our NewHα data set. This approach determines the eigenvectors (called V1, V2, and V3), formed from linear combinations of the input parameters, that are orthogonal to one another. One of the advantages of the technique is the ability to examine correlated measurements. This is important for the $M_\star$–Z–SFR relation, since the metallicity and SFR measurements are strongly correlated with
the derived stellar mass. Given these correlations, the application of the PCA technique allows us to examine whether a tilt in the direction of the SFR is present for a plane parameterization. This technique has been used by Lar13 and Hunt et al. (2012) to determine the best-fit planar description for the $M_\star$–$Z$–SFR relation. We conduct our PCA analysis on the covariance matrix of our data set with three variables:

$$\begin{align*}
x_1 & \equiv \log \left( \frac{M_\star}{M_\odot} \right), \\
x_2 & \equiv 12 + \log (\text{O/H}), \text{ and} \\
x_3 & \equiv \log \left( \frac{\text{SFR}_{\text{H}α}}{M_\odot \text{ yr}^{-1}} \right). \end{align*}$$  

To account for measurement uncertainties in the PCA, we conduct Monte Carlo realizations of our data, where the stellar mass, SFR, and oxygen abundance for each galaxy in the sample are drawn 100,000 times from a Gaussian probability distribution defined by the 1σ errors in each parameter. We then fit each simulated sample of 119 galaxies using the PCA code available through the NASA IDL Astronomy User’s Library.

We find that the first two principal components account for 78.8% ± 1.6% and 15.2% ± 1.5% of the variance, respectively. The first principal component, which has the largest variance, is $V_1 = (0.610, 0.183, 0.771)$. The other two eigenvectors are $V_2 = (0.690, 0.352, -0.629)$, and $V_3 = (-0.384, 0.923, 0.087)$. In Figure 11, the data are projected in the planes defined by these principal components.

Since $V_1$ and $V_2$ have the largest dispersions, they can be interpreted as vectors that lie along the best-fit plane, while $V_3$ is the vector that is orthogonal to the plane. Figure 11 illustrates that $V_3$ has the least amount of variance with an rms of ≈0.18 dex. This low dispersion is critical, as it suggests that $V_3$ provides a mathematical description for the best-fit plane such that a combination of stellar mass, SFR, and metallicity yields a constant:

$$\alpha x_1 + \beta x_2 + \gamma x_3 = \delta,$$  

with $(\alpha, \beta, \gamma, \delta) = (-0.384, -0.03, 0.923 \pm 0.02, 0.087, 0.04, +4.301, -0.57)$. The $V_3$ results from our Monte Carlo realization are shown in Figure 12. A summary of our PCA results, using different metallicity calibrations (M91; T04) and sample selections, can be found in Table 8.

Assuming that our data can be described by a plane, $\gamma$ can be interpreted to signify the importance of the SFR in the correlation. The PCA shows that $\gamma$ is non-zero ($\approx 3\sigma$ significance), suggesting that the plane which best describes our data set is moderately tilted in the SFR dimension.

4.4.2. Two-parameter Regression

Another approach for finding the best-fit plane is linear regression, whereby one parameter is modeled in terms of only two other parameters. We consider a plane parameterization used to describe local galaxies (Lar10), where the stellar mass is treated as the dependent variable:

$$\log \left( \frac{M_\star}{M_\odot} \right) = \beta_3 Z + \gamma_3 \log \left( \frac{\text{SFR}_{\text{H}α}}{M_\odot \text{ yr}^{-1}} \right) + \delta_3,$$  

where $Z \equiv 12 + \log (\text{O/H})$. We conduct the regression using the IDL routine MPFIT (Markwardt 2009), which uses the Levenberg-Marquardt least-squares minimization technique. As with the PCA, we also perform a Monte Carlo simulation to determine the uncertainties in the fit. Here, the Gaussian randomization only occurs in the two independent variables (SFR and metallicity) and measured uncertainties in the dependent variable (stellar mass) are accounted for in the least-squares minimization. The results of our Monte Carlo simulation are shown in Figure 13, and are reported in Table 9 using two different metallicity calibrations (T04; M91). The best fitting parameters that describe the NewH$\alpha$ sample are $\beta_3 = 0.67^{+0.13}_{-0.11}$, $\gamma_3 = 0.50^{+0.04}_{-0.05}$, and $\delta_3 = 3.75^{+1.02}_{-1.01}$.

While Equation (7) was reported to yield the lowest $\chi^2$ in all three observables for local SDSS galaxies (Lar13), it can be viewed as counter-intuitive.20 A better description of the plane, which is a simple extension of the $M_\star$–$Z$ relation, is:

$$Z = \alpha_Z \log \left( \frac{M_\star}{M_\odot} \right) + \gamma_Z \log \left( \frac{\text{SFR}_{\text{H}α}}{M_\odot \text{ yr}^{-1}} \right) + \delta_Z.$$  

The regression fitting for our sample using this projection, as shown in Figure 13, yielded $\alpha_Z = 0.23 \pm 0.02$, $\gamma_Z = 0.01^{+0.02}_{-0.03}$, and $\delta_Z = 6.61^{+0.18}_{-0.12}$ for T04 metallicities. The results of our $Z = f(M, \text{SFR})$ regression are consistent with our previous $M_\star$–$Z$ least-squares fitting, which found a slope ($\alpha_Z$) of 0.25 and a constant offset ($\delta_Z$) of 6.23 (Section 4.3). This regression analysis demonstrates that a strong secondary dependence on the SFR for a $M_\star$–$Z$–SFR plane is not present in our data set. We summarize our $Z = f(M, \text{SFR})$ regression results for T04 and M91 in Table 10.

20 Other galaxy properties have been extensively compared against the stellar mass (i.e., the latter is treated as the independent variable).
4.4.3. Three-dimensional $\chi^2$ Minimization

One of the limitations of the two-parameter regression approach—used to study the SDSS sample by Lar10 and Lar13—is the arbitrary choice of the independent and dependent variables, as we have discussed. To address this, we consider a three-parameter fit that simultaneously minimizes $\chi^2$ in all three dimensions. We assume that the data can be described by a plane as given by Equation (6). This method complements the PCA, since it is less susceptible to outliers that directly affect the covariance matrix, and hence the principal components (see Section 5.2 for further discussion). It is a three-dimensional extension of the $\chi^2$ estimator used by Tremaine et al. (2002), for example. To obtain meaningful errors, we scale our measurement uncertainties to yield a reduced $\chi^2$ of 1. We find a best fit of $(\alpha, \beta, \gamma, \delta) = (-0.37 \pm 0.05, 0.92 \pm 0.02, 0.10 \pm 0.05, 4.54 \pm 0.64)$. These values are similar to those determined from PCA, again suggesting that there is at most a moderate dependence of metallicity on the SFR for Ho-selected galaxies from the NewHo survey.

4.4.4. Non-planar Formalism of Mannucci et al. (2010)

As previously stated, a curved-surface parameterization may be a better representation of the $M_*-Z$–SFR relation. With this in mind, we split our sample into low-mass and high-mass subsamples and perform PCA. The results are summarized in Table 8. We find that the planes that best fit the low-mass sample are significantly different from those that best fit the high-mass sample.

We therefore consider a non-planar fit between the three derived properties following Man10, who determined a curved-surface representation of the $M_*-Z$–SFR relation at local redshifts. Man10 calculated metallicities for local SDSS galaxies with two separate emission-line flux ratio measurements—the Nagao et al. (2006) [N II] A6583/H$\alpha$ calibration and the Maiolino et al. (2008) R$\alpha_3$ calibration. In cases where both measurements agree within 0.25 dex, an average of the two was used. Since [N II]/H$\alpha$ measurements do not exist for our sample, direct comparison of the NewHo sample to Man10 is difficult. In particular, while we could examine whether the $M_*-Z$–SFR relation exists in our sample using only R$\alpha_3$-based metallicities estimated from the Maiolino et al. (2008) calibration, we note that this approach has yet to be conducted with SDSS galaxies (i.e., excluding [N II]/H$\alpha$ measurements). A Maiolino et al. (2008) R$\alpha_3$-based $M_*-Z$–SFR relation is beyond the scope of this paper. Therefore, we choose to compare to the relation determined by Yat12, who followed the same procedure as Man10 but used T04 metallicities.

Note. See Section 4.4.1 for further details. PCA plane defined as $\alpha \log (M_*/M_\odot) + \beta [12 + \log (O/H)] + \gamma \log (SFR/(M_\odot \text{yr}^{-1})) = \delta$. The rms perpendicular to the PCA plane is provided in Column 8.

$^a$ The $R_{\alpha_3}(3 \sigma)$ and $R_{\alpha_3}(5 \sigma)$ samples are selected by requiring detections of [O ii], [O iii], and H$\alpha$ at 3$\sigma$ and 5$\sigma$, respectively.
We determine a second-order polynomial fit of metallicity as a function of a linear combination of mass and SFR:

$$\alpha = \log \left( \frac{M_*}{M_\odot} \right) - \alpha \log \left( \frac{\text{SFR}}{M_\odot \text{ yr}^{-1}} \right),$$

where $\alpha$ is a free parameter chosen to minimize the scatter of metallicity. Here, $\alpha = 0$ corresponds to the $M_*-Z$ relation while $\alpha = 1$ refers to metallicity having an inverse dependence with the specific SFR.

We consider a range of $\alpha$ values, and illustrate in Figure 14 the dispersion of the best-fit second-order polynomial. This result demonstrates that scatter in metallicity is minimized at $\alpha \sim 0.05$ (i.e., suggesting weak dependence on the SFR). High values of $\alpha (\geq 0.5)$ can be excluded, suggesting that a strong dependence on SFR does not exist. However, we cannot exclude moderate dependence (e.g., $\alpha = 0.19$ for local galaxies as determined by Yat12, since the scatter in metallicity does not significantly change for $\alpha \leq 0.5$. This result is illustrated in Figure 15, where we plot the best-fit second-order polynomial for both $\alpha = 0.05$ and $\alpha = 0.19$.

5. DISCUSSION

As discussed in the introduction, the detailed relation between galaxy stellar mass, SFR, and gas-phase metallicity
is important for understanding inflows and outflows of gas, and the chemical evolution of galaxies. The shape of this relation and the degree to which it does or does not evolve with redshift can provide insights into whether the processes governing the interaction between galaxies and their surrounding medium are “fundamental” in the sense that they may not differ substantially at various points in cosmic time.

Several studies (e.g., Man10; Lar10; Lar13) have reported that along with the well-established strong correlation between mass and metallicity, there is a moderate, but significant correlation with the SFR. Furthermore, a number of studies, including Man10 and Hunt et al. (2012), have indeed found that galaxies at redshifts up to z ~ 3 can be described by the same $M_* - Z - \text{SFR}$ relation. However, contradictory results have

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**Table 9**

| Sample | $N$ | Metallicity | $\beta_M$ | $\gamma_M$ | $\delta_M$ |
|--------|-----|-------------|-----------|-----------|-----------|
| $R_{23}(3\sigma)$ | 119 | T04 | 0.67$^{+0.11}_{-0.11}$ | 0.50$^{+0.04}_{-0.05}$ | 3.75$^{+1.02}_{-1.01}$ |
| $R_{23}(3\sigma)$ | 119 | M91 | 0.77$^{+0.16}_{-0.13}$ | 0.51$^{+0.04}_{-0.05}$ | 2.88$^{+1.35}_{-1.21}$ |
| $R_{23}(5\sigma)$ | 90 | T04 | 0.90$^{+0.05}_{-0.05}$ | 0.24$^{+0.03}_{-0.05}$ | 1.89$^{+0.49}_{-0.42}$ |
| $R_{23}(5\sigma)$ | 90 | M91 | 1.07$^{+0.08}_{-0.06}$ | 0.23$^{+0.02}_{-0.03}$ | 0.45$^{+0.57}_{-0.65}$ |

**Note.** See Section 4.4.2 for further details. Regression plane defined as log ($M_*/M_\odot$) = $\beta_M [12 + \log (\text{O/H})] + \gamma_M \log (\text{SFR}/(M_\odot \text{yr}^{-1}))$ + $\delta_M$.

The $R_{23}(3\sigma)$ and $R_{23}(5\sigma)$ samples are selected by requiring detections of $[\text{O} \text{II}]$, $[\text{O} \text{III}]$, and H$\beta$ at $3\sigma$ and $5\sigma$, respectively.
recently been reported: Sánchez et al. (2013) and Hughes et al. (2013) were unable to find a significant correlation with the SFR, and argue that previous results based on the SDSS data set were spurious due to aperture effects (for further discussion, see Section 4 of Sánchez et al. 2013). Also, Zahid et al. (2014) found evidence for redshift evolution in the $M_* - Z$ SFR relation.

In Section 4.4.3 of this paper, we examined whether the $M_* - Z$ SFR relation at $z \sim 0.8$ exists using the NewH$\alpha$ data set—and if it does, to determine whether it is consistent with previous analyses of local galaxies from the SDSS data set. To facilitate comparison to local results, we followed previous approaches by assuming that the $M_* - Z$ SFR relation can be described by a plane or a surface. For the planar description, we used PCA, two-parameter regression, and $\chi^2$ minimization with metallicities calibrated against T04. We found that the NewH$\alpha$ data show a moderate dependence ($\gamma \approx 0.1$) of the $M_* - Z$ relation on SFR. This is slightly lower than the dependence found in the local universe ($\gamma \approx 0.16; \text{Lar13}$). For the curved-surface parameterization, we use least squares fitting to describe a second-order polynomial between metallicity and a combination of mass and SFR. This analysis excludes a strong dependence of the $M_* - Z$ relation on SFR; however, it cannot distinguish between moderate and no dependence.

How do we interpret our results, and where do they fit in within the current debate on the $M_* - Z$ SFR relation? We address these questions by first investigating whether some limitation(s) of our analyses or data set may obscure the true underlying relationship. We ask:

1. Is our result biased or affected by some limitation of the NewH$\alpha$ data set (Section 5.1)?
2. Is our result biased or affected by the chosen plane-fitting techniques (Section 5.2)?
3. Finally, is our result biased or affected by our assumed parameterizations of the data set (Section 5.3)?

### 5.1. Limitations of the NewH$\alpha$ Data Set

The following sample limitations may, individually or in combination, bias our measurement of the SFR dependence of the $M_* - Z$ SFR relation: (1) small sample size, (2) measurement uncertainties, and (3) restricted coverage of parameter space. These limitations apply generally to any study attempting to construct a $M_* - Z$ SFR relation.

In this work, we focus on the first possible limitation: the small size of the NewH$\alpha$ sample (119 galaxies) used for studying the $M_* - Z$ SFR relation. To understand the effects of sample size we construct “mock” samples from the SDSS DR7 sample. Here, the MPA-JHU catalog provides total stellar masses from fitting the $u'g'r'i'z'$ photometry (Salim et al. 2007), total SFRs primarily from Balmer emission lines (Brinchmann et al. 2004), and metallicity within the optical fibers following T04. Restricting our sample to galaxies with estimates of stellar mass, metallicity, and SFR, and redshift $z = 0.07$ and $z = 0.30$, we have a working SDSS sample of 90,686 galaxies.

We therefore begin with a randomly selected subsample of 150 galaxies and then consider improvements to our base sample by increasing the sample size. We fit each SDSS subsample with a plane using the PCA technique, as discussed in Section 4.4.1, for direct comparisons with our NewH$\alpha$ results. For the smallest subsample, we find little dependence on the SFR, with $\gamma \approx 0.02$. We then increase the sample size in increments of 150 galaxies, with the expectation that the larger sample size will provide more definitive constraints on SFR dependence. However, even with a sample of 1950 galaxies (13 times larger than the base sample), $\gamma$ remains at or below 0.05. Extending the PCA analysis to the largest sample possible ($N = 90,686$), we find that a surprisingly weak dependence exists on the SFR ($\gamma = 0.02$) for a planar description of the $M_* - Z$ SFR relation. This dependence is roughly three to eight times weaker than that found by Lar13, but consistent (within errors) with results from the analysis based on the NewH$\alpha$ data set reported here ($\gamma \approx 0.087 \pm 0.03$). This is best demonstrated in Figure 12 where the mock SDSS sample, with similar sample

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### Table 10

| Sample$^a$ | N  | Metallicity | $\alpha Z$ | $\gamma Z$ | $\delta Z$ |
|------------|----|-------------|-----------|-----------|-----------|
| (1)        | (2) | (3)         | (4)       | (5)       | (6)       |
| $H\alpha$-based SFRs | | | | | |
| $R_{23}(3\sigma)$ | 119 | T04 | $0.23 \pm 0.02$ | $0.01\pm0.02$ | $6.61\pm0.18$ |
| $R_{23}(3\sigma)$ | 119 | M91 | $0.19 \pm 0.02$ | $0.00\pm0.02$ | $6.97\pm0.15$ |
| $R_{23}(5\sigma)$ | 90  | T04 | $0.26_{-0.02}^{+0.03}$ | $0.00\pm0.02$ | $6.37\pm0.25$ |
| $R_{23}(5\sigma)$ | 90  | M91 | $0.22 \pm 0.03$ | $-0.04\pm0.02$ | $6.68\pm0.20$ |

**SED-based SFRs**

| $R_{23}(3\sigma)$ | 119 | T04 | $0.25 \pm 0.02$ | $-0.03\pm0.02$ | $6.39\pm0.19$ |
| $R_{23}(3\sigma)$ | 119 | M91 | $0.23 \pm 0.03$ | $-0.03\pm0.02$ | $6.81\pm0.14$ |
| $R_{23}(5\sigma)$ | 90  | T04 | $0.28_{-0.03}^{+0.02}$ | $-0.04\pm0.03$ | $6.15_{-0.19}^{+0.25}$ |
| $R_{23}(5\sigma)$ | 90  | M91 | $0.23 \pm 0.03$ | $-0.04\pm0.02$ | $6.60_{-0.19}^{+0.20}$ |

Note. See Section 4.4.2 for further details. Regression plane defined as $12 + \log(O/H) = \alpha Z \log(M_*/M_\odot) + \gamma Z \log(SFR/(M_*/yr^{-1})) + \delta Z$.

$^a$ The $R_{23}(3\sigma)$ and $R_{23}(5\sigma)$ samples are selected by requiring detections of [O ii], [O iii], and H/β at 3σ and 5σ, respectively.
size \((N = 150)\) to the NewH\(\alpha\) sample, is shown by the dashed (blue) line contours.

How can the results of our experiments with mock SDSS samples be reconciled with the results of Lar13? The sample used by Lar13 used stricter selection cuts. Their strictest constraint is on the S/N for the [O III] \(\lambda5007\), H\(\beta\), H\(\alpha\), and [N II] emission lines (requiring at least 8\(\sigma\)). The H\(\alpha\) restriction biases their sample toward higher SFRs, while the [O III] restriction preferentially selects against metal-rich galaxies, leaving metal-poor galaxies with higher SFRs in the sample. Interestingly, we do find that a S/N restriction of 8 on the nebular emission lines yielded a higher SFR coefficient \((\gamma \approx 0.08-0.14\) with the standard PCA\) based on sample sizes that span 150–31,477 galaxies.

The mock SDSS samples used in the analysis described in this section, on the other hand, were constrained by similar emission-line restrictions (3\(\sigma\) detection) used for the NewH\(\alpha\) data set, and achieved results more consistent with the NewH\(\alpha\) results. To further demonstrate this point, we also selected from the SDSS galaxies with similar \((\leq 0.1\) dex) stellar masses and SFRs to those in the NewH\(\alpha\) sample (hereafter “mock-highz SDSS”). Because local galaxies have lower SFRs, six of 119 NewH\(\alpha\) galaxies do not have a “local analog.” The results of the PCA for the mock-highz SDSS sample are shown as dotted (purple) line contours in Figure 12, and are in better agreement with the NewH\(\alpha\) PCA results. These comparison results suggest that the differences in sample selection may therefore produce the observed discrepancy between the results of NewH\(\alpha\) and the results of Lar13.

5.2. Limitations of PCA

Another potential issue with our investigation is our reliance on the PCA technique to find the plane that best describes the \(M_\star–Z–SFR\) relation, and to compare to results based on local galaxy samples. This technique has shortcomings, particularly in its sensitivity to outliers. PCA finds eigenvectors (or principal components) formed from linear combinations of input parameters \((M_\star, Z,\) and SFR\). Since variance-dependent calculations are used to determine the principal components, outliers may strongly skew PCA results. Considering the uncertainties of derived quantities and large size of the SDSS sample, there are significant numbers of (true) outliers in the sample that would suggest that the PCA technique is unreliable for the SDSS.

This is particularly demonstrated when we account for measurement uncertainties through Monte Carlo techniques in the PCA fitting (see Section 4.4.1). We find a different best-fit plane (albeit one that still has a low \(\gamma\)) when compared with a standard PCA (i.e., without considering uncertainties). This is expected because of the uncertainties on the SFRs: at least 32\% of the SDSS sample deviates significantly \((\geq 0.22\) dex; see Figure 16\) from what is likely the best-fitting plane. When performing the same analysis with an SDSS sample similar to that of Lar13, we also find a different result for \(\gamma, \sim 0.12\) versus the reported result of 0.16.

We suggest that instead of PCA, three-dimensional \(\chi^2\) minimization (see Section 4.4.3) should be the preferred method of parameterizing the \(M_\star–Z–SFR\) relation as a plane. The three-dimensional \(\chi^2\) minimization technique fits all three observables simultaneously and is less susceptible to outliers; galaxies with more uncertain measurements are downweighted relative to those with more precise measurements. In the case of the NewH\(\alpha\) data set, our results are consistent between PCA and three-dimensional \(\chi^2\) fitting, suggesting that our sample is not as severely affected by the PCA analysis. Nevertheless, we recommend caution when proceeding with PCA analysis without understanding the effects of outliers.

5.3. Limitations of the Parameterization of the \(M_\star–Z–SFR\) Relation

In much of our analysis—including our investigation of potential sample size and PCA technique limitations—we have adopted a plane to describe our data. However, as noted in...
Section 4.4.4, this assumption may be wrong. If there is in fact a $M_\ast-Z-SFR$ relation that is fundamental (i.e., universally describes galaxies at all redshifts), and there is curvature in that relation, studies which assume a plane parameterization in their analysis may mistakenly infer evolution in the relation. That is, evolution in a planar relation may actually be a result of sampling different parts of the curved surface relation with respect to redshift. At $z \sim 0.8$, the NewH$\alpha$ sample has lower averagemetallicity and higher average SFR than the local SDSS sample does. Furthermore, if the $M_\ast-Z-SFR$ relation is curved, the results from a plane fit can be different if the sample is limited in parameter space. This is demonstrated in Section 4.4.4 when we split our sample into low-mass and high-mass subsamples. The plane that best fits the low-mass sample is significantly different from the one that fits the high-mass sample. This implies that our sample follows a non-planar projection—a discrepancy is unsurprising if there is no truly “good” planar fit.

With this in mind, we follow the procedure of Man10 and Yat12 to find the projection of least scatter, as described in Section 4.4.4. In this projection, the parameter $\alpha$ describes the dependence of the $M_\ast-Z$ relation on the SFR. Our data set excludes a strong dependence on SFR ($\alpha \gtrsim 0.5$); however, it cannot distinguish between moderate ($\alpha \sim 0.2$) and no dependence. This result is consistent with those reported for local galaxies ($\alpha = 0.19$; Yat12).

We note that although several $M_\ast-Z-SFR$ studies have followed the methods of Man10 (Yates et al. 2012; Andrews & Martini 2013), the effects of binning the SDSS sample by both mass and SFR have been a point of some contention, as Lar13 have argued that the grid adopted for data binning can effectively change the shape of the curved-surface $M_\ast-Z-SFR$ relation. In addition, this method of projection of least scatter relies on an initial assumption of a polynomial functional form.

We therefore suggest that future work be done to investigate non-parametric methods of fitting the $M_\ast-Z-SFR$ relation. For instance, the Kolmogorov–Smirnov (K–S) test is used to compare a one-dimensional sample with a reference probability distribution. An extension of the K–S test to three dimensions would be ideal for fitting the $M_\ast-Z-SFR$ relation while avoiding assumptions about the shape or functional form of the relation.

6. CONCLUSIONS

We have studied the relationships between stellar mass, SFR, and metallicity using a sample of 299 galaxies at $z \sim 0.8$ selected by the presence of H$\alpha$ emission in a narrow bandpass filter. Deep optical spectra obtained with Magellan IMACS enable us to measure gas-phase metal abundances with various theoretical and empirical oxygen-based calibrations, and to compare them to SFRs estimated from the H$\alpha$ luminosity and stellar masses from SED modeling.

Our emission-line galaxy sample spans stellar masses from $\sim 10^9$ to $6 \times 10^{11} M_\odot$, H$\alpha$-based SFRs between 0.4 and 270 $M_\odot$ yr$^{-1}$, and metallicities from $12 + \log (O/H) = 8.3$ to 9.1 ($Z/Z_\odot = 0.4–2.6$) on a metallicity scale based on the M91 calibration.

We compared H$\alpha$-based SFRs with SFRs estimated from SED fitting (i.e., FUV-based SFRs). We found that once both measures were corrected for dust attenuation with optical depths computed from SEDs, the two measures agreed well (median offset of $\sim 0.09$ dex) with low dispersion ($\sim 0.2$ dex). In addition, this agreement holds for the full range of stellar mass and for high SFRs ($\gtrsim 100 M_\odot$ yr$^{-1}$).

Based on a linear least-squares fit over stellar masses between $10^9.1 M_\odot$ and $10^{11.7} M_\odot$, the $M_\ast-Z$ relation for our sample is $12 + \log (O/H) = (0.25 \pm 0.03) \log \left( \frac{M_\ast}{M_\odot} \right) + (6.23 \pm 0.33)$. This is consistent with previously reported results for galaxy samples at similar redshifts. At fixed stellar mass, the $M_\ast-Z$ relation for our sample is systematically lower by 0.1 dex in metallicity than the local SDSS relation of T04.

Similarly, we found a NewH$\alpha$ $M_\ast-SFR$ relation of $\log \left( \frac{\text{SFR}_{\text{NewH} \alpha}}{M_\ast \text{yr}^{-1}} \right) = (0.75 \pm 0.07) \log \left( \frac{M_\ast}{M_\odot} \right) - (6.73 \pm 0.67)$, which is consistent with literature results at similar redshifts (within 0.15 dex in SFR of previous results). This consistency is somewhat surprising given that the NewH$\alpha$ sample is H$\alpha$ selected, which might bias our relation toward higher SFR. However, this suggests that our sample is in fact relatively complete down to low H$\alpha$ EWs.

We then calculated the best-fit plane describing the stellar masses, SFRs, and metallicities of the NewH$\alpha$ sample using three methods: PCA, two-parameter regression, and three-
dimensional χ² minimization. The fits resulting from all these analyses at z ~ 0.8 showed only a moderate secondary dependence on the SFR, weaker than that reported by Lar13 and Lar13. In addition, we considered a curved-surface parameterization following Man10, and found that the NewH sample is consistent with local studies (i.e., a weak dependence of the M*–Z relation on SFR; Yat12), and excludes a strong SFR dependence.

To better understand the possible implications of these results, we asked whether some limitation of our data set and/or analysis may obscure a stronger or weaker dependence on the SFR by using mock samples drawn from the SDSS.

We started by examining possible issues associated with the small size of our sample. Using a randomly selected subsample of 150 SDSS DR7 galaxies using the PCA technique, we found a dependence on the SFR that was three to eight times weaker than the SDSS study of Lar13. Somewhat surprisingly however, increasing the sample size did not significantly change this result, even using the largest possible sample (N ∼ 90,000). We learned that differences in the adopted signal-to-noise cuts may lead to apparently significant differences in the level of the second parameter dependence on the SFR. By imposing cuts on the mock sample that were more similar to the ones used to form the NewH data set, we found a weaker SFR dependence more consistent with the one reported here. Further work is needed to reconcile these results with recent studies based on integral field unit and drift-scan observations of local galaxies which find that there is no secondary dependence on the SFR (Hughes et al. 2013; Sánchez et al. 2013).

We also examined potential issues in our fitting analysis, and the lessons learned here are of use for future M*–Z–SFR studies. For example, we find that the PCA technique is highly sensitive to outliers and measurement uncertainties, and three-dimensional χ² minimization may be preferred as a more robust plane-fitting technique. This is particularly true for the sample size analysis described above, as there are significant numbers of true outliers in the SDSS data set.

We conclude that future work should include the following. Locally, the SDSS galaxies excluded by the Lar13 analysis should be examined more closely, and potential systematics in SFR and Z measurements due to SDSS aperture effects can be verified directly with forthcoming integral field spectroscopic surveys (e.g., MaNGA and SAMI). Future works, particularly those based on higher redshift samples, should also account for data set limitations in constraining a possible weak secondary dependence in the SFR. Here, we have addressed the effects of small sample size, but limited coverage of parameter space and relatively large measurement uncertainties may also have biasing effects. Finally, we stress the need for a non-parametric method of fitting a three-dimensional data set in order to truly determine an M*–Z–SFR relation without making assumptions about the shape or functional form of the relation.

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