Mass–Metallicity Relation and Fundamental Metallicity Relation of Metal-poor Star-forming Galaxies at 0.6 < Z < 0.9 from the eBOSS Survey

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Abstract

The stellar mass–metallicity relation (M*–Z; MZR) indicates that the metallicities of galaxies increase with increasing stellar masses. The fundamental metallicity relation (FMR) suggests that galaxies with higher star formation rates (SFRs) tend to have lower metallicities for a given stellar mass. To examine whether the MZR and FMR still hold at poorer metallicities and higher redshifts, we compile a sample of 35 star-forming galaxies (SFGs) at 0.6 < z < 0.9 using the public spectral database (v5_10.0) of emission-line galaxies from the extended Baryon Oscillation Spectroscopic Survey. These galaxies are identified for their significant auroral [O III]λ4363 emission line (S/N ≥ 3). With the electronic temperature metallicity calibration, we find nine SFGs that are extremely metal-poor galaxies with $12 + \log(O/H) \leq 7.69$ (1/10 $Z_\odot$). The metallicity of the most metal-deficient galaxy is $7.35 \pm 0.09$ (about 1/20 $Z_\odot$). Compared to the SFGs with normal metallicities in the local and high-redshift universe, our metal-poor SFGs have more than 10 times higher SFRs at a fixed stellar mass. We create a new mass–SFR relation for these metal-poor galaxies at 0.6 < z < 0.9. Due to the higher SFRs and younger stellar ages, our metal-poor SFGs deviate from the MZR and FMR in the local universe toward lower metallicities, confirming the existence of FMR, as well as the cosmic evolution of MZR and FMR with redshift.

Key words: galaxies: abundances; galaxies: distances and redshifts; galaxies: evolution; galaxies: ISM; galaxies: photometry; galaxies: starburst

1. Introduction

The gas-phase heavy-element abundance in the interstellar medium (ISM), known as “metallicity”, is a fundamental quantity that reflects the evolutionary stage of galaxies. The metallicity of a galaxy has been influenced by a lot of key processes in galaxy formation that remains to be deeply understood. The metal content within a galaxy seems to be primarily set by metal enhancement by star formation, but diluted in the short-term by the cosmological gas inflow and ejected by large-scale outflow via galactic winds (e.g., Dalcanton 2007; Dvè et al. 2011; Lilly et al. 2013; Wang et al. 2018). The inflowing gas provides the raw fuel for star formation on a longer timescale, while the galactic outflow enriches the ISM and inflowing gas. The baryons are cycling in and out of galaxies and may lead to a direct impact on the stellar masses (M*), metallicities (Z), and star formation rates (SFRs) of the galaxies. For this reason, the stellar mass–metallicity relation (MZR), the “main-sequence” relation (MSR) between galaxy SFRs and stellar masses, and the fundamental metallicity relation (FMR; M*–SFR–Z) may serve as observational constraints on models of galaxy evolution, which provides a better understanding of the build-up of galaxies across cosmic time.

The MZR, established by Lequeux et al. (1979) and developed by a series of studies (e.g., Tremonti et al. 2004; Mannucci et al. 2010; Andrews & Martini 2013), indicates a trend that the metallicities of galaxies increase with increasing stellar masses. Mannucci et al. (2010) and Andrews & Martini (2013) found that metallicity has an anti-correlation with SFR at a given stellar mass, and they constructed the M*–SFR–Z relation (or FMR).

However, Sánchez et al. (2013) and Barrera-Ballesteros et al. (2017) argued that MZR is independent of the SFR. In addition, the evolution of MZR with redshift has also been explored for years (e.g., Savaglio et al. 2005; Maiolino et al. 2008; Zahid et al. 2011; Yuan et al. 2013; Lian et al. 2015; Ly et al. 2016b), ever since the launch of larger telescopes and deeper spectroscopic surveys. These studies suggest the existence of cosmic evolution for MZR, which means that galaxies at higher-z universe tend to have lower metallicity at a fixed stellar mass.

There are a variety of methods to determine metallicity (Kewley & Ellison 2008). Some calibrations are based on the photoionization models for H II regions by reproducing some emission-line ratios, like [(O II)]λ3727 + [O III]λλ4959, 5007/Hβ (R23; Kobulnicky & Kewley 2004), [N II]λ6583/[O III]λλ3727 (N2O2; Kewley & Dopita 2002). Some other calibrations are empirical fits to the electronic temperature ($T_e$) method with strong-line ratios for H II regions and galaxies, like [(O III)]λ5007/Hβ /[N II]λλ6583/Hα and [N II]λ6583/Hα (O3N2, N2; Pettini & Pagel 2004). However, there are some problems when using these strong-line metallicity calibrations. For example, the MZRs with different calibrations have different shapes and normalization values (Kewley & Ellison 2008). For high-z star-forming galaxies, these calibrations may not be valid, since their physical conditions (e.g., gas density, ionization, N/O abundance) of the interstellar gas are significantly different from those in the local universe (Ly et al. 2016b).

The metallicity calibration with the electronic temperature of ionized gas, using the [O III]λ4363/[(O III)]λ5007 ratio, which is also called the $T_e$ method (Aller 1984), is considered the most reliable approach to determine the gas-phase oxygen-to-hydrogen...
\(\frac{\text{O}}{\text{H}}\) abundance (Izotov et al. 2006). The weak \([\text{O} \text{III}]/\lambda 4363\), produced by H II regions with high enough temperatures, can only be detected in metal-poor emission-line galaxies. For the local universe, some previous studies have made enormous efforts to enlarge the sample size of metal-poor galaxies with \(T_e\)-based metallicities (e.g., Izotov et al. 2006; Berg et al. 2012; Izotov et al. 2012; Gao et al. 2017; Hsyu et al. 2018). Izotov et al. (2006) found six new extremely metal-poor galaxies (12 + log(\(\text{O} / \text{H}\)) \(\leq 7.69\)) from 310 emission-line galaxies (ELGs) with \(S/N[\text{O} \text{III}]\lambda 4363 > 2\) in Sloan Digital Sky Survey (SDSS) Data Release 3 (DR3) data set. Berg et al. (2012) also investigated 19 new metal-poor galaxies with \(S/N[\text{O} \text{III}]\lambda 4363 > 4\) using the MMT telescope. In the SDSS DR7, Izotov et al. (2012) found seven metal-deficient galaxies with 12 + log(\(\text{O} / \text{H}\)) \(\leq 7.35\). Based on the photometric colors and morphologies in SDSS DR12, Hsyu et al. (2018) determined 45 blue compact dwarf galaxies (BCDs) with 12 + log(\(\text{O} / \text{H}\)) \(\leq 7.65\). However, the weak \([\text{O} \text{III}]/\lambda 4363\) is even harder to detect for galaxies at \(z \geq 0.2\). Some studies used large telescopes, such as Keck II, MMT, and VLT, to search the metal-poor galaxies with \([\text{O} \text{III}]/\lambda 4363\) detection at 0.5 \(\leq z \leq 1.0\) (e.g., Hoyos et al. 2005; Kakazu et al. 2007; Amorín et al. 2014; Ly et al. 2014, 2015, 2016b). In total, the number of metal-poor galaxies with \(S/N[\text{O} \text{III}]\lambda 4363 > 3\) is less than 300.

The metal-poor galaxies play an essential role in understanding the galaxy evolution, especially for the galaxies at the early stage of evolution, or for those that evolve slowly. The low metallicities of these galaxies also suggest that they might have significantly metal-poor gas inflows or metal-enriched gas outflows. The ISM in these galaxies is nearly pristine and could shed light on the ISM properties at the galaxy formation time. Furthermore, these galaxies are located in the very early stage of chemical evolution, a large sample of metal-poor galaxies is necessary to improve the determination of primordial \(^4\text{He}\) abundance (Izotov & Thuan 2004) predicted by the standard Big Bang nucleosynthesis model.

In this work, we try to search the new metal-poor galaxy candidates at 0.6 \(\leq z < 0.9\) by their \([\text{O} \text{III}]/\lambda 4363\) line from the The Extended Baryon Oscillation Spectroscopic Survey (eBOSS) survey, and then explore the cosmic evolution of MZR and FMR with metallicities derived using direct method. In our next work, using the strong-line metallicity calibrations, C. Huang et al. (2018, in preparation) will divide all the ELGs in the eBOSS survey into different bin regions, based on stellar mass, SFR, and the 4000 Å break (\(D_{4000}\)), primarily to explore the cosmic evolution of MZR and FMR.

This paper is organized as follows. In Section 2, we describe the methodology for detecting and measuring nebular emission lines, the measurements of metallicity and stellar mass, the selection for star-forming galaxies, and SFR determination. In Section 3, we provide results and discussion concerning the main-sequence relation, the MZR and FMR based on our metal-poor galaxies. Finally, we present the main results in Section 4. Throughout this paper, we adopt the solar metallicity (\(Z_\odot\)) as 12 + log(\(\text{O} / \text{H}\)) = 8.69 (Allende Prieto et al. 2001) and a flat \(\Lambda\text{CDM}\) cosmology with \(\Omega_\Lambda = 0.7\), \(\Omega_m = 0.3\), and \(H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}\).

### 2. The Data Analysis

#### 2.1. The eBOSS Overview

The eBOSS (Dawson et al. 2016), one of the three core programs in the SDSS-IV (Blanton et al. 2017), will map the distribution of galaxies and quasars at redshift \(z \sim 0.6–3.5\) and improve constraints on the nature of dark energy. This survey started in 2014 July and will create the largest volume survey of the universe to date when it finishes in spring 2020. eBOSS will target about 300,000 luminous red galaxies (LRGs) over 7500 deg\(^2\) (0.6 \(\leq z < 0.8\), 1.89,000 ELGs (Comparat et al. 2016) over 1000 deg\(^2\) (0.6 \(\leq z < 1.0\), and 73000 quasars over 7500 deg\(^2\) (0.9 \(\leq z < 3.5\), and then provide the spectra with coverage of 3600–10300 Å at a resolution of \(R \sim 2000\). The eBOSS team has delivered a public Value Added Catalog\(^6\) (VAC; “spAll-v5_10.0.fits”) together with spectral data covering \(\sim 2480\) deg\(^2\) footprint. These data include all sources observed in the first two years of SDSS-IV operations (Abolfathi et al. 2018). From the 3,008,000 objects in the VAC, we select 345,584 galaxies as the parent sample based on the following criteria: (1) \(z_{\text{warning}} = 0\), (2) \(\text{class} = \text{“GA-LAXY”}\), (3) \(\text{platequality} \neq \text{“bad”}\), and (4) 0.6 \(\leq z < 1.0\).

#### 2.2. Spectral Fitting and Emission-line Measurements

With the spectra of these 345,584 galaxies in hand, we first use the color excess \(E(B–V)\) map of the Milky Way (Schlegel et al. 1998) to correct the Galactic reddening for these spectra. Then we mask out the optical emission lines and reproduce the underlying stellar continuum using STARLIGHT code (Cid Fernandes et al. 2005), adopting the combination of 45 single stellar populations (SSPs) from Bruzual & Charlot (2003, hereafter BC03) model and the Chabrier (2003) initial mass function (IMF). These SSPs consist of 15 ages in the range of 1 Myr–13 Gyr and three different metallicities (0.01, 0.02, 0.05). After subtracting the stellar continuum from the spectrum, we use multiple Gaussians profiles to measure the fluxes of emission lines (e.g., \([\text{O} \text{III}]/\lambda 3727\), H\(_\gamma\), \([\text{O} \text{III}]/\lambda 4363\), H\(_\beta\), \([\text{O} \text{III}]/\lambda 4959\), 5007) with IDL package MPFIT (Markwardt 2009). We also estimate the signal-to-noise ratios (S/Ns) for these emission lines following the method in Ly et al. (2014), which determines the flux with

\[
\text{Flux} = \sum_{-2.5\sigma_c}^{+2.5\sigma_c} [f(\lambda - l_c) - \langle f \rangle] \times l',
\]

and assumes the noise as

\[
\text{Noise} = \sigma(f) \times l' \times \sqrt{N_{\text{pixel}}},
\]

Here, \(\sigma_G\) is the Gaussian width, \(\langle f \rangle\) and \(\sigma(f)\) are the median value and standard deviation of flux densities within 200 Å-wide region of spectral continuum, excluding the skylines and emission lines, respectively. \(l_c\) is the center wavelength of emission lines, \(l'\) is the spectral dispersion, and \(N_{\text{pixel}} = 5\sigma_G / l'\). Finally, we assume the “Case B” recombination model and the Calzetti et al. (2000) reddening formalism to derive the color excesses \(E(B–V)\) and correct the fluxes for these emission lines. We set \(E(B–V)\) to zero if the observed ratio H\(_\gamma\)/H\(_\beta\) is higher than the intrinsic ratio (H\(_\gamma\)/H\(_\beta\))\(_0\) = 0.468 (Hummer & Storey 1987).

#### 2.3. Primary Sample Selection

In order to obtain accurate SFRs with emission-line luminosities and reliable metallicities with electronic temperature, we select these spectra with the following criteria: \(S/N[\text{O} \text{III}]\lambda 4363 > 3\),

\[\text{https://data.sdss.org/sas/dr14/eboss/spectro/redax/v5_10_0/}\]
As a result, we get a subsample of 319 galaxies.

2.4. The Stellar-mass Determination from Spectral Energy Distribution (SED) Modeling

Since the coverage of rest-frame spectra in our subsample is very narrow (<3000 Å), the stellar masses derived by fitting stellar continuum with STARLIGHT code are not credible. We perform the SED fitting with multi-photometric (g, r, z, W1 (3.4 μm), W2(4.6 μm) bands) measurements using the IDL code library FAST developed by Kriek et al. (2009).

Because the magnitude values of z band in SDSS have significant uncertainties, we preferentially collect the MODELFUX values of g, r, z, W1, W2 bands for 158/319 galaxies from the Legacy Surveys7 (Lang 2014; Raichoor et al. 2017; Zou et al. 2018). The Legacy Surveys produce an inference model catalog of the sky from a series of optical and infrared imaging data. The MODELFUX values of g, r, z bands for the rest 161/319 galaxies are collected from the eBOSS VAC Catalog, while the MODEL MAG values of W1, W2 bands for 78/161 galaxies are derived by cross-matching with the All WISE Source Catalog (Wright et al. 2010). Additionally, we correct the broadband (g, r, z bands) photometry by subtracting the contribution of strong emission lines from our spectroscopic, which has been used in previous studies (e.g., Atek et al. 2011; Pirzkal et al. 2013; Izotov et al. 2014; Ly et al. 2014).

In the SED fitting, we adopt the Chabrier (2003) IMF, the Bruzual & Charlot (2003) stellar templates with four metallicities (0.004, 0.008, 0.02, 0.05), and an exponentially decreasing star formation model SFR ∝ e−t/T∗ to synthesize magnitudes. We set the stellar population ages ranging from 0 to 10 Gyr and also assume the Calzetti et al. (2000) reddening formalism, allowing E(B−V) to vary from 0 to 2.0. Varying the input photometry with their photometric errors, we repeat the SED fitting 1000 times. The stellar mass and its error are assumed as the median value and 1σ value in the distribution of fitting results. The median and standard deviation of the errors on stellar mass estimation in SED fitting are 0.26 ± 0.18 dex, while the uncertainties in SSP selections and mass-to-light ratio are about 0.28 dex (Section 3.4, in detail) and 0.1 dex (Bruzual & Charlot 2003), respectively.

2.5. T_e-based Metallicity Determination

To determine the gas-phase metallicity for our SFGs with significant detection of [O III]λ4363, we use the T_e method (e.g., Aller 1984; Izotov et al. 2012; Ly et al. 2016a; Bian et al. 2018). In general, one needs to use the [S II]λλ6717, 6731 doublet lines to determine the electron densities (n_e) and the electron temperatures T_e. However, since the [S II] doublet lines are redshifted out of our spectral coverage, we assume n_e = 100 cm−3, as is used in Ly et al. (2014). Per our previous work (Gao et al. 2017; Lin et al. 2017), we use the python package PYNEB8 developed by Leridiana et al. (2015) to calculate the metallicity. In the calculation process, we set the atomic recombination data and atomic collision strength data for a series of ions (O+3, O++; Gao et al. 2017, in detail). We also follow an iterative method in Nicholls et al. (2014) to determine the temperature of O+3 region T_e([O II]) with the temperature of O++ region T_e([O III]) and the total oxygen abundance, [O/H] = 12 + log(O/H).

For the uncertainty in metallicity determination, we simulate the emission lines according to the measured fluxes and errors, and repeat the metallicity calculation 1000 times. We regard the median value of the 1000 measurements as the measurement value, and the 1σ value of the distribution as the error. The median and standard deviation of uncertainties for metallicity are 0.15 ± 0.07 dex.

2.6. Exclusion of Active Galactic Nucleus (AGNs) and Final Sample Selection

Due to the absence of the emission lines Hα and [N II]λ6583 for all spectra in the subsample, we exclude the galaxies that harbor AGNs using the “Mass-extinction” diagram (MEx: Juneau et al. 2011; Trump et al. 2013), instead of the BPT diagram (Baldwin et al. 1981; Kewley et al. 2001; Kauffmann et al. 2003). There are 136/319 galaxies located in the star-forming region. However, taking the T_e-based metallicity in Section 2.5 into consideration, we have 81/136 galaxies with effective metallicities. Then we inspect the spectra of the remaining 81 galaxies visually, and exclude 9/81 Seyfert galaxies with high ionization lines [Ne v]λ3425 and [He II]λ4686 (Izotov et al. 2012; Ly et al. 2014), as well as 37/81 spectra with fake [O III]λ4363 detection or contaminated by OH skylines. Finally, our final SFG sample consists of 35 galaxies.

The sample selection is shown in Figure 1. All symbols represent the 319 candidates in subsamples selected with signal-to-noise of emission lines in Section 2.3. Green and red stars represent the 183 AGNs in MEx-AGN region and nine Seyfert galaxies, respectively. Gray triangles and magenta diamonds show the 55 galaxies without effective metallicities and 37 galaxies with fake [O III]λ4363 detection or contaminated by OH skylines. Blue filled circles denote our final SFG sample. Figure 2 shows the eBOSS spectra for six representative [O III]λ4363-detected SFGs, which span a rest-frame wavelength range from 3400 Å to 5100 Å. For each panel, the spectral ID (plate − mjd − fiberid), redshift, S/N([O III]λ4363), and T_e-based metallicity are also given in the top left. The OH skylines are denoted by the vertical gray shaded bands, with darker bands indicating stronger skylines.

2.7. SFR Estimation From Hβ

In addition to stellar mass and oxygen abundances, we can estimate the dust-corrected SFRs using the Hβ luminosities L_{cor}(Hβ). Assuming a Chabrier (2003) IMF and solar metallicity, the SFR calculated in Kennicutt (1998) can be written as

\[
SFR(M_\odot yr^{-1}) = 4.4 \times 10^{-42} \times (H\alpha/H\beta)_0 \times L_{cor}(H\beta) \text{ (erg s}^{-1})
\]  

where the intrinsic ratio (Hα/Hβ)_0 = 2.86. However, for the galaxies with lower metallicities, the SFRs estimated by the Equation (3) will be overestimated since the greater escape of ionizing photons from more metal-poor O star atmospheres. Ly et al. (2016a) gave the metallicity-corrected SFRs as

\[
\log(SFR_{cor}) = \log(SFR) + 0.39y + 0.127y^2,
\]

where y = log(O/H) + 3.31.

We summarize the basic information, properties, and measurements of the final [O III]λ4363-detected SFGs selected from

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7 http://legacysurvey.org/

8 http://www.iac.es/proyecto/PyNeb/
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**Figure 1.** Flux ratio [O III]/Hβ as a function of stellar mass (i.e., the MEx diagram). One-hundred eighty-three (green stars) and nine (red stars) galaxies are identified as AGNs via the black solid Juneau et al. (2011) demarcation lines, and the presence of high ionization lines [Ne v]λ3425 and [He II]λ4686, respectively. Thirty-seven galaxies (maiden diamonds) are found with fake [O III]λ4363 detection or severely contaminated by OH skylines. Blue filled circles denote the SFG sample. Fifty-five galaxies (gray triangles) have ineffective metallicities. Blue filled circles denote our final SFG sample. The error bars show the median values of measurement uncertainties for stellar mass and [O III]/Hβ ratio. eBOSS in Table 1. We find nine SFGs are extremely metal-poor with $12 + \log(O/H) \leq 7.69$ (i.e., poorer than 1/10 $Z_\odot$). The metallicity for the most metal-deficient galaxy (ID: 7396-56809-134, $z = 0.68$) is $7.35 \pm 0.09$, about 1/20 $Z_\odot$.

### 3. Results

#### 3.1. Star-forming Main Sequence

In Figure 3, we show the distributions of $T_e$-based metallicities versus redshifts for some samples of [O III]λ4363-detected SFGs at 0.6 < $z$ < 0.9, including 35 SFGs in our eBOSS sample (the blue circles), 28 SFGs from the DEEP2 sample (the magenta triangles) from Ly et al. (2015), 4 SDF MMT/Hectospec sample (the purple squares), and 24 SDF Keck/DEIMOS sample (the green diamonds) from Ly et al. (2016a). The redshifts of our SFGs span from 0.6 to 0.9. Compared with other samples, most of our SFGs (24/35) are located in 0.6 < $z$ < 0.7, while most of the DEEP2 and SDF sample range from 0.7–0.9.

In Figure 4, we plot the metallicity-corrected SFRs derived with H/β luminosities as a function of the stellar masses from SED fitting to compare against other metal-poor SFG samples. The symbols are the same as in Figure 3. We also perform the linear fitting for these metal-poor galaxies and give the best relation as

$$\log(SFR/M_\odot \text{ yr}^{-1}) = 1.24(\pm0.11) \log(M_*/M_\odot) - 10.09(\pm0.10),$$

shown with solid magenta line. Overlaid as blue and green stripes are the results based on Hα-selected galaxies at $z \sim 0.8$ (de los Reyes et al. 2015) and mass-selected SFGs at $z = 0.5–1.0$ (Whitaker et al. 2014), respectively. The local star-forming main sequence derived from the SDSS sample of SFGs is also shown in the gray stripe (Salim et al. 2007). The difference between the MSR in the local and high-redshift universe is also consistent with the result that the rate of declining SFR with redshift is not a strong function of stellar mass (Zheng et al. 2007). Compared with the SFGs with normal metallicities, the metal-poor SFGs in our sample are found to have more intense star formation activities. If extrapolating the $M_*/$SFR relation to lower $M_*$, we find the SFRs in our sample are enhanced by 1.0–3.0 dex above the $M_*/$SFR relation in the local universe (Salim et al. 2007) and are 0.5–2.0 dex higher than the normal SFGs at $z = 0.5–1.0$ (Whitaker et al. 2014) or $z \sim 0.8$ (de los Reyes et al. 2015). The coverage of stellar masses and SFRs of our eBOSS SFGs is similar to the DEEP2 sample.

#### 3.2. Stellar Mass–Metallicity Relation

In Figure 5, we plot the relation between gas-phase metallicity and stellar mass (i.e., MZR) for some samples of [O III]λ4363-detected SFGs at 0.6 < $z$ < 0.9, including metal-poor SFGs in our eBOSS sample and three other samples, the symbols for which are the same as in those in Figures 3 and 4. The black solid and dashed lines represent the local MZR and its limits derived from the stacked spectra by Andrews & Martini (2013) based on $T_e$ metallicity calculation, respectively. The solid magenta line represents the MZR for SFGs at 0.5 < $z$ < 1.0 derived by Ly et al. (2016b). As shown in the figure, most of our eBOSS metal-poor SFGs show lower metallicities than the MZRs in Andrews & Martini (2013) and Ly et al. (2016b) systematically, by about 0.7 dex and 0.3 dex, respectively. Besides, we note that the metallicities in eBOSS SFGs are lower than the metallicities in the DEEP2 sample about 0.37 dex.

In the previous studies, Savaglio et al. (2005) identified a strong correlation between stellar mass and metallicity for 56 galaxies based on R23 method at the high-$z$ universe, and for the first time, found clear evidence for the cosmic evolution of MZR. Lian et al. (2016) also used the R23 method to compare the metallicities of BCDs in the local and intermediate-$z$ (0.2 < $z$ < 0.5) universe, but did not find a significant deviation in MZR. Determining the metallicities for 66 [O III]λ4363-detected galaxies with the electron temperature metallicity calibration, Ly et al. (2016b) found the MZR at high redshift have lower metallicities, about 0.25 dex, than the MZR in Andrews & Martini (2013) at all stellar masses. In this work, our SFGs also have systematically lower metallicities than the local MZR, confirming the existence of the cosmic evolution of MZR with redshift. Meanwhile, our SFGs also locate below the MZR at 0.5 < $z$ < 1.0 in Ly et al. (2016b), which may be caused by the higher SFRs, higher stellar masses and/or the uncertainties of stellar mass measurements. Because of the shallow limited-magnitude in eBOSS, these relatively more massive (8.0 < log($M_*/M_\odot$) < 9.5) metal-poor galaxies may be preferably chosen in the sample selection (Izotov et al. 2014).

#### 3.3. Fundamental Metallicity Relation

The stellar mass–SFR–metallicity relation (FMR) is constructed by Mannucci et al. (2010) and Andrews & Martini (2013) to significantly decrease the scatter in MZR, which indicates that the metallicity is anti-correlated with SFR at a
Figure 2. The eBOSS spectra for six representative [O III] $\lambda$4363-detected SFGs, which span a rest-frame wavelength range from 3400 Å to 5100 Å, cover the domains of [Ne V] $\lambda$3425 to [O III] $\lambda$5007. The insets provide a zoomed view of H$\gamma$ and [O III] $\lambda$4363. The spectral ID (plate − mjd − fiberid), redshift, S/N([O III] $\lambda$4363) and $T_e$-based metallicity are also given in the top left. The vertical gray shaded bands denote the OH skylines, with darker bands indicating stronger skylines.
| ID       | R.A. (deg) | DECL. (deg) | z    | E(B-V) (mag) | S/N | D_4000 | EW(H\beta) (\AA) | H\beta (10^{-17} erg s^{-1}) | [O III] λ5007/V | [O III] λ5007/H\beta | \log(M_*/M_\odot) | \log(M/ \text{King}) | logT_e/K | 12 + \log(O/H) |
|---------|------------|-------------|------|--------------|-----|--------|------------------|-----------------------------|----------------|----------------------|----------------|----------------------|----------|----------------|
fixed stellar mass. In Figure 6, we show the FMR for some samples of $\text{[O III]}\lambda4363$-detected SFGs at $0.6 < z < 0.9$, including 35 SFGs in our eBOSS sample (the blue circles), 28 SFGs from the DEEP2 sample (the magenta triangles; Ly et al. 2015), 4 SDF MMT/Hectospec sample (the purple squares), and 24 SDF Keck/DEIMOS sample (the green diamonds; Ly et al. 2016a).

For a direct comparison, we adopt the SFR coefficient $\alpha = 0.66$ from Andrews & Martini (2013) and give the local FMR with its limits as the black solid and dashed lines. We can find that 10/35 of our metal-poor SFGs can be well fitted by the local FMR within a deviation of 0.14 dex, while the other 25/35 SFGs have the metallicities below the local FMR with an average value 0.43 dex. Furthermore, we also use the linear relation with the same slope of 0.43 in Andrews & Martini (2013) to fit all these data, and find that the best relation (shown as the solid magenta line) has an offset of about 0.16 dex below the local FMR, with a dispersion (standard deviation of the residuals) about 0.32 dex.

Our results confirm the existence of FMR, which means that the metal-poor galaxies with higher SFRs have lower metallicities at a same stellar mass. The offset of FMR also indicates the trend that, similar to MZR cosmic evolution, FMR evolves toward lower metallicity at a fixed stellar mass and SFR in the earlier universe. We note that our SFGs have smaller $D_{n4000}$ indices ($0.5 < D_{n4000} < 1.0$) with a median value of 0.8. The cosmic evolution of FMR may be caused by the fact that SFGs at intermediate-$z$ and high-$z$ have much younger SSPs than those in the local universe. This result is consistent with the result in Lian et al. (2015) that galaxies with smaller $D_{n4000}$ typically have lower metallicity at a fixed stellar mass, suggesting that the galaxy stellar age plays an essential role in the MZR and FMR for high-redshift SFGs.

3.4. Discussion for Metallicity and Stellar Mass Determinations

In the process of determining the metallicity with electron temperature, we usually need the $\text{[S II]}\lambda6717/\text{[S II]}\lambda6731$ ratio to estimate the electron density $n_e$, and then use the $\text{[O III]}\lambda\lambda4959,5007$ line ratios. The distributions of $T_e$-based metallicities and redshifts for some samples of $\text{[O III]}\lambda4363$-detected SFGs at $0.6 < z < 0.9$, including 35 SFGs in our eBOSS sample (the blue circles), 28 SFGs from the DEEP2 sample (the magenta triangles; Ly et al. 2015), 4 SDF MMT/Hectospec sample (the purple squares), and 24 SDF Keck/DEIMOS sample (the green diamonds; Ly et al. 2016a) are shown in Figure 3. The star-forming main-sequence relation for some samples of $\text{[O III]}\lambda4363$-detected SFGs at $0.6 < z < 0.9$, the symbols for which are the same as those in Figure 3. The solid magenta line is the best linear fitting relation for above metal-poor galaxies. Overlaid as blue and green stripes are the results based on H$\alpha$-selected galaxies at $z \sim 0.8$ (de los Reyes et al. 2015) and mass-selected SFGs at $z = 0.5$–1.0 (Whitaker et al. 2014), respectively. The local star-forming main sequence derived from the SDSS sample of SFGs is shown as the gray stripe (Salim et al. 2007).

The relation between gas-phase metallicity and stellar mass (i.e., MZR) for some samples of $\text{[O III]}\lambda4363$-detected SFGs at $0.6 < z < 0.9$, the symbols for which are the same as those in Figure 3 are shown in Figure 5. For a direct comparison, the local MZR and its limits derived from the stacked spectra by Andrews & Martini (2013) are given as black solid and dashed lines, while the MZR for SFGs at $0.5 < z < 1.0$ derived by Ly et al. (2016b) is shown as the solid magenta line.
The fundamental metallicity relation (FMR) for some samples of \([\text{O III}]\lambda4363\)-detected SFGs at \(0.6 < z < 0.9\), which symbols are same as in Figure 3. For a direct comparison, the local FMR derived from the stacked spectra by Andrews & Martini (2013) is also given as the black solid and dashed lines. The best FMR relation we note that the \(\lambda\lambda7320, 7330\) ratio. Due to the absence of \(\text{O III}\) lines in our spectra, we follow the method in Nicholls et al. (2014) to determine the \(T_e(\text{O III})\). If calculating the metallicities using the \(T_e(\text{O II})-T_e(\text{O III})\) relation from Izotov et al. (2012) and Andrews & Martini (2013), we will yield higher \(T_e(\text{O II})\) values with an average offset about 0.03 dex, which will result in lower metallicities by about 0.05 dex. In order to make a direct comparison with the metal-poor SFGs selected from SDF and DEEP2 surveys, we assume the Chabrier (2003) IMF and Bruzual & Charlot (2003) SSPs, following Ly et al. (2014) and Ly et al. (2016a), to estimate the stellar masses. However, different assumptions on IMFs and SSPs will lead to some differences in the stellar mass determination (e.g., Bruzual & Charlot 2003; Brinchmann et al. 2008; Parikh et al. 2018). In Figure 7, we show the comparison of stellar mass determination with two different SSP libraries (Bruzual & Charlot 2003; Maraston 2005) and three IMFs (Salpeter 1955; Kroupa 2001; Chabrier 2003) for the subsample of 319 galaxies selected in Section 2.3. If using the Bruzual & Charlot (2003) SSPs, we note that the stellar masses estimated by Salpeter (1955) IMF have a systematic offset about 0.22 dex above those by Chabrier (2003) IMF, consistent with Sánchez et al. (2016), while having a smallest dispersion about 0.07 dex. If we adopt the Salpeter (1955) IMF, the offset between stellar masses with Bruzual & Charlot (2003) and Maraston (2005) SSPs is about −0.18 dex, and the dispersion is about 0.28 dex. However, as Bruzual & Charlot (2003) pointed out, the Chabrier (2003) IMF is physically motivated, and it shows a better fitting to the counts of low-mass stars and brown dwarfs in the Galactic disk. Compared with the Chabrier (2003) IMF, the Salpeter (1955) IMF leads to a systematic overestimation of stellar mass. In brief, the different assumptions in metallicity calibration and mass determination will have a nearly insignificant effect on the MZR and FMR for our metal-poor SFGs in eBOSS.

4. Summary

In this work, we use the spectroscopic data of eBOSS in the SDSS DR14 data set to search for metal-poor galaxies with \([\text{O III}]\lambda4363\) detection at \(0.6 < z < 0.9\), and to explore the cosmic evolution of MZR and FMR. We have determined the metallicity with the electron temperature method based on the \([\text{O III}]\lambda4363/\lambda5007\) ratio. The stellar masses are derived from the SED fitting with multi-photometric measurements, and the SFRs are estimated from the H\(\beta\) luminosities. The primary results are summarized as follows.

1. We select a sample of 35 metal-poor star-forming galaxy candidates with \(S/N (\lambda4363) \geq 3.0\) and have a median value of \(12 + \log(O/H) = 7.83\) ranging from 7.35–8.22 (Figure 3). Nine SFGs are found to be extremely metal-poor with \(12 + \log(O/H) \leq 7.69\), in which the most metal-deficient galaxy is \(7.35 \pm 0.09\), about \(1/20 Z_{\odot}\).

2. We find that the SFRs of our SFGs are enhanced by 1.0–3.0 dex above the \(M_–/\text{SFR}\) relation (Salim et al. 2007) in the local universe (Figure 4). Based on a few of
the metal-poor galaxy samples, we create a new $M_\star$-SFR relation for these galaxies at $0.6 \leq z \leq 0.9$, shown as Equation (5).

3. Our SFGs have systematically lower metallicities than the local MZR in Andrews & Martini (2013), confirming the existence of the cosmic evolution of MZR with redshift reported in previous studies (Figure 5). Furthermore, we also find that the metallicities of these metal-poor SFGs have a systematic offset about 0.16 dex below the local FMR (Figure 6), indicating that galaxies have lower metallicities at a fixed stellar mass and SFR in the earlier universe.

We attribute the cosmic evolution of FMR to the stellar age of galaxies at different redshifts (Section 3.3). In our next work, we will stack the spectra, for all ELGs in the eBOSS survey, in bins of stellar mass, SFR and $D_{\text{L}} = 4000$, to significantly enhance the S/N of emission lines, and then mainly explore the cosmic evolution of MZR and FMR.

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