Spatially resolved mass–metallicity relation at z ~ 0.26 from the MUSE-Wide Survey

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ABSTRACT

Aims. Galaxies in the local universe have a spatially resolved star-forming main sequence (rSFMS) and mass–metallicity relation (rMZR). We know that the global mass–metallicity relation (MZR) results from the integral of the rMZR, and it evolves with redshift. However, the evolution of the rMZR with redshift is still unclear because the spatial resolution and signal-to-noise ratio are low. Currently, too few observations beyond the local universe are available, and only simulations can reproduce the evolution of the rMZR with redshift.

Methods. We selected ten emission-line galaxies with an average redshift of z ~ 0.26 from the MUSE-Wide DR1. We obtained the spatially resolved star formation rate (SFR) and metallicity from integral field spectroscopy (IFS), as well as the stellar mass surface density from 3D-HST photometry. We derived the rSFMS and rMZR at z ~ 0.26 and compared them with those of local galaxies.

Results. We find that the rSFMS of galaxies at z ~ 0.26 has a slope of ~0.771. The rMZR exists at z ~ 0.26, showing a similar shape to that of the local universe, but a lower average metallicity that is about ~0.11 dex lower than the local metallicity. In addition, we also study the spatially resolved fundamental metallicity relation (rFMR) of these galaxies. However, there is no obvious evidence that an rFMR exists at z ~ 0.26, and it is not an extension of rMZR at a high SFR.

Conclusions. Similar to their global versions, the rSFMS and rMZR of galaxies also evolve with redshift. At fixed stellar mass, galaxies at higher redshift show a higher SFR and lower metallicity. These suggest that the evolution of the global galaxy properties with redshift may result from integrating the evolution of the spatially resolved galaxy properties.

Key words. galaxies: abundances – ISM: abundances – galaxies: evolution – galaxies: star formation

1. Introduction

We can understand the evolution of galaxies by analyzing their gas-phase chemical abundance. The inflow and outflow of gas, the stellar wind, and supernova explosions play a critical role in shaping the gas-phase metallicity (Z) of the galaxies. These processes are closely related to other properties of galaxies, the most important of which is the stellar mass (M\textsubscript{st}). Therefore, the mass–metallicity relation (MZR) should naturally appear (Lequeux et al. 1979). At the same time, the inflow and outflow of gas can regulate the enrichment process of metals. The inflowing gas dilutes the metal and increases the star formation rate (SFR), and the feedback from the star formation and active galactic nucleus (AGN) will blow away the metal that has formed. Some studies (Lara-López et al. 2010; Mannucci et al. 2010) have found that the three parameters M\textsubscript{st}, Z, and SFR can form a closer relation, called fundamental metallicity relation (FMR). In this relation, a galaxy with a higher SFR at a given M\textsubscript{st} tends to have lower Z, which does not evolve with the redshift.

On the one hand, as the redshift survey continues to deepen, the MZR has been observed at different redshifts in recent decades, from the local universe to z ~ 3.5. It has been discovered that the MZR will evolve with the redshift (e.g., Tremonti et al. 2004; Maiolino et al. 2008; Zahid et al. 2014; Gao et al. 2018a; Huang et al. 2019; Sanders et al. 2021). This evolution has many reasons. For example, the galaxies in the local universe have longer histories, which means that they have experienced a longer period of gas consumption and metal enrichment than high-redshift galaxies. Yabe et al. (2015) hypothesized that galaxies at high redshift have more gas inflow and outflow, while Lian et al. (2018) conjectured that galaxies at high redshift have more metal outflow and a steeper slope of the initial mass function (IMF). Ma et al. (2016) used high-resolution cosmological zoom-in simulations and found that the evolution of the MZR is associated with the evolution of the stellar and gas mass fractions at different redshifts.

On the other hand, spatially resolved spectroscopy of local galaxies became feasible, and resolved-to-scale relations can be detected (Sánchez 2020). The corresponding surface densities replace all extensive quantities in the resolved scaling relation. Integral field spectroscopy (IFS) surveys, such as CALIFA (Sánchez et al. 2012) and MaNGA (Bundy et al. 2015) have enabled us to find the local version of global scale relations.
on subgalactic scales. One of them is the resolved star formation sequence (rSFMS) (e.g., Cano-Díaz et al. 2016; Hsieh et al. 2017; Pan et al. 2018; Jafariyazani et al. 2019), which refers to the relation between the stellar mass surface density ($\Sigma_s$) and the SFR surface density ($\Sigma_{SFR}$). Another is the resolved mass-metallicity relation (rMZR) (e.g., Rosales-Ortega et al. 2012; Sánchez et al. 2013; Barrera-Ballesteros et al. 2016; Gao et al. 2018b), which refers to the relation between the $\Sigma_s$ and its local metallicity. The rMZR is regarded as a more fundamental relation than the global MZR because it can reproduce the global rate and the metallicity profile along the galactocentric radius well (Barrera-Ballesteros et al. 2016). Similar to the FMR and rMZR, the spatially resolved FMR (rFMR) can also be developed. However, there is a lack of clear evidence for the existence of the rFMR in studies of $z \sim 0$ galaxies (e.g., Sánchez et al. 2013; Gao et al. 2018b; Sánchez 2020).

However, due to the low spatial resolution and signal-to-noise ratio (S/N) at high redshift, the evolution of the rMZR and rFMR with redshift is still unclear. Recently, a few works have studied this. Trayford & Schaye (2019) have used the EAGLE simulation to study it and reported that the normalization of rMZR strongly evolves with redshift. Similar to the evolution of the global MZR, the lower the redshift, the higher the metallicity. They also reported that the shape of the rMZR also evolves strongly when the AGN feedback is taken into account. Patrício et al. (2019) have analyzed three gravitationally lensed galaxies at $z \approx 0.6$, 0.7, and 1. However, they found higher metallicities than in the local universe at the same $\Sigma_s$ possibly caused by the differences in sample selection and metallicity calibration. Gillman et al. (2022) have observed 22 main-sequence galaxies at $z \sim 1.5$, but found that the evolution of the rMZR is inconsistent with the evolution of the global MZR. This work uses a sample selected from the IFS survey to focus on the rMZR at higher redshifts and compare it with that of local galaxies. Their rSFMS and metallicity gradient are also studied.

This paper is organized as follows. In Sect. 2 we describe our selection criteria of the sample and the measurements from the data. In Sect. 3 we present our results of the rMZR and other resolved properties and discuss whether our result is an extension of the local rFMR for a high SFR. In Sect. 4 we summarize the main conclusion of this work. Throughout this paper, we adopt a $\Lambda$-CDM cosmology with $\Omega_M = 0.7$, $\Omega_{\Lambda} = 0.3$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$. The IMF we adopted is the Chabrier (2003) IMF.

2. Data

2.1. Data source overview

In order to derive the spatially resolved properties of galaxies in the intermediate-redshift universe, we need an IFS data set and multiband photometric images. We selected the spectroscopy of the MUSE-Wide Survey (Urrutia et al. 2019) and the photometric data of 3D-HST (Brammer et al. 2012; Skelton et al. 2014) as the data source. In addition, we also collected the morphological parameters of galaxies from the Dark Energy Spectroscopic Instrument (DESI) Legacy Imaging Survey (Dey et al. 2019).

2.1.1. MUSE-Wide DR1

The MUSE-Wide Survey is a blind 3D spectroscopic survey in the CANDELS/GOODS-South and CANDELS/COSMOS regions. The final survey will cover $100 \times 1$ arcmin$^2$ MUSE fields. Each MUSE-Wide pointing has a depth of one hour and hence targets more extreme and more luminous objects over ten times the area of the MUSE-Deep fields (Bacon et al. 2017). The MUSE instrument performed it on the Very Large Telescope (VLT) in the wide-field mode, which provides medium-resolution spectroscopy at a spatial sampling of 0.2$''$ per spatial pixel and an extended range, covering 4750–9350 Å with a resolution of $\sim$2.5 Å. We used the first data release (DR1) (Urrutia et al. 2019) of the MUSE-Wide Survey, which covers the first 44 CANDELS/GOODS-S pointings of the 100 final pointings. This data release provides datacubes of the observed 44 fields and a catalog of 1602 emission line sources with redshifts in the range of $0.04 \leq z \leq 6$. All catalogs and spectra can be accessed at the MUSE-Wide official website.

2.1.2. 3D-HST

3D-HST is a Hubble Space Telescope (HST) Treasury program to provide Wide Field Camera 3 (WFC3) and Advanced Camera for Surveys (ACS) grism spectroscopy over four extragalactic fields (AEGIS, COSMOS, GOODS-South, and UDS), augmented with previously obtained data in GOODS-North. In addition to the grism spectroscopy, the project provides reduced WFC3 images in all five fields, extensive multiwavelength photometric catalogs, and catalogs of derived parameters such as redshifts and stellar masses. These ancillary data come from a wide range of other public programs, most notably the CANDELS Multi-Cycle Treasury program (Grogin et al. 2011; Koekemoer et al. 2011). We used the GOODS-South field of the first comprehensive photometry release of 3D-HST, dubbed version 4.1, including reduced WFC3 F125W, WFC3 F140W, WFC3 F160W, ACS F435W, ACS F606W, ACS F775W, and ACS F850LP image mosaics, which cover the 44 fields of MUSE-Wide DR1 completely.

2.1.3. DESI Legacy Imaging Survey

The DESI Legacy Imaging Surveys produce an inference model catalog of the sky from a set of optical and infrared imaging data, comprising 14 000 deg$^2$ of extragalactic sky visible from the northern hemisphere in three optical ($g, r, z$) and four infrared bands. Since we already have a higher spatial resolution 3D-HST image, we only used the data of the size and ellipticity of the galaxy to select our sample. We used the Sweep catalogs of DESI Legacy Imaging Surveys Data Release 9.

2.2. Sample selection

We selected the sample from the MUSE-Wide DR1 emission line catalog, which includes 3057 emission lines of the integrated spectra of 1602 galaxies.

We used the following rules to select the source. Firstly, the emission lines (H$\alpha$, H$\beta$, [O III] 5007, and [N II] 6583) should be detected (the S/N of integrated spectrum is $>5$). Secondly, the galaxy should not be at the edge of the MUSE-Wide field. Thirdly, there should be no AGN feature. Lastly, the effective radius should be $R_e > 0.6$, and the axis ratio should be $b/a > 0.3$ in the rest-frame optical band.

We used the COMMENT column in the emission line catalog to exclude AGN, which are classified by matching the X-ray catalog of the 7Ms Chandra Deep Field South (Luo et al. 2017). We obtained the morphological parameters ($R_e$ and $b/a$)
by matching the sweep catalog of the DESI Legacy Imaging Survey. After our selection, a total of ten galaxies meet our requirements. Their MUSE white-light images (created from datacubes by summation over the spectral axis; Herenz et al. 2017) and HST color images are shown in Fig. 1. The white error bar in each panel of Fig. 1 indicates the full width at half maximum (FWHM) of the point spread function (PSF) of the MUSE-Wide field. Their detailed information is listed in Table 1. The mean redshift of our sample is \( \bar{z} \approx 0.26 \).

Figure 2 shows the distribution of the stellar mass, SFR, and \( R_e \) of our galaxies with the distribution of all MUSE-Wide low-redshift galaxies.

We remeasured the morphological parameters of these galaxies using HST F850LP images with the GALFIT software\(^2\) (Peng et al. 2010). We used the remeasured \( b/a \) and \( R_e \) derived by GALFIT as the final parameters. These morphological measurements are shown in Table 2. The results measured by van der Wel et al. (2012) in \( F125W \) were also added in the table for reference. We note that the measured value of \( R_e \) of 133001029 is significantly higher than other measurements, but this is not important and has no effect on the following discussion and conclusions.

### 2.3. Measurements from MUSE-Wide

#### 2.3.1. Spectral fitting

We adopted a process similar to that described by Yao et al. (2022) in MaNGA to process these spectra. For each galaxy, we cut out a 40 \( \times \) 40 datacube from the field it belongs to and performed spectral fitting for each spaxel. Before the spectral fitting, we first corrected all spectra for Galactic extinction. We used the color excess \( E(B - V) \) map of the Milky Way (Schlegel et al. 1998) and the extinction law presented by Cardelli et al. (1989). We first moved each spectrum to the rest-frame, masked its main emission line, and then performed a low-order polynomial fitting to obtain the continua. After subtracting the continua from the origin spectra, we used MPFIT (Markwardt 2009) to perform Gaussian fitting on their emission lines (H\( \alpha \), H\( \beta \), [O\( \text{III} \)]\( \lambda 5007 \), and [N\( \text{II} \)]\( \lambda 6583 \)) and then obtained their fluxes. The S/Ns of these emission lines were estimated following Ly et al. (2014).

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\(^{2}\) <https://users.obs.carnegiescience.edu/peng/work/galfit/galfit.html>
Notes. From left to right, the columns correspond to (1), (2), (3), and (4) the unique id, RA, Dec and redshift of the galaxy, taken from the emission line catalog of MUSE-Wide; (5), (6), and (7) the morphological parameters remeasured by GALFIT; (8) the stellar mass remeasured by matching the 3D-HST photometry catalog.

Table 1. Basic information of the ten galaxies in our sample.

| Unique ID   | RA (deg) | Dec (deg) | Redshift | $R_e$ (arcsec) | Sersic n | $b/a$ | Total stellar mass (log($M_\odot$/M$_\odot$)) |
|------------|---------|-----------|----------|---------------|----------|------|---------------------------------|
| 102021103  | 53.074  | -27.8240  | 0.247    | 0.76 ± 0.00   | 1.00 ± 0.01 | 0.662 ± 0.003 | 9.19 ± 0.17 |
| 106002013  | 53.080  | -27.8083  | 0.288    | 0.68 ± 0.01   | 1.87 ± 0.01 | 0.873 ± 0.004 | 9.21 ± 0.11 |
| 113001007  | 53.115  | -27.8271  | 0.232    | 1.79 ± 0.03   | 1.55 ± 0.02 | 0.322 ± 0.003 | 9.24 ± 0.18 |
| 122003050  | 53.131  | -27.8291  | 0.214    | 1.73 ± 0.01   | 1.66 ± 0.01 | 0.578 ± 0.001 | 10.09 ± 0.25 |
| 124002008  | 53.161  | -27.8323  | 0.242    | 1.11 ± 0.00   | 1.34 ± 0.01 | 0.325 ± 0.001 | 9.82 ± 0.12 |
| 131007064  | 53.110  | -27.7802  | 0.337    | 0.61 ± 0.00   | 1.29 ± 0.00 | 0.327 ± 0.001 | 10.09 ± 0.11 |
| 133001029  | 53.144  | -27.8137  | 0.215    | 3.37 ± 0.06   | 2.93 ± 0.03 | 0.762 ± 0.003 | 10.58 ± 0.24 |
| 136002114  | 53.116  | -27.7775  | 0.247    | 0.93 ± 0.00   | 1.60 ± 0.01 | 0.274 ± 0.001 | 10.24 ± 0.06 |
| 139009211  | 53.142  | -27.7651  | 0.366    | 0.66 ± 0.01   | 1.53 ± 0.01 | 0.544 ± 0.004 | 9.01 ± 0.40 |
| 142002070  | 53.084  | -27.7655  | 0.232    | 1.11 ± 0.00   | 1.20 ± 0.01 | 0.713 ± 0.003 | 9.55 ± 0.10 |

Table 2. Comparison of morphological measurements.

| Unique ID   | $R_e$ (a) | $R_e$ (b) | $R_e$ (c) | $b/a$ (a) | $b/a$ (b) | $b/a$ (c) |
|------------|-----------|-----------|-----------|-----------|-----------|-----------|
| 102021103  | 0.75      | 0.76      | 0.78      | 0.68      | 0.66      | 0.68      |
| 106002013  | 0.64      | 0.68      | 0.62      | 1.00      | 0.87      | 0.82      |
| 113001007  | 1.52      | 1.79      | 1.38      | 0.45      | 0.32      | 0.31      |
| 122003050  | 1.84      | 1.73      | 1.44      | 0.57      | 0.58      | 0.57      |
| 124002008  | 1.19      | 1.11      | 1.07      | 0.42      | 0.32      | 0.34      |
| 131007064  | 0.68      | 0.61      | 0.52      | 0.33      | 0.33      | 0.32      |
| 133001029  | 1.64      | 3.37      | 1.73      | 0.75      | 0.76      | 0.74      |
| 136002114  | 0.99      | 0.93      | 0.77      | 0.41      | 0.27      | 0.27      |
| 139009211  | 0.88      | 0.66      | 0.47      | 0.45      | 0.54      | 0.46      |
| 142002070  | 1.35      | 1.11      | 1.19      | 0.63      | 0.71      | 0.63      |

Notes. (a) Measured in the DESI Sweep catalog. (b) Measured in this work in F850LP. (c) Measured by van der Wel et al. (2012) in F125W.

Therefore, we stacked spaxels into bins to improve the S/N. We used the package VorBin\(^3\), which is a Python implementation of the 2D adaptive spatial binning method of Cappellari & Copin (2003). It uses Voronoi tessellations to bin data to a given minimum S/N.

VorBin requires the user to provide a value of the S/N of each spaxel. This average is greatly affected by low values and less affected by high values, which ensures that every emission line has a high enough S/N to calculate the metallicity. If we only input the S/N of one emission line (e.g., [O III]λ5007), the S/N of the other emission lines may not meet our requirements. Here, we defined a custom S/N, the harmonic mean of the S/N of the four emission lines (Hα, Hβ, [O III]λ5007, and [N II]λ6583), and used it as the input of VorBin.

We stacked the spectra of all spaxels belonging to each bin and then averaged the stacked spectrum. We used the same steps as in Sect. 2.3.1 to refit the averaged spectrum in each bin. We discarded the bins whose custom S/N was still lower than 3 after stacking. Finally, we obtained 699 Voronoi bins in our ten sample galaxies. Table 3 lists the final number of Voronoi bins for each galaxy, and Fig. 3 shows the Hα emission map before and after VorBin. We corrected the fluxes of emission

Fig. 2. Stellar mass, SFR, and $R_e$ of our galaxies (in red) and all low-redshift MUSE-Wide emission line galaxies (in gray). All values are matched from the 3D-HST GOODS-S photometric catalogs. The dashed black line represents the highest redshift at which the Hα and [N II] emission line can be observed ($z < 0.42$). This is limited by the wavelength range of MUSE.

2.3.2. Spaxel binning

We used the S/N of the emission line of the integrated spectrum of the entire galaxy to select the target galaxy. However, this cannot guarantee that the S/N of the emission line of each spaxel can meet the requirements for the accurate calculation of metallicity.

\( ^3 \) https://pypi.org/project/vorbin/
line is too weak to be observed. Only a few studies (Yao et al. 2022) have used the low-redshift IFS survey, let alone the high redshift. Therefore, we used the strong-line calibration relation to calculate the abundance. Commonly used calibration relations include R23 (Kobulnicky & Kewley 2004), N2O2 (Kewley & Dopita 2002), N2, and O3N2 (Pettini & Pagel 2004). Here, according to our sample selection conditions, the O3N2 method was adopted. The diagnostic O3N2 index is defined as

\[ \text{O3N2} \equiv \log \left( \frac{[\text{OIII}]\lambda5007}{\text{H}^\beta} \times \frac{\text{H}^\alpha}{[\text{NII}]\lambda6583} \right) \]

and the calibration of O3N2 diagnostic we used, improved by Marino et al. (2013) using CALIFA data, is

\[ 12 + \log(O/H) = 8.505 - 0.221 \times \text{O3N2}, \]

with O3N2 ranging from −1.1 to 1.7. The typical error for the metallicity calibration with the O3N2 diagnostic is 0.08 dex.

### 2.4. Measurements from 3D-HST

Although the IFS of MUSE-Wide can provide spatially resolved continua, their S/Ns are too low to determine their stellar mass well, and the wavelength range is limited. Therefore, we used multiband photometry data from HST.

#### 2.4.1. Image processing of HST

The PSF and the sampling rate of the image provided by the 3D-HST are not the same as those from MUSE. In order to match each pixel of the HST image with MUSE, we used the photutils \(^4\) (Bradley et al. 2021) package to create a convolved kernel from HST to MUSE. The 3D-HST data release provides the PSFs of HST. The PSFs in different fields of MUSE were taken from Table 2 of Urrutia et al. (2019) and were assumed to be Gaussian. Then we used the reproj \(^5\) package to project the HST image to the exact coordinates and sampling rate as MUSE.

For the matched HST images, we stacked the electron flux and error (in units of electrons s\(^{-1}\)) in each bin and used the inverse sensitivity (in units of erg cm\(^{-2}\) Å\(^{-1}\) electron\(^{-1}\)) parameter given by the 3D-HST to convert the electrons s\(^{-1}\) into AB magnitudes to facilitate subsequent processing.

#### 2.4.2. Mass surface density

We derived stellar mass surface densities (\(\Sigma_\ast\)) by measuring the photometry in multiple HST bands (F435W, F606W, F775W, F850LP, F125W, F140W, and F160W) for each bin corresponding to MUSE. We used the FAST (Kriek et al. 2009) SED-fitting code, with the Bruzual & Charlot (2003) stellar synthesis models, an exponentially decaying star-forming history, and the Calzetti et al. (2000) dust attenuation law. We converted the output masses into mass surface densities by

\[ \Sigma_\ast = \text{M}_\ast / A. \]

### 3. Result and discussion

This section mainly lists the results of the rMZR of our sample, and we also give the results of the rSFMS and metallicity gradients and compare them with other works. The IMF and metallicity calibrator is consistent.

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\(^4\) https://github.com/astropy/photutils

\(^5\) https://github.com/astropy/reproject
3.1. \( \Sigma - \Sigma_{\text{SFR}} \) relation (rSFMS)

The results of the rSFMS are shown in Fig. 4. The average uncertainties of \( \log \Sigma \) and \( \log \Sigma_{\text{SFR}} \) are 0.32 and 0.19 dex, respectively. They are displayed as error bars in the lower right corner of Fig. 4. Our SFR is located between that of the local universe \((z < 0.15; \text{Hsieh et al. 2017})\) and that of the universe with higher redshift \((0.7 < z < 1.5; \text{Wuyts et al. 2013})\), which is in line with the expectation that the SFR will increase with the increase in redshift. We performed an ordinary least-squares linear fitting on our sample, and the result is

\[
\log \Sigma_{\text{SFR}} = (0.571 \pm 0.026) \log \Sigma - (6.190 \pm 0.203),
\]

whose slope is much shallower than those of \text{Wuyts et al. 2013} (0.95), \text{Cano-Díaz et al. 2016} (0.72) and \text{Hsieh et al. 2017} (0.715), whether it is compared with that at high or at low redshift.

We also compared the results with \text{Jafarizayani et al. 2019}, who used \( \text{H} \alpha \) and SED-fitting to derive the SFR based on the same MUSE-Wide data. The fitted slopes are 0.43 and 0.78, respectively. We note that the slope they obtained with \( \text{H} \alpha \) is shallower than ours and that of their SED-fitting. They suggested that the slope of \( \text{H} \alpha \) is shallower than that of the SED-fitting because of the inside-out quenching of star formation. However, because in our sample the rSFMS shape flattens at the low-mass end, the S/N selection might lead to a shallow slope of our \( \text{H} \alpha \)-based rSFMS. We estimated the completeness of the low-mass end \((\log \Sigma < 7.0)\) of our sample and find that it is lower than 50%. Therefore, we refit the bins with \( \log \Sigma > 7.0 \), and the result is

\[
\log \Sigma_{\text{SFR}} = (0.771 \pm 0.032) \log \Sigma - (7.812 \pm 0.249),
\]

whose slope is between that of the local universe and that of the higher-redshift universe. The slope is consistent with the simulation of \text{Trayford & Schaye 2019}, who reported that the slope of the rSFMS grows with increasing redshift.

3.2. \( \Sigma - Z \) relation (rMZR)

Figure 5 shows the results of rMZR. The average uncertainty of metallicity derived from the noise is \( \sim 0.11 \) dex, displayed as the vertical error bar in the lower right corner. We performed an orthogonal distance regression (ODR) fitting to minimize the sum of the squares of both the \( x \) residual and the \( y \) residual to our sample, and the fitting function is from \text{Moustakas et al. 2011},

\[
12 + \log (\text{O}/\text{H}) = a + b(\log \Sigma - c)e^{-(x-c)},
\]

whose coefficients corresponding to the ODR fit of the above function to our Voronoi bins are \( a = 8.47 \pm 0.02, b = 0.0002 \pm 0.0011, \) and \( c = 12.36 \pm 5.08 \). The residual variance is 0.006.

Here we mainly compare our result with the local star-forming galaxies selected from MaNGA DR14 \text{(Gao et al. 2018b)}. Taking into account the systematic errors between different strong-line metallicity calibrators, we used the O3N2 calibrator \text{(Marino et al. 2013)}, which is also adopted in
Gao et al. (2018b). Figure 5 shows that our high-redshift sample shows an rMZR similar to that of the local galaxies, but our metallicities are below those of the local galaxies overall. The average downward shift is -0.11 dex. In addition, considering that $M_*$ also has a certain influence on the rMZR (Barrera-Ballesteros et al. 2016; Gao et al. 2018b), in order to rule out whether our low metallicity is caused by low $M_*$ (our average log $M_*$ is $\approx 9.7$), we used the dashed blue curve in Fig. 5 to indicate the $M_* - \Sigma_* - Z$ relation fitted by Gao et al. (2018b) at the same average $M_*$. When we consider their $M_*$, the average downward shift is $\sim 0.09$ dex. Therefore, we can conclude that the low local metallicity of our sample is not caused by their low $M_*$, but that the local metallicity evolves with redshift. This result is consistent with the scenario that the length of the history of star formation determines the local metallicity. When they reach the same $\Sigma_*$, galaxies with higher redshifts have a shorter history of star formation, a lower metal production, and a higher SFR and more intense gas outflow than lower redshifts galaxies.

In addition, we also compared the relation between the residuals of our fitting and other properties. Barrera-Ballesteros et al. (2016) pointed out that the residuals in the best-fitting rMZR correlated with specific star formation rate ($sSFR = \Sigma_{SFR}/\Sigma_*$) and $M_*$. However, Gao et al. (2018b) directly reported the relation between $M_*$, $\Sigma_*$, and $Z$. In order to verify whether these relations still exist at higher redshift, we show the relation between the residual of metallicity ($\Delta [12+\log(O/H)] = Z_{\text{obs}} - Z_{\text{fit}}$) and $sSFR$ and $M_*$ in Fig. 6.

Fig. 6. Relation between $\Delta [12+\log(O/H)]$ and $sSFR$ and $M_*$. Each red dot represents the median value of a galaxy, whose error bar indicates the 32% and 68% quantiles of the distribution of all Voronoi bins of the galaxy. The gray dots in the lower panel represent Voronoi bins, and the error bar in the upper right corner indicates the uncertainty on each axis. The horizontal dashed gray line represents the average value of the uncertainty of our measured metallicity. The upper left corner is the Pearson correlation coefficient.

Gao et al. (2018b). Each red dot represents our Voronoi bins, and the error bar in the lower right corner represents the average value of the uncertainty on each axis. The thick red line represents the linear fit of all Voronoi bins, and the thick black line represents the average value of the uncertainty on each axis. The horizontal dashed gray line represents the average value of the uncertainty of our measured metallicity. The upper left corner is the Pearson correlation coefficient.
3.3. Metallicity gradient

We also measured the profiles in the metallicity of these galaxies to obtain their gradients. The results of our five galaxies are galaxies whose $R_e < \text{FWHM}$, and dashed lines are galaxies whose $R_e \geq \text{FWHM}$.

3.4. Is the rMZR at $z \sim 0.26$ an extension of rFMR under high SFR?

Some studies have postulated that the FMR will not evolve with redshift during the last half of cosmic history (e.g., Mannucci et al. 2010; Cresci et al. 2012; Huang et al. 2019). The SFR of a galaxy will increase as the redshift increases. At the same time, some other studies questioned the existence of the (r)FMR or suggested that the SFR should be substituted by another parameter (e.g., Sánchez et al. 2013; Bothwell et al. 2016; Barrera-Ballesteros et al. 2018). Compared with the local ones, our results have higher $\Sigma_{\text{SFR}}$ and lower metallicity. In order to verify whether the rFMR exists in our sample and whether our result is an extension of the rFMR under high $\Sigma_{\text{SFR}}$, we compared our sample with that Gao et al. (2018b), shown in Fig. 8. The SFR coefficient ($\alpha$) of FMR we adopted is 0.32 (Mannucci et al. 2010). The $\Delta_{\text{local}}$ means the difference between the observed value and the value predicted by the fitted local sample relation in Gao et al. (2018b) (observed value minus predicted value).

The top panel of Fig. 8 shows that our Voronoi bins at $z \sim 0.26$ are all located in the bottom right corner of the local sample, and there is no apparent correlation between the residuals of $\Sigma_{\text{SFR}}$ and the metallicity residuals. The Pearson correlation coefficient is $\rho = -0.28$ with $p = 6 \times 10^{-14}$, and the Spearman correlation coefficient is $r = -0.25$ with $p = 3 \times 10^{-11}$. These coefficients indicate a weak correlation. As a result, we cannot conclude that our sample has a significant rFMR, which is consistent with the research results for the local universe. The deficiency of metal and the intensity of the star formation in our galaxies could be a measurable effect of galaxy evolution.

The bottom panel of Fig. 8 directly shows the rFMR of our Voronoi bins at $z \sim 0.26$ and the local sample. We find that when $\alpha = 0.32$, the rFMR of our sample does not entirely coincide with the local rFMR. The $\alpha$ derived from different metallicity calculation methods may be different (e.g., Andrews & Martini 2013, ...
\[ \alpha = 0.66 \]. We tried to determine \( \alpha \) by minimizing the dispersion of the fit of rFMR, and we found that when \( \alpha = 0.51 \), the dispersion of the rFMR reaches a minimum value of \(-0.061 \text{dex}\), but it is only \(-0.007 \text{dex}\) lower than when \( \alpha = 0 \) (i.e., there is no rFMR at all). This improvement is much smaller than that of Mannucci et al. (2010). However, even if \( \alpha \) increases to 0.51, our sample still does not coincide with the local sample of Gao et al. (2018b) in the rFMR diagram. This result means that our sample is not an extension of the rMZR under high \( \Sigma_{\text{SF}} \) if rFMR exists and \( \alpha \) is not much different from the global ones. Therefore, the existence of rFMR and its evolution with redshift need to be studied further.

4. Summary

We used the Legacy Surveys to select sources in the fields of MUSE-Wide DR1 and selected ten emission line galaxies dominated by star formation with an average redshift of \( z \sim 0.26 \). We measured their \( \Sigma_* \) with the 3D-HST images and derived their spatially resolved metallicity and \( \Sigma_{\text{SF}} \) with the MUSE-Wide IFS data. We summarize the main conclusions below.

1. The rMZR exists at \( z \sim 0.26 \) and the shape is similar to that of the local universe, but the average metallicity is 0.11 dex lower than that of the local universe. Both \( M_* \) and sSFR have weak effects on the residuals of rMZR, and the effects are weaker than the uncertainties in metallicity measurements. After considering the influence of \( M_* \), the decrease in metallicity is still 0.09 dex. This result indicates that the rMZR evolves with redshift.

2. After we removed the low-\( \Sigma_* \) parts that may cause serious selection effects, our slope of the rSFMS at \( z \sim 0.26 \) is \(-0.771 \), which is between the slopes of the local universe and the higher-redshift universe, which is consistent with the trend predicted by simulations.

3. The metallicity gradient is negative but low, within the range of other the gradients in previous work. However, due to the error and PSF, the measurement result of the gradient is not accurate.

4. We have no clear evidence that the rFMR exists at \( z \sim 0.26 \). Moreover, the high \( \Sigma_{\text{SF}} \) and low metallicity we observed are not the extension of the local rFMR under high \( \Sigma_{\text{SF}} \). The evolution of the global properties of galaxies with redshift may be an integration effect of the evolution of the spatially resolved properties of galaxies.

However, the sample we used is small, the redshift range is narrow, and there is a significant measurement error. The questions remain how the rMZR evolves with the redshift and how it reproduces the evolution of the MZR with redshift. We look forward to a broader and deeper IFS survey in multiple bands to answer these questions.

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