Subgalactic Scaling Relations with \( T_c \)-based Metallicities of Low-metallicity Regions in Galaxies: Metal-poor Gas Inflow May Have Important Effects?

Yao Yao\(^1\), Haiyang Liu\(^1\), Xu Kong\(^1\), Yulong Gao\(^2\), Guangwen Chen\(^1\), Xinkai Chen\(^2\), Zhixiong Liang\(^1\), Zesen Lin\(^1\), Yimeng Tang\(^1\), and Hong-Xin Zhang\(^1\)

\(^1\) CAS Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei 230026, People’s Republic of China; \(^2\) School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, People’s Republic of China

Abstract

The scaling relationship is a fundamental probe of the evolution of galaxies. Using the integral field spectroscopic data from the Mapping Nearby Galaxies at Apache Point Observatory survey, we select 1698 spaxels with a significant detection of the auroral emission line \([\text{O III}]{\lambda}\lambda 4363.2031\) from 52 galaxies to investigate the scaling relationships at the low-metallicity end. We find that our sample’s star formation rate is higher and its metallicity is lower in the scaling relationship than the star-forming sequence after removing the contribution of the Fundamental Metallicity Relation. We also find that the stellar ages of our sample are younger (<1 Gyr) and the stellar metallicities are also lower. Morphological parameters from the Deep Learning catalog indicate that our galaxies are more likely to be mergers. These results suggest that their low-metallicity regions may be related to interaction; the inflow of metal-poor gas may dilute the interstellar medium and form new metal-poor stars in these galaxies during interactions.

Unified Astronomy Thesaurus concepts: Scaling relations (2031); Metallicity (1031); Star forming regions (1565)

1. Introduction

The scaling relationship is important for understanding the formation and evolution of galaxies. One of the well-established relationships is the correlation between star formation rate (SFR) and stellar mass \((M_*)\), which is the so-called star-forming main sequence (SFMS). Another important relationship is the stellar mass–metallicity relation (MZR), which indicates that galaxy metallicities increase with increasing \(M_*\), and reflects the balance between the gravitational potential and galactic feedback. It was established by Lequeux et al. (1979) and has been extended by a series of studies for decades (e.g., Tremonti et al. 2004; Mannucci et al. 2010).

The SFMS and MZR are both established primarily by global galactic parameters. It is also important to understand whether galactic local parameters (e.g., stellar mass surface density \(\Sigma_*\), SFR surface density \(\Sigma_{\text{SFR}}\), and local metallicity) are more fundamental to probe the global SFMS and MZR. Recently, with the emergence of integral field spectroscopy (IFS) surveys, spatially resolved scaling relationships have also been developed. Rosales-Ortega et al. (2012) demonstrated the existence of a local relation between \(\Sigma_*\), metallicity, and \(\Sigma_{\text{SFR}}\) using 38 nearby galaxies from the PPAK IFS Nearby Galaxies Survey (Rosales-Ortega et al. 2010) and the Calar Alto Legacy Integral Field spectroscopy Area (CALIFA; Sánchez et al. 2012) survey. Cano-Díaz et al. (2016) found a spatially resolved SFMS on a ~1 kpc scale with a slope of ~0.7 in the local universe from CALIFA IFS data. More research on the spatially resolved scaling relationship followed (e.g., Barrera-Ballesteros et al. 2016; Gao et al. 2018, hereafter G18; Liu et al. 2018).

Metal-poor galaxies/regions play an essential role in galaxy evolution, especially for the galaxies at the early stage of their evolution, or for those that evolve slowly. Understanding the various properties of galaxies at low metallicity in the MZR can help us uncover some important processes in galaxy evolution. Low metallicities of galaxies/regions suggest that they might have significant metal-poor gas inflows or metal-enriched gas outflows. (Kunth & Östlin 2000). However, the slope and scatter of the low-metallicity end of the local MZR is still not clear. The reason is that current methods of investigating the local MZR are mainly based on the strong emission lines method, which may not be accurate enough for the calibration at low metallicity (López-Sánchez et al. 2011). The electron temperature \((T_e)\) method (Aller 1984; Izotov et al. 2006; Pilyugin et al. 2010), which is also called the direct method, based on the anticorrelation between metallicity and \(T_e\), can obtain the metallicity directly and avoid the systematic error of low metallicity with high ionization parameter. It needs auroral line ratios such as \([\text{O III}]{\lambda}\lambda 4363.2031/\lambda 5007\) to calculate \(T_e\). Auroral lines are two orders of magnitude fainter than strong lines, which makes the direct method very challenging to apply. But with the sample size of the current IFS surveys rapidly expanding in recent years, we finally have the data set to apply the direct method by searching for resolved \([\text{O III}]{\lambda}\lambda 4363\) emission lines for a large and representative sample of galaxies.

In this work, we select HII regions with a significant \([\text{O III}]{\lambda}\lambda 4363\) emission line detection from Sloan Digital Sky Survey (SDSS) IV Mapping Nearby Galaxies at APO (MaNGA) survey (Bundy et al. 2015) and present their local SFMS and MZR. The paper is organized as follows. Section 2 describes the sample selection and the calculation of physical parameters,
Section 3 presents our main results. Section 4 discusses influences of metallicity calibrations and the potential role of mergers in our sample. Finally, Section 5 gives our conclusions. We adopt a flat cosmology with $\Omega_{\Lambda} = 0.7$, $\Omega_m = 0.3$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$ to determine distance-dependent measurements.

2. Data

2.1. MaNGA DR15 Overview

The MaNGA survey, one of the three core programs in SDSS-IV (Blanton et al. 2017), is an IFS survey targeted at ~10,000 nearby galaxies that are selected from the NASA Sloan Atlas catalog (NSA; Blanton et al. 2011; Bundy et al. 2015). The redshifts of these target galaxies span a range of $0.01 < z < 0.15$. The spectral coverage is 3600–10300 Å with a resolution of $R \approx 2000$ (Drory et al. 2015). The FWHM of the reconstructed point-spread function is about 2.5 (Law et al. 2016). Recently, SDSS DR15 publicly released IFS observations and ancillary data products of 4621 galaxies (Aguado et al. 2019). Comparing with DR14, there are many improvements in DR15, with the Data Reduction Pipeline (DRP; Law et al. 2016), such as the flux calibration and spectral line-spread function estimation. DR15 also provides entirely new Data Analysis Pipeline products (DAP; Westfall et al. 2019), which provides the measurements of Balmer series lines and strong forbidden lines, including [O II] $\lambda$3727, [O III] $\lambda$ 4959,5007, and [N II] $\lambda$6583 (Belfiore et al. 2019), facilitating our data analysis. In this work, we treat these 4621 galaxies from the DRP and DAP as the parent sample.

2.2. Rough Sample Selection

In order to identify regions with strong [O III] $\lambda$4363 from all MaNGA data cubes more efficiently, we first select spaxels according to the following criteria:

1. $b/a > 0.3$.
2. no “bad” flag in “DRP3QUAL.”
3. signal-to-noise ratio $S/N(H_\alpha) > 3$, $3 > S/N(H_\beta) > 3$, $S/N ([O III] $\lambda$3727) > 3$, $S/N([O III] $\lambda$4959,5007) > 3$, $S/N ([N II] $\lambda$6583) > 3$, and $S/N([O III] $\lambda$4363) > 5$.
4. not active galactic nucleus (AGN).

The values of $b/a$ are from the NSA catalog, representing the projected ratio of the semiminor axis to the semimajor axis of galaxies. This limitation is to avoid the severe dust attenuation in galactic disks. The fluxes and noise levels of all emission lines except [O III] $\lambda$4363 are derived based on the DAP hybrid bin, while the fluxes and noise levels of [O III] $\lambda$4363 are fitted to a single Gaussian profile by ourselves following Ly et al. (2014). All data of emission lines have been processed by Galactic extinction correction, moving to rest frame, and intrinsic dust extinction correction, in turn. We use the color excess $E(B - V)$ map of the Milky Way (Schlegel et al. 1998) and the Cardelli et al. (1989) extinction law to correct for Galactic extinction and use the Balmer decrements under the Case B recombination and apply the Calzetti et al. (2000) attenuation law to correct for intrinsic dust extinction. For spaxels with $H_\alpha / H_\beta < 2.86$ (Hummer & Storey 1987), we assume the extinction to be zero. The [N II]-based BPT diagnostic diagram (Baldwin et al. 1981) is adopted to avoid possible AGN contamination, and only spaxels below the Kauffmann et al. (2003a) demarcation curve are selected. Thus, we obtain a rough selected sample with 3565 spaxels.

2.3. Spectral Fitting and Further Sample Selection

In Section 2.2, to search for spaxels with an obvious [O III] $\lambda$4363 emission line quickly, we fit the spectra with a single Gaussian profile without subtracting the stellar continuum. So the selection is rough and needs to be refined. In this Section, we re-fit the stellar continuum and emission lines for our rough selected sample.

Following the procedure of Gao et al. (2017), we use the STARLIGHT software (Cid Fernandes et al. 2005) to obtain the best-fit stellar continua, which are then subtracted from the observed spectra. The fitting is based on the built-in stellar library (Bruzual & Charlot 2003) of STARLIGHT and a Chabrier (2003) initial mass function (IMF). The stellar library includes 45 single stellar populations, consisting of 15 stellar ages ($t_\ast$, ranging from 1 Myr to 13 Gyr) and 3 different stellar metallicities ($Z_\star = 0.004, 0.02, \text{ and } 0.05$). Several stellar properties, such as $M_\ast$, $Z_\star$, and $t_\ast$, can be derived from the output of STARLIGHT. In order to ensure the consistency of flux measurements, we use MPFIT (Markwardt 2009) to refit emissions lines that we are interested in (e.g., [O II] $\lambda$3727, [O III] $\lambda$4363, $\lambda$5007, [O III] $\lambda$4959,5007, H$\alpha$, [N II] $\lambda$6548,6583, and [S II] $\lambda$6717,6731). After obtaining the fluxes of emission lines, we apply the Balmer decrement (Hummer & Storey 1987) and the Calzetti et al. (2000) attenuation curve to them again. Finally, we get the final emission fluxes of this work, rather than the DAP data and the rough flux measurements in Section 2.2. In order to verify the accuracy of our fitting, we compared our fitting results with the DAP results. Details of the comparison are in Appendix A.

Because [O III] $\lambda$4363 emission might be contaminated by cosmic rays or other noise, further selection is needed to remove fake detections. First of all, we remove galaxies whose spaxel numbers in the rough selected sample are less than 5. Then, we calculate the $S/N$ ratio at $\lambda = 4020$ Å and remove the spaxels with $S/N < 5$ to ensure that the uncertainty of stellar mass is less than 0.11 dex (Cid Fernandes et al. 2005). Spaxels whose fluxes of [O III] $\lambda$4363 are too excessive to calculate a valid metallicity are also removed, which may be caused by noise. Next, we manually check the continuum fitting status and emission line fitting status of each spectrum. We remove those spectra whose [O III] $\lambda$4363 lines do not have well-defined profiles or for which the velocities have significant deviations from those of other emission lines. After manual inspection, our final sample consists of 1698 spaxels from 52 different galaxies.

In addition, we also select all star-forming regions in these 52 galaxies. The requirements of $S/N$ are the same as those for the [O III] $\lambda$4363 regions without the [O III] $\lambda$4363 emission line to calculate their metallicities by applying the strong line method.

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5 http://www.nsatlas.org
6 https://www.sdss.org/dr15/manga/manga-analysis-pipeline/

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7 Available at http://www.starlight.ufsc.br/downloads/.
2.4. SFR Surface Density and Metallicity Calculation

2.4.1. SFR Surface Density

We use the Hα luminosity to determine the dust-corrected SFR for each spaxel, assuming a Chabrier (2003) IMF. The SFR calibration from Kennicutt (1998) is:

\[
\text{SFR}(M_\odot \text{yr}^{-1}) = 4.4 \times 10^{-42} L_{\text{H}_\alpha} \text{(erg s}^{-1}) \nonumber .
\]

The size of each spaxel of MaNGA is 0.56 × 0.672, so the projection corrected area is given by

\[
A = \left[ D(z) \times 0.5 \times \frac{\pi}{3600 \times 180} \right]^2 \times \frac{1}{b/a},
\]

where \(D(z)\) is the angular diameter distance of the galaxy. As a result, the \(\Sigma_{\text{SFR}}\) and \(\Sigma_{\text{met}}\) of each spaxel are

\[
\Sigma_{\text{SFR}} = \frac{\text{SFR}}{A}, \quad \Sigma_{\text{met}} = \frac{M_\text{met}}{A}.
\]

2.4.2. Te, O and Oxygen Abundance

Here, we adopt the formulation from Pilyugin et al. (2010) to calculate the \(T_e\), \(O^{+}/\text{H}^+\) abundance and \(O^+/\text{O}^+\) abundance of each spaxel. For our metallicity estimation, we adopt a standard two-zone temperature model with \(t_2 = 0.672, t_3 = 0.314\) (Pilyugin et al. 2009). Because the most important ions of oxygen in H II regions are \(O^+\) and \(O^{+}\), we take the sum of the abundances of these two ions as the abundance of oxygen.

To all star-forming galaxies without the requirement of S/N ([O III]λ4363) ≥ 3, which are described at the end of Section 2.3, we apply the formula to our MaNGA catalog. For the rest of the galaxies, we use the \(T_e\) metallicities of 313 H II regions, ranging from \(12 + \log(O/\text{H}) \sim 7.0\) to \(\sim 8.7\), with a mean difference of 0.049 dex.

2.5. Uncertainty Estimate

Our uncertainty consists of two parts, part one is converted from the error spectrum provided by the MaNGA DATA_CUBE (\(\sigma_{\text{errspec}}\)) and part two comes from two independent observations of the same galaxy (8256-9102 and 8274-9102) in our sample (\(\sigma_{\text{independobs}}\)). Our final uncertainty \(\sigma\) is determined by rooting the sum of the squares of the above two parts:

\[
\sigma = \sqrt{\sigma_{\text{errspec}}^2 + \sigma_{\text{independobs}}^2}. \nonumber
\]

For uncertainties of \(\Sigma_{\text{SFR}}\) and \(12+\log(O/\text{H})\) from the error spectrum (\(\sigma_{\text{errspec}}\)), we adopt a Monte Carlo method and repeat the calculation 1000 times. For every spectrum, we produce a series of fluxes for each emission line with a Gaussian distribution, assuming its average to be the measured line flux and the standard deviation to be the measured error. The median of metallicity uncertainty is 0.07 dex, and the median of \(\Sigma_{\text{SFR}}\) uncertainty is 0.008 dex. For uncertainties of \(\Sigma_{\text{met}}\) from the error spectrum, we directly adopt 0.11 dex (Cid Fernandes et al. 2005), because the S/N ratios of our continua are all greater than 5.

For uncertainties from two independent observations, we can get a distribution by taking the difference between the quantities at the same coordinates. We use the standard deviation of this distribution as the uncertainty. The standard deviations (\(\sigma_{\text{independobs}}\)) of \(\Sigma_{\text{SFR}}\), \(\Sigma_{\text{met}}\), and metallicity are 0.10 dex, 0.17 dex, and 0.10 dex, respectively. The final uncertainty (\(\sigma\)) of \(\Sigma_{\text{SFR}}\), \(\Sigma_{\text{met}}\), and metallicity are 0.10 dex, 0.20 dex, and 0.12 dex, respectively.

3. Result

Comparing to previous studies (e.g., Barrera-Ballesteros et al. 2016; Gao et al. 2018), this work uses the newest DR15 data as the initial sample and focuses on the [O III]λ4363 selected star-forming regions. Because of the weakness of [O III]λ4363 emission lines, our sample is much smaller than a normal star-forming sample, and its overall properties are also very different from those of normal a star-forming sample. The SDSS images and metallicity profiles of four galaxies with the most spaxels in our 52 [O III]λ4363 selected objects are shown in Figure 1. Other galaxies are shown in Appendix B. We perform a linear fit to the profile of the metallicity of each galaxy along the radius.

3.1. Global SFMS and Morphology

We first investigate the global properties of these galaxies. Figure 2 shows the mass distribution and the \(M_* - \text{SFR}\) relation (global SFMS) comparing with all MaNGA galaxies and SFGs in G18, which contains 1122 galaxies and \(8 \times 10^5\) spaxels. SFRS are retrieved from the MPA–JHU catalog (Kauffmann et al. 2003b).^8 Galaxies whose SFR are not available in the MPA–JHU catalog are not shown in the figure. We can see that our [O III]λ4363 selected galaxies are located in the upper star-forming region, and their total \(M_*\) values are lower than for the rest of the normal SFGs. The median mass (\(\log(M_*/M_\odot)\)) of our [O III]λ4363 selected galaxies is 9.25 and the median mass (\(\log(M_*/M_\odot)\)) of SFGs in G18 is 9.68. However, we have noticed that some of our sample are located too low on the \(M_* - \text{SFR}\) diagram, indicating that these galaxies may not be star-forming. We have checked these galaxies and find that there are indeed local star-forming regions in these low-SFR galaxies. This indicates that a galaxy with a lower global SFR may also have more intense star formation locally.

Subsequently, we match the MaNGA Deep Learning DR15 Morphology catalog (DL; Domínguez Sánchez et al. 2018) to extract their morphological parameters, the \(T\)-Type value and the probability of merger, which have been widely used in previous works (e.g., Meert et al. 2014; Fischer et al. 2018; Chen et al. 2020). This catalog is trained by Deep Learning algorithms using Convolutional Neural Networks based on the catalog of Nair & Abraham (2010) and color images. Due to the particularity of our sample in \(M_*\) and SFR, which may cause a systematic offset in morphological parameters, we select galaxies with the same \(M_*\) and SFR distributions as our sample from the MaNGA survey to construct a control sample. The distributions of morphology are shown in Figure 3. Here, we regard galaxies with a merger probability greater than 0.7 as mergers. We found that 18 galaxies in our 52 galaxies are merging, accounting for 34.6%, which is higher than the 14.8% of all MaNGA galaxies and 13.0% of the control sample. We also perform a Kolmogorov–Smirnov test between our sample and the control sample and get a \(p\)-value of \(T\)-Type ~ \(10^{-8}\), and a \(p\)-value of \(P\) (merge) ~ \(10^{-10}\). Table 1 show the information of the 30 galaxies with the most spaxels in our final sample, which occupy the main part (~84%) of all our spaxels. We check their SDSS images and find that they are all blue in color and

^8 https://www.sdss.org/dr12/spectro/galaxy_mpajhu/
irregular in morphology (e.g., see Figure 1), and some of them seem to be in interaction. These observational features are consistent with the morphological parameters from the DL catalog. More details will be discussed in Section 4.3. Therefore, we can conclude that the galaxies we selected not only have a lower \( M_* \) and a higher SFR, but also they are later types and have a higher merger ratio in morphology, and this is not because of their low \( M_* \) and high SFR.

We also check the locations of our selected spaxels in these sample galaxies. We find that most spaxels are located within a single star-forming region. These regions in most galaxies (42 galaxies) are located at the periphery of the galaxy. Regions of eight galaxies are in the center of the galaxy. Two are distributed across the entire galaxy, and the remaining two cannot be distinguished because their host galaxies have a lower projected axis ratio.

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**Figure 1.** Left panel: the SDSS images of five galaxies with the most spaxels in our sample 52 \([\text{O} \text{ III}] \lambda 4363\) selected objects. The field of view of each image is 50". Right panel: the radial profiles of the metallicity of the corresponding galaxy. Gray dots are all star-forming spaxels without the requirement of S/N\([\text{O} \text{ III}] \lambda 4363\) \(\geq 3\), which are described at the end of Section 2.3. Gray lines are the linear fit to the gray dots. Green dots and blue dots represent the PG16 and \( T_e \)-calibrated metallicity of our \([\text{O} \text{ III}] \lambda 4363\) selected spaxels, respectively. The vertical dashed line represents the effective radius of the galaxy. Both of the two independent observations of the same galaxy (8274-9102 and 8256-9102) are shown in the second and third row of the figure, respectively.
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Figure 2. Top panel: the histograms of the normalized $M_\odot$ distribution. The blue filled histograms represent our 52 [O III]$\lambda$4363 emission galaxies, the gray filled histograms represent the star-forming sample in G18, and the gray hollow histograms represent all MaNGA galaxies in the DRP catalog. The vertical dashed lines of different colors indicate the median of the corresponding mass distribution. Bottom panel: $M_\star$–SFR relation (SFMS) of MaNGA galaxies. Blue dots represent our 49 galaxies (5 of 52 galaxies cannot be matched in the MPA–JHU catalog), whose error bars represent the $1\sigma$ error ($16\% \sim 84\%$). Gray dots are all of the galaxies in MaNGA DR15. The main-sequence relation for SFGs in the local universe (Salim et al. 2007) is shown as the black dashed line.

Here, we compare the location distribution of our [O III] $\lambda$4363 selected spaxels in our 52 galaxies and the star-forming spaxels in the same galaxy (Figure 4). The distances to the center are in units of effective radius ($R_e$) and have already been corrected by $b/a$. It is found that there is no obvious deviation between the location distribution of our regions and the overall star-forming regions.

3.2. Local Properties and Scaling Relations

Since MaNGA has spatially resolved IFU spectra, the main focus of this work is on the local properties of these galaxies, such as $\Sigma_\star$, $\Sigma_{\text{SFR}}$, local metallicity, and their scaling relationship. The $\Sigma_\star$–$\Sigma_{\text{SFR}}$ relationship is plotted in Figure 5, and $\Sigma_\star$–$Z$ is plotted in Figure 6. The edges of the diagram show the normalized distributions of the corresponding parameters. The scatter panel shows the local SFMS: the $\Sigma_\star$–$\Sigma_{\text{SFR}}$ Relation for our [O III]$\lambda$4363 selected spaxels. We perform a linear fit to our spaxels and find that

$$\log \Sigma_{\text{SFR}} = (0.67 \pm 0.01) \log \Sigma_\star - (6.35 \pm 0.09).$$  

(6)

The correlation coefficient is 0.80, and the residual standard deviation is 0.24. The uncertainties of the slope and intercept are obtained by a 1000 times bootstrap method, and the following fittings are also the same. The units of $\Sigma_\star$ and $\Sigma_{\text{SFR}}$ are $M_\odot$ kpc$^{-2}$ and $M_\odot$ yr$^{-1}$ kpc$^{-2}$, respectively. A similar fit is done for the star-forming spaxels in G18 and results in

$$\log \Sigma_{\text{SFR}} = (0.61 \pm 0.00) \log \Sigma_\star - (6.71 \pm 0.03).$$  

(7)

The correlation coefficient is 0.61, and the residual standard deviation is 0.39. We can see that our sample have a higher $\Sigma_{\text{SFR}}$ than G18’s sample at a given $\Sigma_\star$. There is also a significant gap in the median of $\log \Sigma_{\text{SFR}}$. Ours is $-1.49$ while G18’s is $-2.24$. Only 10 spaxels (0.56%) of our sample are within the $1\sigma$ (68%) dispersion of the local SFMS of G18. These results indicate that the SFR of our sample is higher than that of the star formation sequence.

Figure 6 shows the local MZR ($\Sigma_\star$–$Z$ relation) of our sample and the normal star-forming sample based on the O3N2 method in G18. We note that the O3N2 calibration adopted by G18 is the ONS-based one from Marino et al. (2013, hereafter M13). This may cause a systematic deviation from the $T_e$ method. We thus transform all metallicities in G18 into the $T_e$-based calibration by the following equation:

$$12 + \log(O/H)_{\text{O3N2, T_e}} = 8.533 - 8.505 - 12 + \log(O/H)_{\text{ONS, T_e}} \times 0.214. \quad (8)$$

For our sample, it is also found that the metallicity increases with increasing $\Sigma_\star$, but the dispersion is large. We find that 229 spaxels (13.5%) of our sample are within the $1\sigma$ dispersion of the local MZR of G18. We simply perform a linear fit to our spaxels and find that

$$12 + \log(O/H) = (0.12 \pm 0.01) \log \Sigma_\star + (7.34 \pm 0.05), \quad (9)$$

with a correlation coefficient of 0.41, and a residual standard deviation of 0.13.

We plot the best-fit $\Sigma_\star$–$Z$ relation of G18’s radial bin sample. Taking into account the weak influence of the total $M_\star$ on the local metallicity (Barrera-Ballesteros et al. 2016; Gao et al. 2018) and the smaller $M_\star$ of our galaxies (see Section 3.1), the best-fit $M_\star$–$\Sigma_\star$–$Z$ relation at $M_\star = 10^9 M_\odot$ is also given to eliminate the influence of the total stellar mass of galaxies.

In Figure 6, we can see that the $\Sigma_\star$–$Z$ relation of our [O III] $\lambda$4363 selected spaxels is still systematically lower than that of the normal star-forming spaxels in MaNGA when considering the total $M_\star$. These spaxels with high $\Sigma_\star$ have anomalously low metallicities (ALM), which are similar to the ALM regions mentioned in Hwang et al. (2019). More details will be discussed in Section 4.3.

We next investigate and compare the local ionized gas properties and stellar properties through emission lines and the continuum of spaxels. The upper two panels of Figure 7 show distributions of two emission line ratios $O_{3}\alpha = \log([O\ III]\lambda4959+[S\ II]\lambda6507)/[O\ II]\lambda3727$ and $N2 = \log([N\ II]\lambda6583/H\alpha)$, while the lower ones are the distributions of the luminosity-weighted $t_\alpha$ and $Z_\alpha$ obtained by STARLIGHT fitting. Among them, $O_{3}\alpha$ can roughly characterize ionization parameters (Kewley et al. 2019), and N2 can roughly characterize their metallicities (Pettini & Pagel 2004). The unit of $t_\alpha$ is yrs and stellar metallicity is $Z_\alpha = Z/H$. When the $S/N$ of the continuum is 5, the uncertainties of $\log(t_\alpha)$ and $\log(Z_\alpha)$ are 0.14 dex and 0.15 dex, respectively (Cid Fernandes et al. 2005), which are displayed by error bars.

Since the SFR of our sample is relatively high overall, and we have noticed the possible local Fundamental Metallicity Relation (FMR; Mannucci et al. 2010), which indicates that
Figure 3. The normalized morphology properties distribution. Morphology data are from the MaNGA Deep Learning DR15 Morphology catalog (DL; Domínguez Sánchez et al. 2018). Blue filled histograms are the final [O III]λ4363 sample in this work. Black hollow histograms are the distribution of all galaxies in the DL catalog. Green filled histograms are the control sample of galaxies whose $M_e$ and SFR distributions are similar to the distribution of our final sample. Each vertical axis is the percentage of the total sample occupied by each bin. The p-values of the Kolmogorov–Smirnov test between our final sample and controlled sample is also shown in each panel.

| Table 1 | Basic Information for 30 Galaxies with the Most Spaxels in Our Sample |
|---------|---------------------------------------------------------------------|
| Galaxy ID | Count | R.A. (deg) | Decl. (deg) | Redshift | $M_e$ (log($M_*/M_\odot$)) | $M_e$ (log($M_*/M_\odot$)) | SFR (log($M_\odot$ yr$^{-1}$)) | T-Type | P(merge) |
| [plate]-[ifu] | (1) | (2) | (3) | (4) | (5) | (6) | (7) | (8) | (9) | (10) |
| 8566-3704 | 173 | 115.22481 | 40.06964 | 0.04160 | 9.45 | – | – | 4.30 | 0.99 |
| 8274-9102 | 124 | 165.10414 | 43.01969 | 0.03745 | 9.58 | 9.02 | 0.52 | 7.00 | 0.34 |
| 8313-1901 | 84 | 240.28713 | 41.88075 | 0.02425 | 8.88 | 9.28 | –0.04 | 1.90 | 0.18 |
| 8615-1901 | 79 | 321.07220 | 1.02836 | 0.01974 | 8.77 | 8.95 | –0.06 | 4.55 | 0.38 |
| 9000-6102 | 68 | 170.88396 | 53.46820 | 0.02719 | 9.45 | 9.41 | –0.05 | 5.27 | 0.73 |
| 7495-6102 | 62 | 204.51286 | 26.33821 | 0.02615 | 8.74 | 8.96 | 0.12 | 5.80 | 0.06 |
| 8942-3703 | 60 | 124.38507 | 28.35783 | 0.01986 | 8.67 | 8.85 | –0.21 | 4.43 | 0.04 |
| 8551-1902 | 54 | 234.59171 | 45.80194 | 0.02135 | 8.43 | 8.90 | –0.13 | 1.74 | 0.04 |
| 8465-6102 | 48 | 197.54970 | 48.62339 | 0.02828 | 9.29 | 8.93 | 0.40 | 3.08 | 0.96 |
| 8458-9102 | 48 | 244.91463 | 47.87321 | 0.02094 | 8.70 | 8.87 | –0.22 | 5.99 | 0.79 |
| 8455-9101 | 47 | 157.18363 | 39.77859 | 0.03004 | 9.66 | 9.53 | 0.13 | 5.46 | 0.79 |
| 8322-9101 | 44 | 199.60756 | 31.46795 | 0.01869 | 9.54 | – | – | 5.31 | 0.89 |
| 8548-3702 | 43 | 243.32681 | 48.39181 | 0.01990 | 8.74 | 8.87 | –0.44 | 4.47 | 0.45 |
| 8257-3704 | 43 | 165.55361 | 45.30387 | 0.02022 | 8.69 | 9.00 | –0.65 | 10.00 | 0.04 |
| 8719-12702 | 41 | 120.19928 | 46.69053 | 0.01938 | 9.49 | 9.65 | –0.04 | 5.57 | 0.43 |
| 8727-3702 | 41 | 54.55405 | 55.54040 | 0.02215 | 8.48 | 8.76 | –0.16 | 11.16 | 0.04 |
| 8239-12704 | 40 | 117.45125 | 48.12956 | 0.01808 | 9.42 | 9.29 | –0.39 | 6.09 | 0.31 |
| 8241-6101 | 40 | 127.04853 | 17.37466 | 0.02087 | 8.63 | 8.62 | –0.38 | 5.98 | 1.00 |
| 8996-12703 | 37 | 171.97836 | 53.00109 | 0.02134 | 8.84 | 8.13 | –0.29 | 6.59 | 0.78 |
| 8715-12704 | 37 | 121.71245 | 50.71853 | 0.02262 | 8.77 | 8.96 | –0.12 | 6.16 | 0.11 |
| 8987-6103 | 33 | 137.26802 | 28.25683 | 0.02166 | 8.67 | 8.64 | –1.93 | 5.12 | 0.30 |
| 8936-6104 | 32 | 117.92943 | 30.44875 | 0.01424 | 8.65 | 6.99 | –1.90 | 4.64 | 0.09 |
| 8987-12707 | 28 | 137.44943 | 27.86231 | 0.02044 | 8.94 | 8.94 | –0.69 | 4.90 | 0.02 |
| 8552-6101 | 28 | 227.01000 | 42.81902 | 0.01801 | 8.66 | 8.64 | –0.88 | 5.74 | 0.82 |
| 9509-3702 | 27 | 122.43975 | 25.88031 | 0.02511 | 9.27 | 9.70 | 0.45 | 4.65 | 1.00 |
| 8147-9102 | 27 | 118.85282 | 26.98635 | 0.01524 | 8.85 | 8.83 | –0.98 | 5.28 | 0.38 |
| 8553-12703 | 25 | 235.95318 | 57.23323 | 0.01355 | 8.61 | 6.20 | –2.10 | 5.65 | 0.34 |
| 8325-12702 | 24 | 209.89514 | 47.14768 | 0.04204 | 9.28 | 9.50 | 0.43 | 6.35 | 0.17 |
| 8458-3702 | 23 | 147.56250 | 45.95731 | 0.02487 | 9.44 | 7.34 | –0.29 | 3.94 | 0.68 |
| 8083-12705 | 22 | 50.17898 | –1.10865 | 0.02091 | 10.09 | 10.02 | –0.03 | 5.44 | 0.34 |

Note. From left to right, the columns correspond to (1) galaxy ID, defined as the [plate]-[ifu] design of the MaNGA observations; (2) the counts of [O III]λ4363 spaxels; (3) and (4) the R.A. and decl. of the IFU; (5) the redshift taken from the NSA catalog; (6) the total $M_e$ taken from the NSA Sérsic mass; (7) the total $M_e$ taken from MPA–JHU catalog (two galaxies cannot match the catalog and have an empty value); (8) SFR taken from the MPA–JHU catalog (some of galaxies cannot match the catalog and have an empty value); (9) the T-Type value of morphology derived from the DL catalog (T-Type < 0 for ETGs, T-Type > 0 for LTGs, T-Type ∼0 for So), whose methodology for training and testing the DL algorithm is described in Domínguez Sánchez et al. (2018); (10) the probability of merger signature (or a projected pair) derived from the DL catalog referenced in (9).

* MaNGA has two independent observations (8256-9102 and 8274-9102) of this galaxy; here, we only select the observation (8274-9102) with a smaller uncertainty for the metallicity.
regions with higher SFRs tend to have lower metallicities at fixed $\Sigma_{\ast}$. In order to verify whether our low metallicities are the result of a high $\Sigma_{\text{SFR}}$ through the FMR, here we also need to control the sample as in Section 3.1. Green histograms in Figure 7 show the distributions of the corresponding properties for the subsample randomly selected from G18, containing 2499 spaxels, whose distribution on the $\Sigma_{\ast} - \Sigma_{\text{SFR}}$ plane is the same as that of our final [O III] λ4363 sample. Thus, we can eliminate the potential impact of FMR.

The distribution of data shows that the ionization parameters, gas phase metallicity, $t_e$ and $Z_{\ast}$ of our sample are obviously different from those of the whole spaxel sample and the control sample in G18. There is only a small difference between the control sample and whole spaxel sample. Therefore, we can conclude that the spaxels we selected not only have a higher $\Sigma_{\text{SFR}}$, but also a higher ionization parameter, a lower gas phase and stellar metallicity, and younger stars, and this is not because of their high $\Sigma_{\text{SFR}}$ under the influence of the FMR.

### 3.3. Nitrogen Abundances

Metals are direct products of stellar nucleosynthesis; elements originating from different nucleosynthetic processes can probe the star formation history and chemical enrichment in galaxies. Here, we calculate the abundance ratios between nitrogen (mostly produced via primary nucleosynthesis in low-metallicity regions, as well as secondary nucleosynthesis of low-mass and intermediate-mass stars from higher-metallicity regions) and oxygen (mostly produced by massive stars on short timescales). The N/O probes the star formation timescale, and the N/O–O/H diagram can also provide a test of the validity of our $T_e$-based abundances. The calculation method used is also from Pilyugin et al. (2010). Since the [N II] λ5755 line is too weak to be detected, we use $t_3$ estimated from $t_3$ instead of $t_{2,N}$ to derive the nitrogen abundance. The $12+\log(O/H)$–log(N/O) relation is shown in Figure 8. The uncertainty of log(N/O) is ~0.06 dex, which is obtained using the same process as in Section 2.5. From Figure 8 we can find that our samples are distributed at the flat low end of the relationship, and compared with the G18 sequence, there is a much higher dispersion and no positive correlation. This is because the nitrogen at the low-metallicity end is mainly produced by primary nucleosynthesis, which produces similar amounts of N and O. As shown by the distribution of randomly resampled gray dots of G18 at low metallicity, the large dispersion of our metallicity measurements is a natural result of the uncertainty.

### 4. Discussion

#### 4.1. Direct Comparison of Strong Line Method

In this work, we directly compare the metallicity of our [O III]λ4363 selected sample with that of G18. Although we have corrected the systematic error of the O3N2-ONS metallicity calculation, the O3N2 strong line method is particularly sensitive to ionization parameters (Pettini & Pagel 2004), and our sample has an excessively high ionization parameter that deviates from the normal one, so it is necessary.
to use the same strong line method to compare their metallicity again.

Here, we use PG16 R-calibrated metallicity, because the applicable metallicity range of the M13 calibration is too narrow to include all our spaxels, while the range of the PG16 calibration is sufficient to include our sample and the G18 sample. The uncertainty of the metallicity is also obtained using the same process as in Section 2.5. The final uncertainty of PG16 metallicity is ∼0.05 dex. For the G18 sample, we recalculate their metallicity using the R calibration of PG16 for consistency.

The new Σₘ*–Σₖ relation is shown in Figure 9. In addition, we also performed an interpolation fitting on the PG16 R-calibrated metallicities of G18 to get a PG16 R-calibrated Σₘ*–Σₖ relation. The interpolation process is the same as in Hwang et al. (2019), so that we can get the expected fitting value of the PG16 metallicity (Z₁₆,PG16) under a given Mₖ and
forming regions in their host galaxies, but also the metallicities of these host galaxies are entirely lower than those of other galaxies with similar $M_*$. Low metallicity is not only a local characteristic, but also a characteristic of the galaxy as a whole. Combined with the above results in Section 3.1, it shows that the appearance of these metal-poor regions is related to the particularity of the entire galaxy. We should note that the selection effects caused by flux limits of auroral emission lines may contribute to these results; we leave this consideration for future work when larger samples become available.

4.3. ALM Region and Merger

In Section 3.2, Figures 6 and 9, we have found that our [O III]λ4363 selected metal-poor sample galaxies are not located at the low-metallicity end of the $\Sigma_{\text{gas}}$–$Z$ relationship of normal star-forming regions. They seem to be ALM regions, selected by their significantly lower (by about 0.14 dex) observed metallicities compared to the expected ones given $\Sigma_{\text{gas}}$ and the $\Sigma_{\text{gas}}$–$Z$ relation in Hwang et al. (2019). These authors found that ALM regions tend to exist in less-massive and disturbed galaxies. They also estimated the ages of these ALM regions to be a few hundred Myr. Here, we use the [O III]λ4363 emission line to select a metal-poor sample to get more accurate metallicities than from the strong line method. In our [O III]λ4363 selected metal-poor sample, the $t_\text{e}$ values are also between 100 Myr and 1 Gyr ($log\langle t_\text{e}\rangle \sim 8.0$–9.0). The distribution of $P(\text{merger})$ shown in the right panel of Figure 3 also shows that our galaxies are likely to experience mergers or interactions compared to those in the control sample. These characteristics are highly consistent with the ALM regions selected by Hwang et al. (2019).

Since the $P(\text{merger})$ from the DL catalog is the result of batch processing, it only gives a statistical merging probability. In fact, whether the merger is true requires further inspection, so we check our galaxies one by one. We review the images and spectra of each galaxy and the surrounding galaxies that may be merging objects. Our inspection finds that 11 of the 52 galaxies in our sample have nearby galaxies confirmed by spectral redshifts, of which six galaxies (plate-ifu = 8566-3704, 8455-9101, 8241-6101, 8139-12702, 9881-9102, and 9194-12701) are within the field of view of the MaNGA IFU, and three galaxies (9509-3702, 8715-12704, and 8452-1902) are within 1'. In addition, the neighbors of three galaxies (8548-3702, 8553-12703, and 8325-12702) have no spectral redshift but are within the uncertainty of their photometric redshifts. Therefore, a total of 12 galaxies may be merging galaxies, accounting for 23.1% of our sample. Therefore, the results of both the DL catalog and the spectral inspection confirm that our sample has a greater merger ratio than the normal SFGs. Merger and interaction can trigger gas infall and star formation, and the inflow of metal-poor gas will dilute the metal-rich ISM and form new metal-poor stars. (Kunth & Östlin 2000), so we can conclude that the interaction is closely related to these metal-poor regions.

5. Conclusion

In this work, we make use of the MaNGA data from SDSS DR15 to investigate the $\Sigma_{\text{gas}}$–$\Sigma_{\text{SFR}}$ and $\Sigma_{\text{gas}}$–$Z$ relationships. We select 1698 spaxels from 52 galaxies with reliable [O III]λ4363 observations. We calculate their local metallicities with the $T_e$ method. We have the following conclusions:

![Figure 10](image-url)

Figure 10. The normalized distribution of metallicity offset ($\Delta[12+\log(O/H)] = Z_{\text{PG16}}(\Sigma_{\text{gas}}, M_*) - Z_{\text{obs}}$). All metallicities are obtained from PG16. Solid border histograms represent the sample we selected by [O III]λ4363. Dashed border histograms represent all star-forming spaxels in our sample galaxies. Dashed---dotted border histograms represent the control sample with similar mass distributions to our sample galaxies. The vertical lines respectively indicate the median of the corresponding border style.
1. There is a local $\Sigma_*-\Sigma_{\text{SFR}}$ relationship and a $\Sigma_*-Z$ relationship in the [O III]$\lambda$4363 emission line selected regions. Among them, in the $\Sigma_*-\Sigma_{\text{SFR}}$ relationship, our SFR is higher overall (99.4% are outside 1$\sigma$ of the SFMS in G18), and in the $\Sigma_*-Z$ relationship, our metallicity is lower overall (86.5% are outside 1$\sigma$), and this is not caused by the FMR.

2. The regions we selected have young stars (<1 Gyr) and their stellar metallicities are also low ($Z_*$ $\sim$0.01). The $t_*$ derived by spectral energy distribution fitting is consistent with the estimated age of the ALM regions reported in Hwang et al. (2019).

3. Most of the galaxies in the selected region are star-forming galaxies with low mass ($\sim$10$^9$ $M_\odot$). These galaxies are late in morphology and have a high merging ratio, reflecting that the metal-poor star-forming regions may be related to interactions. The infall of metal-poor gas may dilute the interstellar medium and form new metal-poor stars in these galaxies during interaction.

However, we do not find direct evidence for the infall of metal-poor gas and the relation between mergers and gas inflows. How the interaction affects the metallicity of galaxies remains to be further studied.

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Appendix A
Comparison of Our Results and DAP

Here, we provide a comparison between the results measured by us and those provided by the DAP. Figure 11 shows the ratio of fluxes of some emission lines. The PG16-based differences between ours and the DAP as functions of [O III] $\lambda$4363 flux and [O III] $\lambda$4363 relative error are shown in Figure 12. The flux and error here are before the intrinsic dust extinction correction. Figure 13 shows the metallicity profile measured by our fitting and the DAP along radius of the first four galaxies that have already been shown in Figure 1.

Since the emission lines we compared are all strong emission lines, it cannot prove that the measurement of the weaker emission lines ([O III]$\lambda$4363) is accurate. However, [O III] $\lambda$4363 is not measured by the DAP; we can estimate its accuracy of fitting through [O I]$\lambda$6300, whose flux is the same magnitude as [O III]$\lambda$4363's. The mean flux of [O III]$\lambda$4363 of our sample is $\sim$0.49 $\times$ 10^{-17} erg s^{-1} cm^{-2}, and the mean flux of [O I]$\lambda$6300 is $\sim$1.17 $\times$ 10^{-17} erg s^{-1} cm^{-2}. The mean relative difference of the [O I]$\lambda$6300 measurement is only $\sim$6%. Therefore, from Figures 11 and 13, we can conclude that our measurement is reliable compared to that of the DAP.

We also calculate the differences between two observations of the same galaxy (8274-9102 and 8256-9102), and they are shown in Figure 14.

![Figure 11](image.png)

**Figure 11.** The distribution of the ratio of the flux values of some emission lines (Hα, [N II], [O II], and [O I]) we measured to the flux values provided by the DAP at the same spaxel.
Figure 12. The difference between our metallicity and the DAP-flux-based metallicity as a function of \([\text{OIII}\lambda 4363 \text{ flux (erg/s/cm}^2\text{)}]^{16-17}\) and the relative error.
Figure 13. Same as Figure 1, but the flux measurements of the right column are from the DAP.
Appendix B

Images of Other Sample Galaxies

Here, we show the SDSS images and radial profiles of the galaxies with the 5th to 22nd most spaxels in Figures 15, 16, and 17.
Figure 15. Same as Figure 1, but the galaxies are ranked 5th to 10th in descending order of spaxels.
Figure 16. Same as Figure 1, but the galaxies are ranked 11th to 16th in descending order of spaxels.
Figure 17. Same as Figure 1, but the galaxies are ranked 17th to 22nd in descending order of spaxels.
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**ORCID iDs**

Yao Yao [https://orcid.org/0000-0002-6873-8779](https://orcid.org/0000-0002-6873-8779)
Xu Kong [https://orcid.org/0000-0002-7660-2273](https://orcid.org/0000-0002-7660-2273)
Yulong Gao [https://orcid.org/0000-0002-5973-694X](https://orcid.org/0000-0002-5973-694X)
Guangwen Chen [https://orcid.org/0000-0002-4742-8800](https://orcid.org/0000-0002-4742-8800)
Xinkai Chen [https://orcid.org/0000-0002-5016-6901](https://orcid.org/0000-0002-5016-6901)
Zhesen Liang [https://orcid.org/0000-0001-8078-3428](https://orcid.org/0000-0001-8078-3428)
Yimeng Tang [https://orcid.org/0000-0003-2876-577X](https://orcid.org/0000-0003-2876-577X)
Hong-Xin Zhang [https://orcid.org/0000-0003-1632-2541](https://orcid.org/0000-0003-1632-2541)

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