The Local Star Formation Rate Surface Density and Metallicity Relation for Star-forming Galaxies

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Abstract

We study the relations between gas-phase metallicity (Z), local stellar mass surface density (Σ_M*) and the local star formation surface density (Σ_{SFR}) in a sample of 1120 star-forming galaxies from the MaNGA survey. At fixed Σ_M*, the local metallicity increases as Σ_{SFR} decreases or vice versa for metallicity calibrators of N2 and O3N2. Alternatively, at fixed Σ_{SFR} metallicity increases as Σ_M* increases, but in the high mass region, the trend is flatter. However, the dependence of metallicity on Σ_{SFR} nearly disappears for N2O2 and N2S2 calibrators. We investigate the local metallicity against Σ_{SFR} with different metallicity calibrators and find negative/positive correlations depending on the choice of the calibrator. We demonstrate that the O32 ratio (or ionization parameter) is probably dependent on star formation rate at fixed local stellar mass surface density. Additionally, the shape of Σ_M*=Z-Σ_{SFR} (fundamental metallicity relation; FMR) depends on metallicity calibrator and stellar mass range. Due to the large discrepancy between the empirical fitting-based (N2, O3N2) electronic temperature metallicity and the photoionization model-dependent (N2O2, N2S2) metallicity calibrations, we conclude that the selection of metallicity calibration affects the existence of FMR on Σ_{SFR}.

Unified Astronomy Thesaurus concepts: Galaxy abundances (574); Galaxy evolution (594); Galaxy chemical evolution (580); Interstellar medium (847); Interstellar emissions (840)

1. Introduction

Understanding the physical process of the interstellar medium (ISM) is a key for determining a complete picture of galaxy formation and evolution. In particular, metallicity over galaxies is one of the physical quantities to implement a hint regarding evolution. The metallicity could produce insights into regulating galaxy outflow properties (Finlator & Davé 2008; Lilly et al. 2013; Belfiore et al. 2016). The enrichment gas outflow and inflow decreased the gas-phase abundance inside a galaxy. The inflows dilute the metal content, while the outflows remove metals from the ISM. The galaxy metallicity will reduce if the outflow gas is enriching beyond the current ISM, either through the direct escape of metal-rich ejection from the supernova explosion (SNe) or through galactic winds with enriched metals.

Lequeux et al. (1979) established the relation of mass-metallicity (MZR), which indicates that the metallicity of the galaxy increases as the stellar mass increases; this relation recognizes that the galactic outflows control the metal content of the interstellar medium. It was presented observationally with the aid of Tremonti et al. (2004), who determined a tight relation spanning three orders of magnitude within the mass and a factor concerning about 0.1 dex into metallicity, using a large sample of star-forming galaxies from the Sloan Digital Sky Survey (SDSS). Moreover, the MZR presents a similar shape impartially concerning the oxygen abundance calibrator, including a clear trend for M_* < 10^{10} M_⊙, then pulling it down to the asymptotic value for higher stellar masses (e.g., Kewley & Ellison 2008).

In particular, Ellison et al. (2008) had already shown the dependence of MZR on star formation rate (SFR). Alternatively, Lara-López et al. (2010) and Mannucci et al. (2010) suggested the correlation between metallicity and SFR, observing that at a fixed mass, the lower metallicity galaxy shows higher SFR. However, both the SFR and metallicity increase with increasing galaxy stellar mass. Besides, numerous studies confirmed the M–Z–SFR (fundamental metallicity relation; FMR) relation (e.g., Mannucci et al. 2010; Hunt et al. 2012; Yates et al. 2012; Andrews & Martini 2013; Salim et al. 2014; Wu et al. 2016; Sánchez Almeida et al. 2018; Sánchez Almeida & Sánchez-Menguiano 2019).

Furthermore, several studies also questioned the presence of the FMR relation. Sánchez et al. (2013) obtained H I regions from the CALIFA data set (Sánchez et al. 2012) but did not find the secondary relation with SFR. Moran et al. (2012) had shown that their data does not demonstrate this secondary relation; however, they suggested a secondary relationship to the gas fraction. Furthermore, Rosales-Ortega et al. (2012) found a correlation with specific SFR (sSFR) based on the equivalent width (EW) of Hα. The local MZR does not exhibit a secondary relation yet maintaining the primary link between stellar mass and SFR. Kashino et al. (2016) revealed that they could not determine the secondary dependence between SFR and MZR presented by Mannucci et al. (2010) for a single metallicity calibrator. More recently, Barrera-Ballesteros et al. (2017) used different metallicity calibrators; at all of the calibrations, they have not found a robust secondary trend of MZR with either SFR or sSFR. However, in a recent review about the FMR, Cresci et al. (2019) found the presence of FMR at fixed stellar mass by reanalyzing the data of CALIFA and SDSS-IV MaNGA.

In addition, the mass–metallicity relation is also mainly important for stellar evolution. Many studies (Moran et al. 2012; Rosales-Ortega et al. 2012; Sánchez et al. 2013; Gao et al. 2018) explored the correlation of the local metallicity and...
the local stellar mass density for local star-forming galaxies using the GASS survey (Saintonge et al. 2011), the CALIFA survey (Sánchez et al. 2012), and the MaNGA survey (Bundy et al. 2015), respectively. Those authors confirmed the existence of a correlation between local metallicity and local surface mass density. Alternatively, they noticed that H II regions with higher mass surface density are more metal-rich than those with lower density.

Moreover, the relation between SFR and ionization parameter are not well understood. Kewley & Dopita (2002) defined the ionization parameter using a two-line ratio [O III]/[O II]. Lately, Nakajima & Ouchi (2014) presented a correlation between the ionization parameter and the global physical properties of galaxies and found that higher ionization parameters are determined in much less massive galaxies with low metallicity. In addition, the anticorrelation between the ionization parameter and metallicity of the H II region was also presented by Dopita et al. (2006). In particular, Kaasinen et al. (2018) find higher ionization parameters toward higher sSFRs for their star-forming galaxies. A high ionization parameter has been proposed as the result of high SFRs, contributing to a larger reservoir of ionizing photons (e.g., Kewley et al. 2013).

Though, significant studies about the local MZR and FMR did not take the sensitivity of the ionization parameter into account regarding the metallicity and SFR. In this study, we use a large spatially resolved sample from the MaNGA IFU survey to investigate the relation of local stellar surface density, metallicity, and local SFR surface density ($\Sigma_{\text{s}}$–$Z$–$\Sigma_{\text{SFR}}$). We also take a look at the effects of the ionization parameter with different metallicity diagnostics.

The paper is organized as follows. In Section 2, we demonstrate the sample selection for star-forming galaxies from the MaNGA survey, the fitting process, the determination of the gas-phase oxygen abundances, the stellar mass surface densities, and other physical parameters. In Section 3, we investigate the distribution and relation of $\Sigma_{\text{s}}$–$Z$–$\Sigma_{\text{SFR}}$ and the dependence of the ionization parameter on metallicity. We discuss the implication of our results of the FMR and $\Sigma_{\text{SFR}}$–$Z$ in Section 4. Finally, we summarize our results in Section 5.

Throughout this paper, we adopt a flat $\Lambda$CDM cosmology with $\Omega_{\Lambda} = 0.7$, $\Omega_m = 0.3$, and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2. Data

2.1. MaNGA Overview

The MaNGA survey examines 10,000 galaxies using an integral field spectroscopy unit (IFU), across 2700 deg$^2$ at local universe $z \sim 0.03$ (Bundy et al. 2015). The wavelength ranges from 3600 to 10300 Å with spectral resolution $R \sim 1400$ to 2600. The standard effective spatial resolution of the extracted data cubes can be used to illustrate by Gaussian with an FWHM $\sim 2.5''$, and the spaxel size of released data cubes is $0.5''$. The MaNGA IFU includes 29 fiber bundles in the SDSS field of view. A further detailed description of MaNGA instrument structure can be found in Drory et al. (2015).

In this study, we extract the MaNGA data from SDSS-IV Data Release 14 (DR14)\(^4\) (Abolfathi et al. 2018) as the initial sample that contains 2812 galaxies.

\(^4\) http://www.sdss.org/dr14/manga/manga-data/catalogs

2.2. Spectral Fitting and Emission-line Measurements

First, we correct the Galactic extinction by applying the color excess $E(B - V)$ using a map of the Milky Way (Schlegel et al. 1998). For this study we use the public STARLIGHT spectral fitting code (Cid Fernandes et al. 2005) to fit the observational continuum spectra with a series of single stellar population models from Bruzual & Charlot (2003), assuming a Chabrier (2003) initial mass function (IMF) and adopting the attenuation law of Calzetti et al. (2000).

The fluxes of strong emission lines (e.g., [O III] $\lambda$5007, [O III] $\lambda$3727, H$\beta$, [O III] $\lambda$4959,5007, H$\alpha$, [N II] $\lambda$6583, and [S II] $\lambda$6717,6731) are fitted with the Gaussian profiles by applying an IDL package MPFIT (Markwardt 2009). Following the method of Ly et al. (2014), we measure the signal-to-noise ratios (S/N) of these emission lines. Using the Balmer decrement and assuming a Calzetti et al. (2000) attenuation law, we correct the interstellar reddening. We presume the intrinsic flux ratio (H$\alpha$/H$\beta$)$_0 = 2.86$ under the case-B recombination.

2.3. Sample Selection

Our parent sample has 2812 galaxies from SDSS DR14, and we use the benchmark of NUV–$r < 4$ to select star-forming galaxies (Li et al. 2015); 1120 galaxies are selected. Our main goal is to select star-forming regions, for which the spaxels have signal-to-noise ratios $S/N(\text{H}$α$) > 5$, $S/N(\text{H}$β$) > 5$, $S/N([\text{O III}]\lambda 3727) > 5$, $S/N([\text{O III}]\lambda 4959,5007) > 5$, and $S/N([\text{N II}]\lambda 6583) > 3$, with continuum $S/N$ greater than 3 and EW of H$\alpha$ greater than 10 Å. We use the Kauffmann et al. (2003) boundary line in the BPT diagram (Baldwin et al. 1981; Kewley et al. 2001; Kaufmann et al. 2003) to exclude the spaxels affected by the active galactic nuclei (AGNs).

Figure 1 illustrates the BPT diagram of about 740,000 spaxels. The grayscale exhibits the spaxel number density. As
shown, our final sample of spaxels is located in the star-forming region.

2.4. Determinations of Metallicity, Star Formation Rate Surface Density, and Stellar Mass Surface Density

Determination of accurate oxygen abundance is more reliable using the electronic temperature or direct method, which can be obtained from the ratio of auroral to nebular intensity lines, such as [O III]λ4363/[O III]λ5007. Getting the oxygen abundance using the direct method is challenging for higher metallicity because [O III]λ4363 becomes fainter. In this study, we will adopt four metallicity calibrations based on strong lines.

(I) The N2O2 calibrator is a more reliable estimator for local galaxies because of the spectral wavelength coverage. For nearby galaxies, we can get the lines of [O II] λ3727 and [N II] λ6583, but for the higher redshift, it is challenging to observe those lines. Additionally, the ratio of [N II] and [O II] is less affected by the ionization distribution, thus the N2O2 can be an oxygen abundance indicator. The calibrated metallicity using the relation in Kewley & Dopita (2002) is given by:

\[
12 + \log(O/H) = \log\left(1.54020 + 1.26602 \times N2O2 + 0.167977 \times N2O2^2\right) + 8.93, \tag{1}
\]

where \(N2O2 = \log([N II]λ6583)/([O II]λλ3727,3729])\), with estimated uncertainty of 0.04 dex.

(II) O3N2: This index is commonly known to depend on strong emission-line flux (Hα, Hβ, [O III]λ5007, [N II]λ6583) to diagnose oxygen abundances in the literature. The diagnostic of O3N2 index (Alloin et al. 1979) is characterized by

\[
O3N2 = \log\left(\frac{[O III]λ5007}{H\beta}\times\frac{H\alpha}{[N II]λ6583}\right). \tag{2}
\]

Pettini & Pagel (2004) recalibrate the O3N2 diagnostic with \(T_e\) based metallicity for H II region samples. Later, Marino et al. (2013) improved the O3N2 calibration with a large sample of H II regions. Here we use the modified O3N2 calibration by Marino et al. (2013), which is given by

\[
12 + \log(O/H) = 8.505 - 0.221 \times O3N2. \tag{3}
\]

(III). N2: Storchi-Bergmann et al. (1994) initially suggested the N2 index as a calibrator because the N2 index strongly correlated with abundance. The diagnostic N2 index (Storchi-Bergmann et al. 1994; Raimann et al. 2000) is described as

\[
N2 = \log([N II]λ6583/H\alpha). \tag{4}
\]

Hence, N2 calibrated metallicity is determined by Marino et al. (2013) and expressed as

\[
12 + \log(O/H) = 8.667 + 0.455 \times N2. \tag{5}
\]

(IV). N2S2: The [N II]λ6583/[S II]λλ6717,6731 diagnostic is sensitive to metallicity and weakly dependent on the ionization parameter. The N2S2 index is defined as:

\[
N2S2 = \log\left(\frac{[N II]λ6583}{[S II]λλ6717, 6731}\right). \tag{6}
\]

and the metallicity calibration relation using the N2 and N2S2 from Dopita et al. (2016) is given as

\[
12 + \log(O/H) = 8.77 + N2S2 + 0.264 \times N2. \tag{7}
\]

The global stellar mass \(M_\star\) and minor-to-major axis ratio (b/a) are extracted from the NSA catalog5 (Blanton et al. 2005; Blanton et al. 2011). Following the method of Barrera-Ballesteros et al. (2016), we generate the local stellar mass surface density \(\Sigma_\star\). We divide the surface mass density in each spaxel from the output results of STARBURST99 by its corresponding physical area and then correct the inclination using the b/a.

We use the dust-corrected Hα emission-line luminosity to determine the SFR for each spaxel, using the formula from Kennicutt (1998) and assuming a Chabrier (2003) IMF.

3. Result

In this section, we utilize the dependence of the \(\Sigma_\star-Z\) relation as a function of the local \(\Sigma_{SFR}\). Moreover, we explore the dependence of the \(\Sigma_\star-Z\) relation on SFR surface density and the ratio of [O III]λ5007/[O II]λλ3727.

3.1. The Dependence of the \(\Sigma_\star-Z\) Relation on Star Formation Rate Surface Density

In Gao et al. (2018), we reported the relationship between the local stellar mass surface density and gas metallicity and found similar relations to Rosales-Ortega et al. (2012) and Sánchez et al. (2013). As proposed in these results, it is necessary to check if the local \(\Sigma_\star-Z\) relationships have a secondary relationship with local \(\Sigma_{SFR}\).

As mentioned above, we investigate the dependence of local metallicity and the local stellar mass surface density \(\Sigma_\star\) as a function of local SFR surface density \((\Sigma_\star-Z-\Sigma_{SFR})\) relation for our samples in Figure 2. We separate our sample into five different bins based on local SFR surface density, and each panel shows different metallicity indicators. The bins range from lower to higher \(\Sigma_{SFR}\) (−3.65, −2.45, −2.2, −2, and −1.65) values. The median values for different star formation ranges are shown as the different color-coded connected lines.

In the top left and right panels of Figure 2, we present the metallicity derived by N2 and O3N2 indexes as a function of the local stellar mass surface density. As shown in these panels, the metallicity increases with increasing local stellar mass surface density.

The bottom left and right panels of Figure 2 show the metallicity derived with N2O2 and N2S2 indexes, respectively. In these panels, the trend of \(\Sigma_\star-Z\) is similar to N2 and O3N2; however, it is not obvious as a function of local \(\Sigma_{SFR}\). Interestingly, we notice that the \(\Sigma_{SFR}\) does not change with increasing metallicity at fixed \(\Sigma_\star\). In particular, the metallicity increases steeply with local stellar mass surface density, while a flatter relation appears at high mass surface density (\(\log(\Sigma_\star) > 7.8\)) for the top two panels.

In the dependence of local MZR on \(\Sigma_{SFR}\) is attributable to the metallicity calculation method between different diagnostics and calibrations, more detail about this

5 http://www.nsatlas.org
discrepancy can be found in previous studies (e.g., Pettini & Pagel 2004; Kewley & Ellison 2008; Sánchez et al. 2012). On the other hand, the Hα based estimation of Σ$_{SFR}$ also affects the shape of Σ$_*$–Z–Σ$_{SFR}$. We will share more details about this reversal relation for those different metallicity indicators in the following sections.

3.2. Star Formation Rate Surface Density and Metallicity (Σ$_{SFR}$–Z) Relation on M$_*$

In the previous section, we examine the relation between Σ$_*$–Z and Σ$_{SFR}$. In this section, we aim further to test the dependence of Σ$_{SFR}$ on the local metallicity comparing different metallicity calibrations at fixed stellar mass and local stellar mass surface density. To quantify this relation, for each subsample, we derive the correlation coefficient to check if it presents any variation with the stellar mass. If the Σ$_{SFR}$–Z changes significantly for each stellar mass bin, the shape of Σ$_*$–Z may truly depend on the Σ$_{SFR}$, as we have shown in the top left and right panels in Figure 2 of Section 3.1.

In Figure 3, we show the distribution of metallicity-SFR surface density at fixed global stellar mass and local stellar mass surface density regardless of Gao et al. (2018). The first column shows the distribution at the low mass range of 9.2 < log($M_*/M_\odot$) < 9.6 and 6.4 < log($\Sigma_*$) < 7.1 with different metallicity calibrations. The second column represents the intermediate-mass bin 9.6 < log($M_*/M_\odot$) < 10.0 and 7.1 < log($\Sigma_*$) < 7.8. The last column indicates the high mass bin 10.0 < log($M_*/M_\odot$) < 10.5 and 7.8 < log($\Sigma_*$) < 8.5. In each panel, the solid red line indicates the best-fit linear relation of Σ$_{SFR}$–Z, and the gray contour represents the scatter of subsamples.

Figure 3. Distribution of metallicity against local stellar mass surface density regarding four different metallicity calibrations, O3N2, N2, N2O2, and N2S2 indexes.

For low mass bin subsamples, we find a clear and strong anticorrelation between Σ$_{SFR}$ and metallicity, with $r = -0.33$ and $r = -0.38$, for metallicity indexes N2 and O3N2, respectively. However, for N2O2 and N2S2 metallicity indexes, no correlation is found at this mass range. Our results regarding correlation coefficients of different metallicities with bins of stellar mass and local surface mass density are shown in Table 1.

As shown in Figure 3, the Σ$_{SFR}$–Z relation at different stellar mass bins shows different slopes for N2, O3N2, N2O2, and N2S2 metallicity calibrators. The trends are slightly similar for those two calibrators of N2 and O3N2. If we focus on the low- and intermediate-mass bins, we can see that the Σ$_{SFR}$–Z slope presents anticorrelation. This trend is consistent with Sánchez Almeida & Sánchez-Menguiano (2019) at stellar mass range 9.2 < log($M_*/M_\odot$) < 9.6 using the O3N2 index. Besides
considering the N2 index, at fixed mass, the metallicity decreases with increasing local $\Sigma_{SFR}$.

As we explored, the relations indicate that for higher (lower) stellar mass bins, the correlation is weak (strong) for $\Sigma_{SFR}$–$Z$. As we have shown for the O3N2 metallicity calibration, at higher stellar mass ($\log(M_*/M_\odot) > 10$), we find a flatter trend, which is similar to the flat MZR at high mass (e.g., Tremonti et al. 2004; Kewley & Ellison 2008; Zahid et al. 2014). However, Figure 3 shows a positive correlation for N2O2 and N2S2 calibrators, but a negative correlation for the N2 index, in the high mass region.

Figure 3. Metallicity distribution in $\Sigma_{SFR}$ space based on O3N2, N2, N2O2, and N2S2 indexes. We separate the plotting range $M_*$ and $\Sigma_*$ into three bins ($M_*$: 9.2, 9.6, 10.0, 10.5 and $\Sigma_*$: 6.4, 7.1, 7.8, 8.5). The left four rows show the lower mass bin for different metallicity calibrations, the middle four panels represent the intermediate-mass range, and the right four panels show a higher mass bin for different metallicity calibrations, respectively. The contour represents the distribution of $\Sigma_{SFR}$–$Z$. The red dashed line in each panel shows the best-fitted $\Sigma_{SFR}$–$Z$ relation of subsamples. Blue symbols and error bars display the median values and standard deviation, respectively.
Generally, this mixed type of behavior is different from the local MZR and FMR at different stellar mass bin regions for star-forming galaxies reported in other studies. The mixed results on these $\Sigma_{\text{SFR}}-Z$ relations were possibly caused by different metallicity estimations, which have systematic errors on calibration, and the calculation of $\Sigma_{\text{SFR}}$ from the strong emission line. The variations among observed behaviors are probably associated with the methods used to measure the oxygen abundance among different studies.

We expect that the different trends in $\Sigma_{\text{SFR}}-Z$ relations for different stellar mass bins, with four metallicity calibrators, might be caused by the dependence of metallicity on ionization parameter. We will discuss the ionization parameter in the following sections.

### 3.3. Dependence of $[\text{O III}]\lambda 5007/\text{H} \beta \lambda 3727$ on Metallicity

In this section, we demonstrate the dependence of $[\text{O III}]\lambda 5007/\text{H} \beta \lambda 3727$ on the metallicity. The ratio of O32 is a proxy of the ionization parameter (Dopita et al. 2000; Kewley & Dopita 2002). In Figure 4, we show the metallicity distribution as a function of the O32 ratio with four different calibrators. Different color means different $\Sigma_{\text{SFR}}$, which is the same as in Figure 2. The median metallicity is shown for bins of varying $\Sigma_{\text{SFR}}$. In particular, at a fixed ratio of O32, the metallicity increases with increasing $\Sigma_{\text{SFR}}$.

In Figure 4 we see that the local metallicity is decreasing with the increasing O32 ratio. As shown in Figure 4, the higher metallicity corresponds with a lower O32 ratio, which is also described by Maier et al. (2004). Dopita et al. (2006) argued that the higher opacity stellar wind causes a strong dependence between chemical abundance and ionization parameter in the surrounding H II region. We investigate that the metallicity calibrator depends on the ionization parameter or the ratio of O32. We expect that the existence of anticorrelation between the ionization parameter and metallicity can interpret the presence of anticorrelation between $\Sigma_{\text{SFR}}$ and metallicity.

### 3.4. The Relation Between the Ratio of O32, $\Sigma_*$, and $\Sigma_{\text{SFR}}$

We now demonstrate the correlation between the ionization parameter, $\Sigma_*$, and $\Sigma_{\text{SFR}}$. In Figure 5, the different colors represent the bins in different ranges of local stellar mass surface density. The connected lines indicate the median values of the ratio of O32 and $\Sigma_{\text{SFR}}$ in each bin of $\Sigma_*$.

The $\Sigma_{\text{SFR}}$ weakly increases with increasing O32, while at the fixed ionization parameter, the regions with higher $\Sigma_*$ have higher $\Sigma_{\text{SFR}}$ simultaneously. We find a weak positive correlation between the O32, $\Sigma_*$, and $\Sigma_{\text{SFR}}$ relation, which is in agreement with Kewley et al. (2015). We support the scenario that a more significant number of stars within H II regions is probably to be main factor accountable for varying the ionization parameter with stellar mass surface density.

### 3.5. The Fundamental Metallicity Relation

As we mentioned in Figure 2, the $\Sigma_*-Z$ is a function of $\Sigma_{\text{SFR}}$; in the upper left and right panels, we demonstrate a clear trend with these two metallicity indicators. In this section, we check the secondary relation of $\Sigma_{\text{SFR}}$. Mannucci et al. (2010) presented the existence of the FMR and estimated the scatter by adopting median metallicity values on the projection MZR space. The projection is described as:

$$\mu_\alpha = \log(\Sigma_*) - \alpha \log(\Sigma_{\text{SFR}}).$$

Interestingly, except at lower stellar mass and higher sSFR, Barrera-Ballesteros et al. (2016) presented that the relationship of $\Sigma_*-Z$ is broadly independent on the total stellar mass of galaxy and sSFR, using the O3N2 metallicity calibrator. Before applying the FMR projection relation, we excluded the galaxies with lower stellar mass, by setting $\log(M_*/M_\odot) > 9.6$, and we use $\alpha = 0.32$ as proposed by Mannucci et al. (2010) to reduce the scatter of our sample.

In Figure 6, we display the local metallicity distribution as a function of FMR projection $\mu_\alpha$, which is consistent with Mannucci et al. (2010). We find that the scatters of our MaNGA sample are $\sigma = 0.28$ dex and 0.26 dex using metallicity calibrations of N2 and O3N2, respectively. We confirm the existence of the trend in Figure 2 that regions with higher $\Sigma_{\text{SFR}}$ have lower metallicity at fixed $\Sigma_*$. However, the $\alpha$ might not be fitted for the lower $\Sigma_{\text{SFR}}$ region (black lines in Figure 6).

### 4. Discussion

In this study, we demonstrate the local $\Sigma_*-Z$ relation and their dependence on the $\Sigma_{\text{SFR}}$ and ionization parameter using different metallicity calibrations for spatially resolved samples about 740,000 spaxels from the MaNGA survey.

We confirm the tight $\Sigma_*-Z$ relation reported by Rosales-Ortega et al. (2012) and Barrera-Ballesteros et al. (2016). Furthermore, we explore the effect of $\Sigma_{\text{SFR}}$ on the local surface mass density and local metallicity relation or the fundamental relation. We found a clear correlation between $\Sigma_*-Z$ and $\Sigma_{\text{SFR}}$ for the metallicity calibration of N2 and O3N2 indices. Our results in Figure 2 are consistent with global and local FMR studies (e.g., Lara-López et al. 2010; Mannucci et al. 2010; Sánchez et al. 2013, 2017, 2019; Salim et al. 2014) only with N2 and O3N2 metallicity calibrations.

#### 4.1. Physical Explanation of O32 Ratio and Local Metallicity

The metallicity anticorrelates with the ratio of O32, which causes the discrepancy with empirical emission lines. Ho et al. (2015) presented a comparison of a different diagnosis, and found that the diagnosis of O3N2 offers higher metallicity than the N2O2 at a higher ionization parameter or vice versa.

The ionization parameter and O32 ratio commonly demonstrate dependence on metallicity since the ionizing spectrum is related to metallicity (Kewley & Dopita 2002). Although low-metallicity stars generate higher ionizing photons and have a harder ionizing spectrum (Leitherer et al. 2014) as that of an anticorrelation with metallicity and ionization parameter. With
these caveats in mind, we present evidence of the anticorrelation of the metallicity and O32, as shown in Figure 4. Furthermore, Sanders et al. (2016) found that the hardness of the ionizing spectrum increases with decreasing metallicity and higher metallicity objects to have lower O32; lower metallicity objects tend to have higher O32 values.

In other words, the lower/higher ionization parameter may vary because of the fluctuation of the hardness of the ionizing spectrum with metallicity. Regarding this, Nagao et al. (2006) proposed two possibilities. The first considers mass–metallicity and mass–age relations. According to this, more massive and older systems are linked to a higher metallicity of galaxies. Due to the decreased luminosity of the ionizing stars, HII regions ionized by later stellar populations are supposed to be distinguished by lower ionization parameters. The other possibility is the relationship between gas metallicity and stellar metallicity, because lower metallicity stars ionize lower metallicity gas. The first possibility can be checked by the O32 ratio with ΣSFR as shown in Figure 5. Indeed, this is related to a fixed mass surface density, and there is an increasing ionization parameter with ΣSFR; this may appear to be due to the fraction of young stars to old stars in a galaxy.

In addition, as we have seen in Figure 2, the results of different metallicity calibrations agree with the suggestions of Curti et al. (2017, 2019), who found the Te method metallicity calibration to have a lower metallicity value than the photoionization model calibrations. Indeed, this indicates that the higher values of N2O2 and N2S2 indexes are reasonable compared to N2 and O3N2 calibrations. The main reason is that this
difference might be caused by the bias at the higher excitation conditions.

4.2. The FMR and $\Sigma_{\text{SFR}}-Z$

Using the metallicity calibration of N2 and O3N2, there is an anticorrelation between metallicity and $\Sigma_{\text{SFR}}$, which is covered in Mannucci et al. (2010); however, it changes to a positive correlation at high mass when we use N2O2 and N2S2 indexes. During this condition, did the FMR exist?

Yates et al. (2012) presented the FMR projection, while the SFR anticorrelates to metallicity at lower stellar masses. Then the relationship inverts to a positive correlation at higher stellar masses. They argued that the inversion is the consequence of gas-rich mergers at higher stellar masses fueling a starburst. Later, Lara-López et al. (2013) found a similar relation at higher mass; it gives the reversal of the FMR, and the higher SFR exhibits higher metallicity. However, Telford et al. (2016) presented the systematic effects of the secondary dependence of the MZR on SFR and compared them with Mannucci et al. (2010), who suggested that the dependence is weaker for the secondary relationship.

The results in Figure 3 show mixed scenarios of negative and positive correlations. For N2 and O3N2 metallicity calibrations at low and intermediate mass, we found the negative $\Sigma_{\text{SFR}}-Z$, which is consistent with Mannucci et al. (2010), suggesting that the lower mass produces lower metallicity and higher $\Sigma_{\text{SFR}}$. On the other hand, this analysis only supports the original FMR if we use N2 and O3N2 indexes. Indeed, Lian et al. (2015) found at fixed stellar mass that the lower metallicity corresponds to a younger stellar population for local Lyman-break analog (LBA) galaxies. For the N2O2 and N2S2 metallicity indicators, the result is challenging to interpret, as we have seen the positive trend for the high mass range. This inverted result is possibly caused by the metallicity calibration. In Section 3, we have seen that for higher $\Sigma_{*}$ using N2O2 and N2S2, the MZR is increasing for higher $\Sigma_{\text{SFR}}$, but is flatter for high mass with N2 and O3N2 calibrators.

Looking back at the two bottom panels of Figure 2, the local metallicity increases with increasing local stellar mass surface density, but there is no trend with local SFR. In Figure 3, the $\Sigma_{\text{SFR}}-Z$ increases with increasing stellar mass. This indicates that the stellar mass and local stellar mass surface density are physically fundamental to drive the local metallicity in H II regions.

Kashino et al. (2016) reported that for local galaxies at low mass, the median value of metallicity is flat or constant. They suggest that this result is due to the dominance of the primary production of nitrogen in less massive galaxies. Their finding is in agreement with our results using the metallicity indicators of N2O2 and N2S2 in Figure 3, which indicate that the $\Sigma_{\text{SFR}}-Z$ relation is constant in the lower mass bins. Furthermore, Kashino et al. (2016) find an anticorrelation between metallicity and SFR in FMR when using Mannucci et al. (2010) metallicity calibration; it retrieves a positive trend when using Dopita et al. (2016) metallicity calibration. This is similar to our result that the trend is reversed when using N2O2 and N2S2 index metallicity calibrations.

More recently, Curti et al. (2019) derived the MZR for a sample of SDSS galaxies with $T_e$ metallicity calibration, they found that the turnover mass and the saturation metallicity are in agreement with previous MZR studies, while showing significantly lower normalization compared to those based on photoionization models. This determination is similar to our result, as shown in Figures 2 and 3. Cresci et al. (2019) also reanalyzed the data of CALIFA and SDSS-IV MaNGA samples and found the secondary relation between MZR and SFR, which is different from the findings in Barrera-Ballesteros et al. (2017) and Sánchez et al. (2017). Cresci et al. (2019) demonstrated that at fixed mass the metallicity depends on SFR and shows an inversion in the high stellar mass region caused by the metallicity calibration and SFR estimation, which is similar to our result.

In conclusion of this section, the different metallicity calibrations give different correlations between the mass surface density, metallicity, and local star formation surface density (in Figures 2 and 3). These results may be caused by the metallicity calibration, the $\Sigma_{\text{SFR}}$ determination, and the ionization parameter. In general, the electron temperature method, derived with the ratios of faint auroral to nebular emission lines (e.g., $[\text{O} \text{III}]/\lambda 3727$/[O III]λ5007) is regarded as the most reliable approach for the metallicity estimation. However, it is not suitable for a spectrum without such an auroral line detection. To estimate the metallicity with these spectra, O3N2 and N2 diagnoses are calibrated by empirical fitting to the electronic temperature metallicity with emission-
line ratios (Pettini & Pagel 2004), while the N2O2 and N2S2 diagnoses are based on the photoionization models for H II regions (Kewley & Dopita 2002; Dopita et al. 2016). Because of the different approaches in the calibration, a large discrepancy is found between the metallicities derived by different calibrators (Morisset et al. 2016). For example, the O3N2 and N2 diagnoses cannot accurately reproduce the supersolar metallicity. The N2O2 and N2S2 calibrators are model-dependent and thus provide some uncertainty. As we investigate in Figure 4, we can see the strong correlation between the ratio of O32 and the local metallicity. This is known because the ionization parameter is sensitive to oxygen abundance. Determination of metallicity using strong emission lines may bias the ionization parameter, and it is necessary to find the accurate oxygen abundance. Due to this, there is a correlation between metallicity and local SFR surface density. Our result is partly consistent with the reported negative correlation between metallicity and SFR (Mannucci et al. 2010; Andrews & Martini 2013), and the positive correlation in Kashino et al. (2016) at the higher mass bins.

5. Summary

This work aims to explore the dependence of the local \( \Sigma_{\text{FMR}} \) relation using the 740,000 spaxels from the MaNGA survey. We try to demonstrate whether or not the local \( \Sigma_{\text{FMR}} \) exists in FMR. We summarize our findings as follows.

1. We present the local \( \Sigma_{\text{FMR}} \) relation using metallicity calibrators of O3N2, N2, N2O2, and N2S2. We find a strong correlation with local \( \Sigma_{\text{FMR}} \) using O3N2 and N2, but the trend is not obvious with N2O2 and N2S2. This means that the existence of FMR probably depends on the metallicity calibrators.

2. We find a mixed relation of \( \Sigma_{\text{FMR}} \sim Z \) (anticorrelation/positive correlation) at lower/higher stellar mass bins according to metallicity derivation. In particular, when using the metallicity from N2O2 and N2S2 indexes, the existence of FMR vanishes at higher masses, while the correlation is retrieved using a similar metallicity scale as Mannucci et al. (2010).

3. We confirm the dependence of the ratio of O32 on metallicity, which means that a higher ionization parameter is found at lower metallicity, and the lower ionization parameter tends to be found at higher metallicity.

4. We provide the FMR after exclusion of low stellar mass, which is a projection of local stellar mass surface density, metallicity, and SFR surface density, and find that the scatters are reduced when using N2 and O3N2 indexes, compared to the \( \Sigma_{\text{FMR}} \) relation.

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