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Abstract


by

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We measure electron density, electron temperature, and oxygen abundance of 35 O3EW\(^1\) galaxies and 37 CLASSY\(^2\) galaxies, which are the closest local analogs of high-redshift galaxies in the epoch of reionization that the James Webb Space Telescope will soon discover and study. These galaxies are rare in the local universe and are selected from an all-sky survey. For galaxies with observable [OIII] $\lambda$4363 line, we can determine their metallicities\(^3\) using the direct method. However, for galaxies with relatively high metallicity ($12 + \log(O/H) \gtrsim 8.7$), the direct method does not work anymore. Hence, we apply the strong-line method proposed by Pilyugin & Thuan (2005)\(^1\) to quantify their metallicities.

Due to the ionization structures in galaxies, our measurements could only estimate these three physical quantities in the starburst region of each galaxy. Therefore, we utilize the existing data cubes obtained from KCWI Integral field spectroscopy to map out them spatially. In this project, we focus on four local galaxies, J0248-0817, J0823+0313, J1044+0353, and J1238+1009, that have high emission-line equivalent width ($W(\lambda5007) > 1000\text{Å}$) and low mass ($\log M_*/M_\odot < 8.0$).

By introducing the Weighted Voronoi Tessellation (WVT) proposed by Diehl and Statler \(^2\), we can group pixels with low signal-to-noise together to obtain the high-

\(^1\)Galaxies selected from the NASA-Sloan Atlas with $W(\lambda5007) > 1000\text{Å}$
\(^2\)COS Legacy Archive Spectroscopic SurveY
\(^3\)Metallicity in Interstellar Medium (ISM) studies is often denoted as $12 + \log(O/H)$
quality metallicity map and distance map. Based on these two mappings, we find a strong trend of steepening metallicity gradient with the weighted distance ranging from 0 to 1.0 kpc. In comparison to the magnitude of internal extinction \( A_V \), we also find that the oxygen abundance is more dependent on the electron density.

After extracting the stellar mass and star formation rate (SFR) from the MPA-JHU Catalog\(^4\), we can show the mass-metallicity relation (MZR), color-coded by SFR, for our CLASSY samples. We can also derive the star formation rates for our O3EW examples using the UV magnitudes obtained from the NASA-Sloan Atlas (NSA)\(^5\). These values are crucial for us to plot the mass-metallicity-SFR relation for our O3EW samples. Both samples cannot be explained well by the MZR proposed by previous studies. The inconsistency in the methods to quantify stellar mass and oxygen abundance between each study can be one possible reason. Another major factor is the limited sample size of our samples, which are not comparable to the sample sizes of previous studies.

\(^4\)https://www.sdss.org/dr12/spectro/galaxy_mpajhu/
\(^5\)https://www.sdss.org/dr13/manga/manga-target-selection/nsa/
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Chapter 1

Introduction

In galaxies, metals can only be produced by nucleosynthesis process in stars before their ejections into the interstellar medium. It is certain that determination of chemical abundances is critical to understand galaxy formation and evolution. As the most abundant metal in the interstellar medium, oxygen displays strong emission lines in the optical region. Besides its strong emission lines, most of its main ionization stages are detectable. Hence, it is relatively straightforward for researchers to focus on the determination of oxygen abundance to update our understanding of how properties of galaxies, like stellar mass, star formation rate (SFR), and galaxy bolometric luminosity, evolve over time.

One of the most reliable methods in measuring oxygen abundance is based on the temperature-sensitive line ratio of oxygen, such as $\text{[OIII]} \lambda 4959, \lambda 5007/\text{[OIII]} \lambda 4363$ [3]. This method, which relies on collisionally-excited lines (CELs) of oxygen, is often denoted as the direct method. However, this method has certain limitations. Since CELs are normally produced in hot gas, these lines are weighted towards the hottest zones of a galaxy [4]. Therefore, the derived electron temperature is always overestimated if the temperature gradient is large in a particular galaxy. Besides this issue, most metal-rich and high-redshift galaxies, with metallicities $12 + \log(O/H) > 8.7$, often has weak auroral
lines like [OIII] $\lambda$4363, so the direct method is not applicable for them \cite{1,5}. Because of these limitations, other alternative methods should be considered to determine the oxygen abundance more accurately.

Alternative methods for determining the oxygen abundance include theoretical calibration methods, such as Bayesian method proposed by \cite{6}, and strong-line methods like P, N2, or O3N2 methods \cite{1,7}. Nevertheless, the differences among these methods are dramatic. For example, the Bayesian method is based on the combination of stellar population synthesis and photoionization models. Instead of only focusing on oxygen and nitrogen lines, it also includes other lines, such as Sulphur, Argon, and Neon, to give more information on the physical conditions of galaxies. At the same time, these weak lines might add additional noise or biases to the procedure of this method. Therefore, it is crucial for researchers to choose the appropriate models and assumptions they use. As models are continuously improved and upgraded, the significant disagreements between each model should be seriously considered.

With the advancement of integral field spectroscopy (IFS), we can now spatially map the electron density, electron temperature, and metallicity across galaxies. These mappings can help researchers better understand the density, temperature, and ionization structures of these galaxies. The metallicity maps can also unveil the interaction history of galaxies. From the analysis of Anomalously Low-Metallicity (ALM) regions in MaNGA star-forming galaxies, Hwang et al. \cite{8} points out the locations of these ALM regions are closely related to the corresponding interaction stage (mergers, close pairs, and isolated) of each galaxy. For the merger-type galaxies, the ALM regions are typically found around the nucleus of the galaxies. On the contrary, the isolated galaxies are likely to have lower metallicity in the outer regions. Therefore, metallicity maps might indicate the inflows or accreted gas (having lower metallicity) gradually move from the outer regions to the innermost regions across the interaction history \cite{8,9}. 


If we want to understand the metallicity of a galaxy in a more comprehensive way, we are required to understand the complex interplays between cosmological gas inflow, metal production by stars, and gas outflows driven by feedback from the stars or the supermassive black hole (SMBH). The inflow gas is the primary source of star formation, and then the star formation converts inflow gas into stars. From the nucleosynthesis process in stars, metals, gas, and energy are ejected (by the dying stars) from the galaxy into the intergalactic medium (IGM) or the circumgalactic medium (CGM). The ejected metals in the IGM and CGM might be re-accreted by the SMBH and be recycled back to the galaxy to enrich the inflowing gas. These intertwined processes strongly influenced the metallicity, stellar mass, and star formation rate of the galaxies\cite{10, 11}. Therefore, the mass-metallicity relation (MZR) in the local universe is not rigorous enough to explain the whole picture of the relation between these two physical quantities. Instead, a more general relation between stellar mass, gas-phase metallicity, and star formation rate (SFR) is suggested. Mannuci et al. \cite{12} concludes that the low-mass galaxies \( \log M_\ast \lesssim 10.9 \) with higher SFR show lower metallicity (Figure 1 in their paper). They also illustrate that the shape of the fundamental metallicity relation (FMR) is not dependent on the galaxy sample, the metallicity determination method, and the way SFR are measured. As a result, it is critical for us to consider the impacts of SFR on the relation between metallicity and stellar mass for our CLASSY samples.

As a result, our study serves a three-fold purpose. Using the direct method and the strong-line method proposed by Pilyugin & Thuan (2005)\cite{11}, we can determine the oxygen abundance for 35 O3EW galaxies and 37 CLASSY galaxies. Then, we can utilize the existing data cubes obtained from KCWI Integral field spectroscopy to spatially map out the oxygen abundance for four low-mass and high star-forming galaxies: J0248-0817, J0823+0313, J1044+0353, and J1238+1009. Considering the impacts of SFR, we can finally find out the mass-metallicity-SFR relation for both samples based on the stellar
masses and SFR that are obtained from the MPA-JHU Catalog and the NSA.
Chapter 2

Method

2.1 Line Flux Measurement

2.1.1 Single-Gaussian Model

To do a non-linear least-squares fit of a model to data or for any other optimization problem, the main task is to write an objective function that takes the values of the fitting variables and calculates either a scalar value to be minimized or an array of values that are to be minimized, typically in the least-squares sense. The objective function we use is the combination of a single gaussian function (line profile) plus a linear function (local continuum). We are using the LMFIT\footnote{https://lmfit.github.io/lmfit-py/} package for fitting line profiles, which uses an interactive algorithm based on the Levenberg-Marquardt method. The iterations attempt to improve the fit by varying the parameters along the gradient of improvement in the chi square. This method requires that the initial values for the parameters be close enough that the gradient leads to the correct solution rather than an incorrect local minimum in the $\chi^2$ multi-dimensional space. The definition of $\chi^2$ is shown in equation
Method Chapter 2

(1).

\[
\chi^2 = \sum_i^N \frac{(y_{meas}^i - y_{model}^i)^2}{\sigma_i^2}
\]

(1)

For equation (1), \(\sigma_i\) is the flux error of each pixel calculated from the \textit{ivar} array in the \textit{fits} file of each spectrum.

Based on the Levenberg-Marquardt method, two examples (\(H_\beta\) and [OIII] \(\lambda 4959, 5007\) lines) of fitting results from the galaxy J0248-0817 are shown below.

![Figure 2.1: Fitting of \(H_\beta\) line profile of J0248-0817 galaxy. Left panel: the red dash line is the single-gaussian model, and the black solid line is the real line profile. Right panel: the red dash line is the horizontal line when residual is zero, and the black solid line is the residual of this fitting of \(H_\beta\) profile.](image)

According to the Figure 2.1 and 2.2, we can know that the fitting of \(H_\beta\) line profile is better (with smaller \(\chi^2\) value). The possible reason is that the line profile of strong emission line like [OIII] is not symmetric. Sometimes, it has obvious blue or red wing, which represents the existence of outflowing or inflowing gas. Therefore, we should better use a double-gaussian model, a broad one and a narrow one, to fit an asymmetric profile. However, the difficulty of using a double-gaussian model is it is hard for us to find the initial guesses of parameters of these two gaussian functions. Since the least-square fitting is
Figure 2.2: Fittings of [OIII] λ4959, 5007 line profiles of J0248-0817 galaxy. **Left panel:** the red dash line is the single-gaussian model, and the black solid line is the real line profile. **Right panel:** the red dash line is the horizontal line when residual is zero, and the black solid line is the residual of this fitting of [OIII] λ4959, 5007 doublet.

Based on Levenburg-Marquardt method, which is sensitive to initial guesses, if our initial guesses are inaccurate, it will find a bad local minimum in the multi-dimensional $\chi^2$ space.

After fitting our single-gaussian model to the line profile, we can use the best value of each fitting parameter to calculate the line flux as follow:

\[
\text{Line Flux} = A \sqrt{\frac{2}{\pi \sigma}} \int_{-\infty}^{\infty} e^{-\frac{(\lambda - \lambda_{\text{cen}})^2}{2\sigma^2}} d\lambda
\]

\[
\text{Line Flux} = \frac{A}{\sqrt{2\pi \sigma}} \sqrt{\pi 2\sigma^2} = A
\]

In the Python program, we assume the constant factor “a” is equal to $\frac{A}{\sqrt{2\pi \sigma}}$, which means the line flux is

\[
\text{Line Flux} = A = \sqrt{2\pi} \cdot \sigma \cdot a
\]
2.1.2 Extinction

To transform from the observed line flux to the internal line flux, we are required to consider the effects of scattering and absorption that result in the reduction in the amount of light from a distant source. This phenomenon is also known as extinction. Extinction can be categorized into two main types: internal extinction and galactic extinction. Galactic extinction represents the effects of Milky Way dust on the line flux, and internal extinction represents the influences of internal dust on the line fluxes. In this project, we are using the derived curve from Fitzpatrick (1999) [13] to correct for the extinction from the Milky Way dust. For internal extinction, we use the SMC extinction curve based on the paper Gordan et al. (2003) [14].

![Extinction Curve](image)

**Figure 2.3:** The extinction curves used for internal and galactic reddening corrections. The solid line is the extinction curve for the Milky Way. The dash line is the extinction curve for SMC.

For the galactic extinction curve $k(\lambda) = \frac{A(\lambda)}{E(B-V)}$ ($A(\lambda)$ is the magnitude of extinction), it is interpolated from Table 3 of Fitzpatrick (1999) [13]. For the color excess $E(B-V)$, we are using the mean $E(B-V)$ value from the website NASA/IPAC Infrared Science...
Then, the correction factor for galactic extinction is the following:

\[
\frac{I_o(\lambda)}{I'(\lambda)} = 10^{0.4A(\lambda)}
\] (4)

The magnitudes of extinction \(A(\lambda)\) is based on the relation \(A(\lambda) = g(\lambda)A_V\), where the values of \(g(\lambda)\) are interpolated from Table 4 (SMC Bar) of Gordan et al. (2003) \[14\]. \(A_V\) then is determined from the following equation:

\[
A_V = \frac{2.5}{g(H_\alpha) - g(H_\beta)} \log \left( \frac{I_{\alpha,o}/I_{\beta,o}}{I_\alpha/I_\beta} \right)
\]

\[
g(H_\alpha) = 0.792; \quad g(H_\beta) = 0.792
\] (5)

Here, \(I_{\alpha,o}/I_{\beta,o}\) is the Case B intrinsic ratio of \(H_\alpha\) and \(H_\beta\) lines at 15,000K from Table 4.2 of Osterbrock (2006) \[3\]. For most of our galaxies, we are using the ratio of \(H_\alpha\) and \(H_\beta\) lines to determine \(A_V\). However, if spectra of some galaxies mess up around \(H_\alpha\) and \(H_\beta\) lines, the ratios of \(H_\beta\) and \(H_\gamma\) lines as well as \(H_\gamma\) and \(H_\delta\) lines are utilized in those cases. In addition, if there is any stellar absorption, which appears as a broad trough under the emission line, in the spectra, we should consider its influence on the ratios of these HI recombination lines. Table 2.1 summarizes the galaxies (mess up around \(H_\alpha\) or \(H_\beta\) line) using the line ratio \(H_\beta/H_\gamma\) or \(H_\gamma/H_\Delta\) (or both) to measure their Balmer Decrements.

Besides J0248-0817, most galaxies don’t have obvious stellar absorption trough, so their line ratios are not corrected for the effects of stellar absorption. However, we have considered the influences of stellar absorption trough on Balmer Decrements of the following four galaxies, J0248-0817, J0823+0313, J1044+0353, and J1238+1009, that are the main targets of this project. For the latter three galaxies, we have utilized all

\[\text{https://irsa.ipac.caltech.edu/applications/DUST/}\]

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Table 2.1: Galaxies use the line ratio $H_\beta/H_\gamma$ or $H_\gamma/H_\Delta$ (or both) to measure their Balmer Decrements. The check-mark and cross-mark symbol indicate whether they use this ratio or not to determine Balmer Decrement.

possible Balmer line ratios, including $H_\alpha/H_\beta$, $H_\beta/H_\gamma$, and $H_\gamma/H_\Delta$ to determine the Balmer Decrement.

We can use a similar approach (as that of galactic extinction) to determine the correction factor of internal extinction using quation (4), but with different magnitudes of extinction $A(\lambda)$.

### 2.1.3 Error Estimation

Motivated by the idea of Monte-Carlo Simulation, the uncertainty on the flux emission line is based on the 68th percentile width of the distribution of measured fluxes obtained by perturbing the spectrum according to the error spectrum and refitting the emission line 1000 times.

### 2.2 Electron Density Diagnostics

#### 2.2.1 Electron Density Measurement

[SII] $\lambda\lambda$6717, 31, and [OII] $\lambda\lambda$3726, 29 are the best examples to measure electron densities in the optical region. Generally, $n_e$ can be determined by comparing the inten-
sities of two lines of the same ion, emitted by two different levels with nearly the same excitation energy. Hence, their relative excitation rates to the two levels depend entirely on the ratio of collision strengths. If the two energy levels have distinct transition probabilities or collisional deexcitation rates, the ratio of intensities, [OII] $I_{\lambda 3729}/I_{\lambda 3726}$, [SII] $I_{\lambda 6716}/I_{\lambda 6731}$, of the lines they emit will depend on $n_e$. To measure the electron density, a multi-level model, including collisional and radiative transitions, is utilized in our project. The Python package *PyNeb* we use is following a similar multi-level model described in Osterbrock (Equation 3.27) \[3\]. This equation is shown in equation (6). For equation (6), the indices $i, j = 1,\ldots,n$; $q_{ij}$ or $q_{ji}$ represents the collisional coefficients between the energy levels $i$ and $j$; $A_{ij}$ or $A_{ji}$ represents the transition probability between the energy levels $i$ and $j$.

In *PyNeb*, if the electron temperature is given, we are able to plug its value into the method *getTemDen* to measure the electron density of specific atoms. Because [OII] $\lambda\lambda 3726$, 29 lines are not detectable in the Sloan’s spectrum of some low-redshift galaxies,
we choose to use [SII] $\lambda\lambda 6716, 31$ lines and its ratio $I_{\lambda 6716}/I_{\lambda 6731}$ to determine $n_e$ for all of our galaxies.

$$\sum_{j \neq i} n_j n_e q_{ji} + \sum_{j > i} n_j A_{ji} = \sum_{j \neq i} n_i n_e q_{ij} + \sum_{j < i} n_i A_{ij}$$

(6)

For some of our extreme local galaxies, if the line ratio of [SII] is larger than 1.50, which exceeds the theoretical limit set by PyNeb, we need to set the lower density limit for these galaxies as $10\ \text{cm}^{-3}$ to avoid the NaN values returned by the method getTemDen.

### 2.2.2 Electron Density Statistical Errors

In an attempt to quantify the statistical error of our measurements of electron density $n_e$, we use a Monte-Carlo method by perturbing each individual line flux according to its uncertainty, recalculating the emission line ratio $I_{\lambda 6716}/I_{\lambda 6731}$, plugging into PyNeb method getTemDen, and repeating the previous steps for 1,000 times to build up a distribution of perturbed electron density. Then, the 68 percentile width of the distribution accounts for the statistical error of electron density.

### 2.2.3 Electron Density Systematic Errors

For the systematic error of electron density $n_e$, we first measure $n_e$ at three electron temperatures 10,000K, 15,000K, and 20,000K. Here, we assume that the minimum and maximum values of our O3EW or CLASSY samples are 10,000, and 20,000K. We also assume $n_e$ at 15,000K is the best value we have and we can then find the differences among these three values. Basically, if $n_e(20,000K) > n_e(15,000K) > n_e(10,000K)$, then the upper systematic error is $n_e(20,000K) - n_e(15,000K)$ and the lower systematic
error is $n_e(15,000K) - n_e(10,000K)$, and vice versa if $n_e(20,000K) < n_e(15,000K) < n_e(10,000K)$.

If we also include the influence of the internal extinction on quantifying the systematic error of $n_e$, we find it only slightly affects the final result. Therefore, we don’t consider the systematic error of the internal extinction in this case.

### 2.3 Electron Temperature Diagnostics

#### 2.3.1 Electron Temperature Measurement

Electron temperature can be predicted by the relative intensities of nebular emission lines. [OIII] $\lambda\lambda 4363, 4959, 5007$ is one of the best examples, which has two upper energy levels with considerably distinct excitation energies occurring in the observable wavelength region. In this case, [OIII] $\lambda 4363$ occurs from the upper level $^1S$, while [OIII] $\lambda\lambda 4959, 5007$ occur from the upper level $^1D$. Since the relative excitation rate to the $^1S$ and $^1D$ levels depend strongly on temperature, the ratio of their emission lines, can be used to measure electron temperature. In general, any electron temperature diagnostics is also a electron density diagnostics, but the impact of electron temperature is specifically dominant for the [OIII] ion. Similar to our measurements of $n_e$, we use the method `getTemDen` of the Python package `PyNeb`. In order to measure the electron temperature $T_\text{e}$, the $n_e$ value we plug into the method `getTemDen` is derived first using the procedure described in Section 2.2.1. Then, we use [OIII] $\lambda\lambda 4363, 4959, 5007$ lines and their ratio $(I_{\lambda 4959} + I_{\lambda 5007})/I_{\lambda 4363}$ to determine $T([\text{OIII}])$ for all galaxy samples we have.
2.3.2 Electron Temperature Statistical Errors

In an attempt to quantify the statistical error of our measurements of electron temperature $T_e$, we also use a Monte-Carlo method by perturbing each individual line flux according to its uncertainty, recalculating the emission line ratio $(I_{\lambda4959} + I_{\lambda5007})/I_{\lambda4363}$, plugging into $PyNeb$ method `getTemDen`, and repeating the previous steps for 1,000 times to build up a distribution of perturbed electron temperature. Then, the 68 percentile width of the distribution accounts for the statistical error of electron temperature.

2.3.3 Electron Temperature Systematic Errors

As illustrated in Section 2.2, since the influence of the systematic error of $A_V$ (internal extinction) on the final result is relatively small, we don’t consider the systematic error of $A_V$. In other words, it is not necessary for us to propagate this error to get the systematic error of $T_e$.
2.4 Oxygen Abundance

2.4.1 Ionization Zone Model

In the study of ISM, the simplified theory of two-ionization-zone model is often assumed: \( t_h \) represents the temperature in the high-excitation zone and corresponds to \( t([\text{OIII}]) \); \( t_l \) represents the temperature in the low-excitation zone and corresponds to \( t([\text{OII}]), t([\text{SII}]), t([\text{NII}]) \)\(^{[15]} \). Usually, the calibrated relation between \( t([\text{OIII}]) \) and \( t([\text{OII}]) \) is derived from photo-ionization model. In this project, we calculate \( t([\text{OII}]) \) based on its density-dependent calibrated relation with \( t([\text{OIII}]) \) given in Hagele et al. (2006)\(^{[16]} \).

\[
t([\text{OII}]) = \frac{1.2 + 0.002 \cdot n_e + \frac{4.2}{n_e}}{t([\text{OIII}])^{-1} + 0.08 + 0.003 \cdot n_e + \frac{2.5}{n_e}}
\]  \( (7) \)

For equation (7), \( t([\text{OII}]) \) and \( t([\text{OIII}]) \) are in units of \( 10^4 K \). Based on the values of \( t([\text{OII}]) \) and \( t([\text{OIII}]) \), we then utilize equations (38), (39), and (40) in Perez-Montero (2017)\(^{[17]} \) to determine the ionic abundances \( \text{O}^+/\text{H}^+ \) and \( \text{O}^{2+}/\text{H}^+ \).

\[
12 + \log\left(\frac{\text{O}^+}{\text{H}^+}\right) = \log\left(\frac{I(3726) + I(3729)}{I(H\beta)}\right) + 5.887 + 1.641 \cdot \frac{1}{t_l} - 0.543 \cdot \log(t_l) + 0.000114 \cdot n_e
\]  \( (8) \)
12 + \log\left(\frac{O^+}{H^+}\right) = \log\left(\frac{I(7320) + I(7330)}{I(H\beta)}\right) \\
+ 7.21 + \frac{2.511}{t_l} - 0.422 \cdot \log(t_l) + \\
10^{-3.40} \cdot n_e(1 - 10^{-3.44} \cdot n_e) \quad (9)

12 + \log\left(\frac{O^{2+}}{H^+}\right) = \log\left(\frac{I(4959) + I(5007)}{I(H\beta)}\right) + 6.1868 \\
+ \frac{1.2491}{t_h} - 0.5816 \cdot \log(t_h) \quad (10)

These calibrated relations are obtained from fittings to *PyNeb* using the collision strengths from Pradhan et al. (2006) [18] and Tayal (2007) [19], which are the default collision strengths of *PyNeb* v0.9.3. However, *PyNeb* has been updated to v1.1.14 and the default collision strengths for O$^+$ is updated to Kisielius et al. (2009) [20]. Therefore, it is necessary for us to derive the new calibrated relations between the ionic abundance of O$^+$ and specific line ratios (similarly for the ionic abundance of O$^{2+}$ and its specific line ratio). The adopted atomic data for is listed in Table 2.2.

Table 2.2: Atomic data used with the *PyNeb* v1.1.14 to calculate ionic abundances, electron density, and electron temperature.

<table>
<thead>
<tr>
<th>Ion</th>
<th>Transition Probabilities</th>
<th>Collision Strengths</th>
</tr>
</thead>
</table>

The first step is to determine the number of variables and their corresponding ranges. Base on the *PyNeb* method *getIonAbundance*, there are three main inputs, which are the
follows:

- Intensity of O$^+$ or O$^{2+}$ doublets respect to the intensity of H$_\beta$ line

1. \( (I_{\lambda3726} + I_{\lambda3729})/I_{H\beta} \) (From 0.10 to 5.1)
2. \( (I_{\lambda7320} and I_{\lambda7330})/I_{H\beta} \) (From 0.001 to 0.100)
3. \( (I_{\lambda4959} and I_{\lambda5007})/I_{H\beta} \) (From 0.8 to 10.9)

- \( t([\text{OII}]) or t([\text{OIII}]) \) (From 0.7 to 2.5 in the units of \(10^4K\))

- Electron Density \( n_e \) (From 10 to 1,000 in the units of \(\text{cm}^{-3}\))

We make the assumption that the temperature of HI is the same as that of the specified ion. For example, when I calculate the ionic abundance of O$^+$, I assume T(HI) is equal to T([OII]). Similarly, when I calculate O$^{2+}$ ionic abundance, I assume T(HI) is equal to T([OIII]). Then, an appropriate step/width for each variable range is chosen to create an input matrix. Each entry of this matrix will be plugged into the PyNeb method `getIonAbundance` to obtain a resulting matrix. The new derived calibrated relations are based on the assumption that they have the exactly same forms as equations (8), (9), and (10). Therefore, if we use the Python method `scipy.optimize.minimize` to minimize the differences between the output values from PyNeb and the values from the new derived calibrations, we can obtain the best-fit value for each coefficient in the new derived calibrations. The initial guess for each coefficient is based on the value from equations (8), (9), or (10). The new calibration relations are shown below:

\[
12 + \log\left(\frac{O^+}{H^+}\right) = \log\left(\frac{I(3726) + I(3729)}{I(H\beta)}\right) \\
+ 5.901 + \frac{1.652}{t_i} - 0.541 \cdot \log(t_i) \\
+ 0.0000799 \cdot n_e
\] (11)
The precision of these three calibrations are better than 0.01 dex for all galaxies, so these calibrations will be utilized to calculate the oxygen abundance and its corresponding error for each galaxy. If \([\text{OIII}]\, \lambda\, 3726\) and \(\lambda\, 3729\) lines are not observable, then equation (12) is applied to determine the ionic abundance of O\(^{+}\). If they are observable, then equation (11) is applied. Moreover, the assumption that \(O/H= (O^{+} + O^{2+})/H^{+}\) is adopted to determine the total oxygen abundance. This assumption is not valid if the HeII \(4586\, \AA\) line is seen in some highly-ionized galaxies. In other words, it can be considered that part of the O is under the form O\(^{3+}\), so we might underestimate the total oxygen abundance for these galaxies like J0248-0817.

However, the direct method doesn’t always work anymore for high-metallicity galaxies with low electron temperature. The reason is that this method is strongly dependent on the temperature-sensitive auroral line [OIII] \(\lambda\, 4363\), which is not observable for these galaxies. As a result, we should use alternative methods to determine the oxy-
gen abundance for these galaxies. The method we choose is the strong-Line method “R23-P” proposed by Pilyugin & Thuan (2005) [1]. For simplicity, we use the following notations throughout the paper: \( R_2 = \frac{I_{\text{[OII]}}}{I_{\text{H}\beta}} \), \( R_3 = \frac{I_{\text{[OII]}}}{I_{\text{H}\beta}} \), \( R = \frac{I_{\text{[OII]}}}{I_{\text{H}\beta}} \), \( R_{23} = R_2 + R_3 \), \( X_{23} = \log R_{23} \), \( N2 = \log(I_{\text{[NII]}}) \), and the excitation parameter \( P \) is defined as \( P = \frac{R_3}{(R_2 + R_3)} \).

The basic idea is simple: the relation between the strong oxygen line ratio, \( R_{23} \), and the oxygen abundance derived from the direct method is calibrated. And then, this calibrated relation is used to determine the oxygen abundance of galaxies for which the auroral line \([\text{OIII}]\lambda4363\) is not observed.

In their paper, Pilyugin & Thuan (2005) [1] suggest the relation between \( R_{23} \) and \( P \) can be written as a polynomial expression:

\[ k_0R_3 = k_1P + k_2P^2 + k_3P^3 \quad (14) \]

Due to the metallicity dependence of \( k_j \), we can assume a linear relationship between \( k_j \) and \( Z \) as follow:

\[ k_j = a_j + b_jZ \quad (15) \]

Then, they derive the upper branch and lower branch calibrations based on their samples as follow:

**For upper branch:**

\[ Z = \frac{R_{23} + 726.1 + 842.2P + 337.5P^2}{85.96 + 82.76P + 43.98P^2 + 1.793R_{23}} \quad (16) \]
For lower branch:

\[ Z = \frac{R_{23} + 106.4 + 106.8P - 3.40P^2}{17.72 + 6.60P + 6.95P^2 - 0.302R_{23}} \]  \hspace{1cm} (17)

Because the calibrated relation of the “R23-P” method is double-valued, we should have an initial understanding about which branch the galaxies lie in the \( R_{23} \) vs. \( 12 + \log(O/H) \) plot. For example, if the oxygen abundance derived from the direct method is less than 8.0, then we can assume this galaxy belongs to the lower branch. Contrarily, if the oxygen abundance derived from the direct method is larger than 8.2, then we can assume this galaxy belongs to the upper branch. However, if the oxygen abundance of a galaxy lies in the transition zone, \( 8.0 < 12 + \log(O/H) < 8.2 \), we should apply the monotonous N2 indicator. The N2 indicator is another possible way for us to break the degeneracy.

Here, four different calibrated relations between N2 and oxygen abundance are included (Yin et al. 2007; Marino et al. 2013; Pettini & Pagel 2004; Perez-Montero & Contini 2009) [7, 28, 29, 30]. Based on each calibration, the corresponding transition zones for N2 indicators are the follows:

1. **Yin et al. 2007**: \(-1.511 < N2 < -1.272\)

2. **Marino et al. 2013**: \(-1.608 < N2 < -1.175\)

3. **Pettini & Pagel 2004**: \(-1.579 < N2 < -1.228\)

4. **Perez-Montero & Contini 2009**: \(-1.354 < N2 < -1.101\)

In our galaxy samples, the following galaxies lie in the transition zone for both criteria that determine whether they belong to the upper or lower branch:

1. **J1025+3622**: its metallicity (the direct method) is around 8.11 and its N2 value is around -1.26. Because these two values indicate it “leans toward” the upper branch.
of the R23-P method, the upper branch value is preferred in this case.

2. J0926+4427: its metallicity (the direct method) is around 8.03 and its N2 value is around -1.43. Because these two values indicate it “leans toward” the lower branch of the R23-P method, the lower branch value is preferred in this case.

![Figure 2.6: Oxygen abundance versus the N2 indicator. O3EW Samples are shown as the solid blue points on the left panel. CLASSY Samples are shown as the solid blue points on the right panel. Pettini & Pagel 2004 (PP04) is plotted as green-dash line. Marino et al. 2013 is shown with black-dotted line. Yin et al. 2007 is plotted as red-solid line. Perez-Montero & Contini 2009 (PMC09) is shown with blue dot-dashed line.](image)

### 2.4.2 Oxygen Abundance Error Propagation

To determine the error of oxygen abundance, we should first measure the errors of specific line ratios (respect to $H_\beta$ line), $n_e$, $T(\text{[OII]})$, and $T(\text{[OIII]})$. For the statistical errors of the line ratios like $(I_{\lambda3726} + I_{\lambda3729})/I_{H_\beta}$, $(I_{\lambda7320} + I_{\lambda7330})/I_{H_\beta}$, and $(I_{\lambda4959} + I_{\lambda5007})/I_{H_\beta}$, we can determine their values based on the Monte-Carlo Simulation described in the previous sections. Moreover, from the errors (statistical and systematic errors) of $n_e$ and $T_e$, which are determined in Section 2.2 and Section 2.3, we can then propagate...
their errors to determine the errors of ionic abundances \( \text{O}^{+}/\text{H}^{+} \) and \( \text{O}^{2+}/\text{H}^{+} \) and the error of oxygen abundance in terms of \( 12 + \log(\text{O/H}) \).

### 2.5 Adaptive Binning

Based on the procedure illustrated above, the oxygen abundance of each star-forming galaxy could be easily determined using the direct method. However, this measurement only represents the metallicity from certain region of the galaxy (starburst region for SDSS spectra). In an attempt to map out the oxygen abundance throughout the whole galaxy, the data cube obtained from the Keck Cosmic Web Imager (KCWI) Integral Field Spectrograph is extremely useful for this purpose. These data cubes are three-dimensional images in which each image pixel contains all spectral information. Nevertheless, the low signal-to-noise ratio \( (S/N)_i \) of each pixel might jeopardize the fidelity of our measurements. To minimize the effect of this, we can locally group these pixels together and increase \( S/N \) of each group. This scheme is often called as binning.

If each pixel has a signal \( S_k \) and the associated noise is \( \sigma_k \), then the computed \( S/N \) of a bin \( V_i \) is

\[
(S/N)_i = \frac{\sum_{k \in V_i} S_k}{\sqrt{\sum_{k \in V_i} \sigma_k^2}}
\]  

(18)

In addition, it is not necessary to apply the binning scheme to each pixel, because some of them have already meet the minimum \( S/N \) we want. Therefore, we require a method to bin the image that has a variable-size bin to adapt to different values of \( S/N \), which is adaptive binning. This leads to the question: How can we select appropriate minimum \( S/N \) for a specific image? To answer this question, we normally need to determine the weakest emission line from the line profiles we intend to measure. For example,
if we want to measure the oxygen abundance of a galaxy using the direct method, we need to first determine its electron temperature by measuring the line fluxes of [OIII] λλ4363, 4959, 5007. In this case, the weakest emission line is [OIII] λ4363.

After selecting the target S/N, an appropriate adaptive binning algorithm should be chose. In this project, we are using a weighted Voronoi tesselation (WVT) method described by Diehl & Statler 2006 (DS06 hereafter) [2]. First, an initial WVT is generated for the 2D image extracted from the 3D data cube using the Bin-Accretion algorithm outlined in Cappellari & Copin 2003 (CC03 hereafter) [31]. Basically, we need to start from the pixel with the highest S/N and we need to accrete more pixels around this pixel until the S/N reaches a target S/N, (S/N)_T, or violates the topological and morphological criteria defined in CC03. Then, we need to calculate the weighted centroid of all previously assigned pixels to find the closest pixel to start the next bin. After assigning all the pixels to the corresponding bins, we are able to find the bins that don’t reach the minimum S/N and reassign to the closest good bin. From the Bin-Accretion algorithm, we can then calculate the (S/N)_i, the area A_i, and the geometric center z_i for each initial bin. These calculations can determine the scalelength δ_i for each bin (equation 19) and all pixels are reassigned based on the new WVT with z_i and δ_i later.

\[ \delta_i = \sqrt{\frac{A_i (S/N)_T}{q(S/N)_i}} \]

\[ q = \text{dimensionless constant depends weakly on bin shape} \quad (19) \]

The algorithm of WVT described above should be iterated many times until there is no significant change in the value of z_i and δ_i of each bin. As a result, the combination of the Bin-Accretion algorithm and the WVT binning method can provide us with appropriate
bins to analyze later.

This WVT method is built in *Python* by Pierre Thibodeaux from Prof. Crystal Martin’s research group. One of the main outputs of this program is the *assign.fits* file, which assigns a special value for all pixels $S_k$ in the same bin $V_i$. Based on this file, essential Python codes are developed to measure the electron density, electron temperature, and oxygen abundance of each bin in the 2D image.
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3.1 Oxygen Abundance Comparisons

Based on the procedure described in Chapter 2, we can now determine the oxygen abundance of 35 O3EW galaxies and 37 CLASSY galaxies using the direct method \((12 + \log(O/H))\) and compare our measurements to the ones extracted from the MPA-JHU Catalog \((12 + \log(O/H))\) (MJ)).

The significant difference between these two distributions are due to the method that is used by the MPA-JHU researchers. They are using the model outlined by Charlot & Longhetti (2001) [32]. Their model is a combination of the stellar population synthesis model by Bruzual & Charlot (1993) [33] and the photoionization model by Ferland (1998, ver. C90.04) [34]. Basically, it attempts to utilize all available emission lines like [OII], [OIII], H\(_{\beta}\), H\(_{\alpha}\), [SII], and [NII], to obtain the statistical distribution of the metallicity and the 50 percentile of the distribution is used to determine the metallicity for each galaxy (Bayesian-based method). For O3EW samples, both methods agree that most galaxies are metal-poor \((12 + \log(O/H) < 8.0)\). On contrarily, the discrepancy of these two methods is more obvious in CLASSY samples that the difference in median values
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Figure 3.1: Comparison between the direct-$T_e$ based oxygen abundance and the oxygen abundance obtained from the MPA-JHU Catalog. For both panels, blue bars represent the distribution for the direct-$T_e$ based oxygen abundance, and orange bars represent the distribution for the oxygen abundance obtained from the MPA-JHU Catalog. The dash line locates the median value of the direct-$T_e$ based oxygen abundance and the dash-dotted line locates the median value of the oxygen abundance obtained from the MPA-JHU Catalog. The left-hand panel shows O3EW samples and the right-hand panel shows CLASSY samples.

Figure 3.1: Comparison between the direct-$T_e$ based oxygen abundance and the oxygen abundance obtained from the MPA-JHU Catalog. For both panels, blue bars represent the distribution for the direct-$T_e$ based oxygen abundance, and orange bars represent the distribution for the oxygen abundance obtained from the MPA-JHU Catalog. The dash line locates the median value of the direct-$T_e$ based oxygen abundance and the dash-dotted line locates the median value of the oxygen abundance obtained from the MPA-JHU Catalog. The left-hand panel shows O3EW samples and the right-hand panel shows CLASSY samples.

of these two oxygen abundance distributions is larger than 0.40. Figure 3.2 can better explain the differences of oxygen abundance derived from these two distinct methods. Even though the differences are smaller than 0.15 for most O3EW samples, most of the Bayesian-based oxygen abundances are 0.2-0.8 dex larger than the direct ones in CLASSY samples. This phenomenon can be possibly explained by the concept of ionization zones. For O3EW samples, if these galaxies are highly ionized, then the temperature gradients of them are relatively small. In other words, the high-ionization zone might occupy most of the regions in the galaxy, so our measurements of $T[OIII]$ can roughly represent the temperature throughout the whole galaxies. Therefore, the oxygen abundance obtained from the SDSS spectra (covers the starburst region) should match with the ones derived from the theoretical model. In comparison, if the galaxies are not highly ionized, then our determinations of $T[OIII]$ in the high-ionization zone cannot represent the temperature throughout the whole galaxies, because the temperature gradients for these galaxies are
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Figure 3.2: The direct-\( T_e \) based oxygen abundance versus the \( \Delta \log(O/H) \) (MJ). The \( \Delta \log(O/H) \) (MJ) is defined as the difference of the direct-\( T_e \) based oxygen abundance and the ones obtained from the MPA-JHU Catalog, which is \( \log(O/H)_{T_e} - \log(O/H) \) (MJ). For both panels, the red-dash line represents \( \Delta \log(O/H) \) (MJ) = \( \pm 0.15 \). The left-hand panel shows the O3EW samples and the right-hand panel shows CLASSY samples.

relatively high. Owing to this fact, the average temperature of CLASSY samples should be much lower than \( T[OIII] \), a situation that leads to a higher oxygen abundance (if we assume the theoretical model can accurately estimate the ionization zones for those galaxies). More discussions about the advantages and caveats of these two methods are illustrated in the next chapter.

For galaxies without observable \([OIII] \lambda4363\) line, we need to apply an appropriate strong-line method to determine the metallicity for them. Based on the fact that the relationship between the strong-line ratios and the metallicity is not one-dimensional (which might causes systematic errors), we choose to use the strong-line method outlined by Pilugin & Thuan in 2005 [1]. The figure below indicates that the difference between this strong-line method and the direct method is acceptable (-0.1 < \( \Delta \log(O/H) \) (P) < 0.1 for most galaxies), so we can use this method to determine the rest of galaxies without observable \([OIII] \lambda4363\) line. It is worth noting here that Figure 3.4 shows the excitation parameter \( P \) for most O3EW samples are around 0.9. On the contrary, the values of \( P \) for CLASSY samples, ranging from 0.3 to 0.9, are more diverse. Because the ionization
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Figure 3.3: $\Delta \log(O/H) (P)$ versus the metallicity determined from the direct method. $\Delta \log(O/H) (P)$ is defined as $\log(O/H)_{Te} - \log(O/H) (P)$. For both panels, the red-dash lines represent $\Delta \log(O/H) (P) = \pm 0.15$. O3EW Samples are shown as the solid blue points on the left panel. CLASSY Samples are shown as the solid blue points on the right panel.

Parameter $P$ is defined as the ratio between $R_3$ and $R_2$, this figure indicates that O3EW samples are more ionized than CLASSY samples. Therefore, it strongly supports my argument about the discrepancy between the direct-$T_e$ based and the Bayesian-based oxygen abundance.

3.2 Metallicity Gradient

To better predict how oxygen abundance varies with the distance to the center of a galaxy, we need to use the WVT method to increase the S/N of the pixels from the three-dimensional KCWI data cube. The center of the galaxy is defined as the pixel(s) that has the maximum signal value of the [OIII] $\lambda 4363$ line (if more than one pixel has the maximum value, then we define the median pixel as the center of a galaxy). This definition is valid because the pixel that has the maximum [OIII] $\lambda 4363$ emission is often close to the pixel that has the maximum [OIII] $\lambda 4959$ or [OIII] $\lambda 5007$ emission. The [OIII] $\lambda 4363$ auroral line also has a strong dependence on the electron temperature, so only the starburst region with extremely high temperature can produce observable [OIII] $\lambda 4363$ line. In addition, we assign a weight to each bin to calculate its weighted distance.
Figure 3.4: Logarithm of the R23 parameter as a function of the metallicity determined from the R23-P method. O3EW Samples (without [OIII] λ4363 line) are shown as the solid blue points on the left panel. The lower branch of the R23-P calibration is shown on the left panel with the ionization parameter equals to 0.5 (black-solid line), 0.7 (black-dotted line), and 0.9 (black-dash line). CLASSY Samples (without [OIII] λ4363 line) are shown as the solid blue points on the right panel. The upper branch of the R23-P calibration is shown on the right panel with the excitation parameter equals to 0.3 (black dash-dotted line), 0.5 (black-solid line), 0.7 (black-dotted line), and 0.9 (black-dash line).

to the center of a galaxy, and the weight is defined as the total emissions from the [OIII] λ4363 line and the [OIII] λ4959, 5007 doublets. The main reason that we use the signal-weighted distance instead of the “raw” distance is that we use a similar approach to defined the centroid of each bin in the adaptive binning procedure. Therefore, we include the contribution from each strong [OIII] emission line to calculate the weighted distance of each bin to the galaxy nucleus. Based on the oxygen abundance map and the distance map, we can spatially map how oxygen abundance varies throughout the whole galaxy (the oxygen abundance map for each galaxy is included in Appendix B). The figure below shows the metallicity gradients for the galaxies J0248-0817, J0823+0313, J1044+0353, and J1238+1009.

Normally, we expect to find that spiral galaxies have negative metallicity gradients,
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Figure 3.5: The direct-$T_e$ based metallicity gradient. The plot of metallicity gradient is generated from the combination of the oxygen abundance map and the distance map (S/N = 10). For each galaxy, the left-hand panel shows the metallicity gradient that is based on the assumption that (for each data point) the electron density $n_e$ and the extinction $A_V$ are determined from its own bin (log(O/H) (own)). For each galaxy, the right-hand panel shows the metallicity gradient that is based on the assumption that (for each data point) the electron density $n_e$ and the extinction $A_V$ are the values derived from SDSS spectra (log(O/H) (fixed)).
because the outer regions form last (they form inside out) and are metal poor. However, it is not what we find for our star-forming galaxies. According to Figure 3.5, we find a strong positive direct-$T_e$ based metallicity gradient with the weighted distance ranging from 0 to 1 kpc (the starburst region). However, for the distant regions (weighted distance $\gtrsim$ 1.0 kpc), the correlation between the oxygen abundance and the weighted distance is weak. One possible reason is that the oxygen abundances cannot be measured for most of the distant regions. This is mainly due to the failure of electron density or temperature measurement by PyNeb that the measured [OII] or [OIII] line ratio might exceed the theoretical maximum limit or might be less than the theoretical minimum limit set by PyNeb. Therefore, these plots of metallicity gradients cannot show clear trends in these regions. We also need to consider about that the calculated oxygen abundances are strongly dependent upon the determination method used. For example, if we choose to use the empirical strong-line method like $R_{23}$, we might find a completely different metallicity gradient for each galaxy. This fact suggests us to use different methods to determine metallicity gradients and find the reasons behind discrepancies between each calibration in the future. Moreover, the discussion about the location of ALM in the chapter of introduction infers that these star-forming galaxies are possibly at the end stage of interaction, because the inflow of low-metallicity gas might gradually moves from the outer regions to the center of the galaxy.

Another interesting point to mention about Figure 3.6 is the difference between the log(O/H) (own) and log(O/H) (fixed) (the definitions are shown in the caption of Figure 3.5). Even though most data points lie around the black-solid line, this figure indicates that log(O/H) (fixed) is larger than log(O/H) (own) for most bins in the galaxy. This phenomenon can be well explained by Figure 3.7. Based on this figure, the value of $\Delta$log(O/H) is weakly dependent upon the internal extinction $A_V$. Nevertheless, we can
see a strong dependence on the electron density \( n_e \) in the slope of the \( n_e \) versus \( \Delta \log(O/H) \) plot. Owing to this relation, the bin with positive \( \Delta \log(O/H) \) is more likely to have smaller electron density. In addition, we have annotated a outlier with its \( n_e \) and \( A_V \) values in each galaxy in Figure 3.6. For these outliers with negative \( \Delta \log(O/H) \), they often have large electron density, which is consistent with the argument illustrated above.

### 3.3 Mass-Metallicity Relation

In the introduction chapter, the discussion about the general relation between stellar mass, metallicity, and SFR suggests that their relation can be better visualized in a three-dimensional space (more discussions in Mannucci et al. (2012) [12]). In other words, MZR should be a two-dimensional projection of this more fundamental relation between these three physical properties. As illustrated by Mannucci et al. (2012) [12], the metallicity of SDSS galaxies is negatively proportional to its sSFR (Figure 6 in their paper). Therefore, in the Mass-Metallicity plane, we need to color our galaxy samples based on their SFR or specific SFR (sSFR) to find whether this fundamental relation exists in our samples or not.

According to Figure 3.8 and Figure 3.9, we can find that there is a positive correlation between the direct-\( T_e \) based metallicity and the stellar mass. Intuitively, this correlation does make sense, because metals are lost via galactic winds for galaxies with small stellar mass or small potential wells. Most of our samples can be fitted well by the MZR that are derived from Lee et al. (2006) and Berg et al. (2012) [37, 38], but some samples lie above these two MZR in the low stellar mass regime (\( 6 \lesssim \log(M_*/M_\odot) \lesssim 7 \)). The locations of these low-stellar-mass outliers are counter-intuitive. We know that the SDSS aperture, which is 3′′ in diameter, covers the central region (starburst region) of a galaxy that tend to have higher metallicities (Searle (1971)) [40]. However, at the low-stellar-
Figure 3.6: The difference between log(O/H) (own) and log(O/H) (fixed). For each galaxy, the left-hand panel shows how log(O/H) (own) varies with log(O/H) (fixed). The blue-solid points represent the bins for each galaxy. The black-solid line represents the locations that the values of log(O/H) (own) matches with the values of log(O/H) (fixed). For each galaxy, the right-hand panel shows how ∆log(O/H), log(O/H) (fixed) - log(O/H) (own), varies with log(O/H) (fixed). The horizontal red-dash line means ∆log(O/H) equals to 0.
Figure 3.7: Electron density $n_e$ and internal extinction $A_V$ as functions of $\Delta \log(O/H)$. For each galaxy, the left-hand panel shows the electron density $n_e$ as a function of $\Delta \log(O/H)$. The right-hand panel shows the internal extinction $A_V$ as a function of $\Delta \log(O/H)$. For each panel, the blue-triangle points represent the bins with $\Delta \log(O/H)$ larger than 0.1; the green-circle points represent the bins with $\Delta \log(O/H)$ smaller than 0.1.
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(a) O3EW

(b) CLASSY

Figure 3.8: The direct-based Mass-Metallicity relation with the data points color-coded by SFR. In both panels, the black dash-dotted line represents the Tremonti et al. (2004) MZR. The brown-circular points represents the median of the Tremonti et al. (2004) MZR. The filled-between areas show the 68% contour and 95% contour respectively of the Tremonti et al. (2004) MZR. Other colored lines with different styles represent various strong line or direct-based calibrations (Curti et al. (2020); Ma et al. (2016); Andrews & Martini (2013); Lee et al. (2006); Berg et al. (2012); Ly et al. (2016)).
Figure 3.9: The direct-based Mass-Metallicity relation with the data points color-coded by specific SFR (sSFR). In both panels, the black dash-dotted line represents the Tremonti et al. (2004) MZR. The brown-circular points represents the median of the Tremonti et al. (2004) MZR. The filled-between areas show the 68% contour and 95% contour respectively of the Tremonti et al. (2004) MZR. Other colored lines with different styles represent various strong line or direct-based calibrations (Curti et al. (2020); Ma et al. (2016); Andrews & Martini (2013); Lee et al. (2006); Berg et al. (2012); Ly et al. (2016)).
mass end of the MZR, galaxies are supposed to be smaller in size than the ones in the high-stellar-mass end. In other words, the low-stellar-mass end of the MZR should be more compact the high-stellar-mass end. However, it is contrary to what we see in our samples (especially CLASSY samples). The fact that some CLASSY samples are actually giant H II regions in the outer disk of a more massive spiral galaxy might account for this deviation. Nevertheless, more analysis is required to explain the locations of these low-stellar-mass samples.

What’s more, neither sample shows there exists a clear relation between metallicity and SFR or metallicity and sSFR at fixed stellar mass. This result contradicts with what previous studies (Mannucci et al. (2012); Andrews & Martini (2013) [12, 10]) find that higher SFR galaxies always have lower metallicities than lower SFR galaxies at fixed stellar mass. One possible explanation is that the sample size of our CLASSY galaxies is not comparable to the previous two studies that both of them have \( \sim 10^5 \) samples. We also need to consider the inconsistency in the methods to determine stellar mass and oxygen abundance between each study. For example, even though Berg et al. (2012) [37, 38] uses the direct method to determine metallicity for each galaxy, they apply a completely different relation (Stasinska (1990)[41]) between [OII] and [OIII] than the one used in this project. Moreover, because most of our galaxies are low-mass galaxies with high SFR, it means our samples have extremely high sSFR that is outside the scope of the previous studies.
Chapter 4

Discussion: Oxygen Abundance Determination Methods

The debate over the issue about the best oxygen abundance determination method is still active in the astrophysics community. Each method has its own limitations and advantages that every astrophysicist should be constantly aware of the fallibility of their inferences. More importantly, each method, including $T_e$-based and strong-line methods, is probably only applicable in certain family of samples, so the physics behind each method must be seriously scrutinized before any application. Through the Results and Discussions section, the question about the limitations of the direct method can be answered as follows. According to Shi et al. [42] and López-Sánchez et al. [43], both studies agree over the statement that the direct method can provide accurate oxygen abundance values closer to the real ones. However, there are some problems limiting the confidence on the attained results from this direct method. Besides the issue of temperature fluctuation mentioned in the Results and Discussions section, another main problem is about the ionization structure of galaxies. Because the temperature-sensitive auroral line of the $O^+$ ion is too weak to be measured in real spectra, the three-excitation zone model
proposed by Garnett [15] is frequently used to derive the electron temperature in the low-excitation zone. This model, however, is far more simplified than the real internal ionization structure of galaxies. Therefore, the real ionization structure is not adequately described by present models [17]. Last but not least, the co-spatiality of electron density and temperature measurements could also be a problematic issue [5]. Measuring a density in one region does not necessarily represent the density in another. As a result, the estimated electron density might be inappropriate for comparing with the Te-based electron temperature, because the regions where they are emitted are not co-spatial with each other.

Because of the weak auroral lines used in the direct method, many researchers choose to apply strong line methods to determine the oxygen abundance in galaxies. These strong line methods can be summarized into two categories. The first category includes the empirical strong line methods, such as, the R$^{23}$-P method outlined in Pilyugin & Thuan [1], and the O3N2 & N2 methods outlined in Marino et al. [7]. On contrary, the second category includes the theoretical strong line methods like the Bayesian method used in Tremonti et al. [6].

Even though these strong line methods are alternative options for researchers to derive the oxygen abundance, each of them has certain limitations. According to the results from modern statistics, the Te-based oxygen abundance is consistent with those derived from the R$_{23}$-P and O3N2 methods, because the latter two are calibrated by the direct method [10]. López-Sánchez et al. [13] also emphasize this point by plotting out the difference between the oxygen abundance of empirical strong line methods and the model value. It is found that the oxygen abundance estimated using the R$_{23}$-P method is 0.3-0.5 dex lower than those model values. Nevertheless, the oxygen abundance is better reproduced by the R$_{23}$-P method in real galaxies where a direct estimation of the electron temperature existed.
The opinions varied between these two studies for the N2 indicator. While Shi et al. [42] argue the N2 indicator is unreliable, López-Sánchez et al. [43] show the scatter is around 0.2-0.25 dex, which is smaller than that of the P method. The possible reason is relevant to the issue of sample bias. The galaxies (∼6000) selected in Shi et al. [42] covered a wide range of metallicities (7.5 < log(O/H) + 12 < 9.0), but Yin et al. [28] indicate that the N2 method is only applicable for low-metallicity galaxies (12 + log(O/H) < 8.5). Therefore, it is reasonable that Shi et al. [42] conclude the N2 method is not consistent with any other method. On contrary, the sample size of López-Sánchez et al. [43] is not large enough that only 33 theoretical spectra (7.3 < 12 + log(O/H) < 9.4) are generated for analysis. As a result, in comparison to the R_{23}-P method, the relatively small scattering of N2 indicator is probably due to this sample size.

These results show dramatic differences between the Te-based (or calibrated) abundance and the model-based (or calibrated) abundance. If someone favors the model-based
abundance, others might argue that the current photoionization models are not advanced enough to properly reproduce the behavior of CELs in real galaxies. Instead, if someone suppose the Te-based abundance is more accurate, others might consider it is only valid for galaxies without obvious temperature fluctuations. Based on these limitations, the recombination line methods using [OII] $\lambda$4650 doublets are commonly considered as a “gold standard” for comparison to other problematic methods [4]. However, these recombination lines are often too weak to be measured in the optical region ($\sim$ 104-106 times fainter than $H_\beta$) [43]. Hence, the recombination line methods are not quite useful in the oxygen abundance determination of most galaxies unless the telescope ability is largely enhanced in the future.
Chapter 5

Conclusion

We have measured the oxygen abundance of 35 O3EW galaxies and 37 CLASSY galaxies using the direct method and the R_{23}-P method outlined in Pilyugin & Thuan (2005) [1]. In comparison to the Bayesian-based oxygen abundance from the MPA-JHU Catalog, we have found the discrepancy between the direct-T_e based and the Bayesian-based metallicity is much smaller in O3EW samples than that in CLASSY samples. This is due to the fact that O3EW samples are more ionized than CLASSY samples, so the temperature fluctuations in those samples are relatively small. For the galaxies without observable [OIII] λ4363 line, although the values of Δlog(O/H) (P) are acceptable for most galaxies (0.1 < Δlog(O/H) (P) < 0.1), it is better for us to find a more updated strong-line method in the literature and compare the differences between each calibration. Because some highly-ionized galaxies might have observable HeII 4586Å line, we need to find a more accurate ionization correction factor (ICF) to account for the fact that part of the O is under the form of O^{3+}.

From the plots of metallicity gradient, we have found that the metallicity is strongly dependent on the weighted distance in the starburst region in each galaxy (with weighted...
distance $\lesssim 1.0$ kpc). However, for the distant regions, the trend is not clear partly because most metallicity of these regions cannot be measured (not included in the plots of metallicity gradient). In addition, the log(O/H) (own) values are usually smaller than the log(O/H) (fixed) values for each bin, because the bin with positive $\Delta \log(O/H)$ tends to have smaller electron density $n_e$. For the future studies, we need to obtain three-dimensional data cubes with higher S/N or increase the target S/N for each bin, if we want to find how the oxygen abundance varies with the distance in the distant regions.

Last but not least, we have plotted our CLASSY samples over the MZR that are derived from previous studies but found that some samples lie above the existing MZR in the low-stellar-mass end. This finding is contradictory to what we have found in the previous studies that suggest the low-mass-end MZR tend to be compact and have homogeneous metallicities, because the SDSS aperture ($3''$) only covers the starburst region in each galaxy. Due to the limited sample size and the discrepancies between each stellar-mass or oxygen abundance determination method, we haven’t found that the relation between SFR and metallicity at fixed stellar mass is clear enough for our CLASSY samples. As a result, we have to collect more star-forming galaxies in the low-stellar mass end of MZR to complete our analysis about the fundamental relation between stellar mass, metallicity, and SFR.
Appendix A

Oxygen Abundance, $Te$, $ne$ Table

Table A.1: The physical quantities for each CLASSY galaxy. The second column lists the oxygen abundance, in the units of $12 + \log(O/H)$, derived with the direct method. The third column lists the oxygen abundance, in the units of $12 + \log(O/H)$, derived with the strong-line method proposed by Pilyugin & Thuan (2005). The fourth column lists the median estimate of the oxygen abundance, in the units of $12 + \log(O/H)$, extracted from the MPA-JHU Catalog. The fourth column lists the electron temperature obtained from the [OIII] line ratio. The fifth column lists the electron density obtained from the [SII] line ratio.

<table>
<thead>
<tr>
<th>Name</th>
<th>OH (Te)</th>
<th>OH (P)</th>
<th>OH (P50)</th>
<th>$T_e([\text{OIII}])$ [K]</th>
<th>$n_e([\text{SII}])$ [cm$^{-3}$]</th>
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<td>7.68</td>
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<td>7.99</td>
<td>$13100_{-76}^{+60}$</td>
<td>85 ± 20</td>
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<td>$17800_{-1200}^{+1300}$</td>
<td>390 ± 50</td>
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<tr>
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<tr>
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<td>$270_{-50}^{+40}$</td>
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<td>150 ± 20</td>
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<td>7.76</td>
<td>7.84</td>
<td>$16900_{-80}^{+100}$</td>
<td>110 ± 20</td>
</tr>
</tbody>
</table>
Table A.2: The physical quantities for each CLASSY galaxy. The second column lists the oxygen abundance, in the units of \(12 + \log (O/H)\), derived with the direct method. The third column lists the oxygen abundance, in the units of \(12 + \log (O/H)\), derived with the strong-line method proposed by Pilyugin & Thuan (2005). The fourth column lists the median estimate of the oxygen abundance, in the units of \(12 + \log (O/H)\), extracted from the MPA-JHU Catalog. The fourth column lists the electron temperature obtained from the [OIII] line ratio. The fifth column lists the electron density obtained from the [SII] line ratio (Continued).

<table>
<thead>
<tr>
<th>Name</th>
<th>OH (Te)</th>
<th>OH (P)</th>
<th>OH (P50)</th>
<th>(T_e ([\text{OIII}]) [K]</th>
<th>(n_e ([\text{SII}]) [cm(^{-3})]</th>
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<td>8.73</td>
<td>13200(^{+640}_{-630})</td>
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<td>...</td>
<td>190 (\pm 40)</td>
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<td>7.76</td>
<td>15200(^{+590}_{-880})</td>
<td>33 (\pm 30)</td>
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<td>13100(^{+110}_{-110})</td>
<td>70 (\pm 20)</td>
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<td>23100(^{+1300}_{-1700})</td>
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<td>13300(^{+330}_{-330})</td>
<td>100(^{+50}_{-40})</td>
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<td>7.90</td>
<td>14800(^{+120}_{-110})</td>
<td>140(^{+20}_{-30})</td>
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<td>8.69</td>
<td>9770(^{+270}_{-240})</td>
<td>110 (\pm 20)</td>
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<tr>
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<tr>
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<td>13800(^{+70}_{-70})</td>
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<td>8.68</td>
<td>...</td>
<td>150 (\pm 30)</td>
</tr>
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</table>
Table A.3: The physical quantities for each CLASSY galaxy. The second column lists the oxygen abundance, in the units of $12 + \log(O/H)$, derived with the direct method. The third column lists the oxygen abundance, in the units of $12 + \log(O/H)$, derived with the strong-line method proposed by Pilyugin & Thuan (2005). The fourth column lists the median estimate of the oxygen abundance, in the units of $12 + \log(O/H)$, extracted from the MPA-JHU Catalog. The fourth column lists the electron temperature obtained from the [OIII] line ratio. The fifth column lists the electron density obtained from the [SII] line ratio (Continued).

<table>
<thead>
<tr>
<th>Name</th>
<th>OH (Te)</th>
<th>OH (P)</th>
<th>OH (P50)</th>
<th>$T_e$([OIII]) [K]</th>
<th>$n_e$([SII]) [cm$^{-3}$]</th>
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<td>8.06</td>
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<td>140 ± 20</td>
</tr>
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<td>8.76</td>
<td>11200$^{+210}_{-210}$</td>
<td>120 ± 20</td>
</tr>
<tr>
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<td>...</td>
<td>18800$^{+3500}_{-4400}$</td>
<td>500$^{+70}_{-80}$</td>
</tr>
<tr>
<td>J1132+5722</td>
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<td>7.67</td>
<td>19100$^{+610}_{-600}$</td>
<td>210 ± 40</td>
</tr>
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<td>20100$^{+120}_{-200}$</td>
<td>290 ± 50</td>
</tr>
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</table>

Table A.4: The physical quantities for each O3EW galaxy. The second column lists the oxygen abundance, in the units of $12 + \log(O/H)$, derived with the direct method. The third column lists the oxygen abundance, in the units of $12 + \log(O/H)$, derived with the strong-line method proposed by Pilyugin & Thuan (2005). The fourth column lists the median estimate of the oxygen abundance, in the units of $12 + \log(O/H)$, extracted from the MPA-JHU Catalog. The fourth column lists the electron temperature obtained from the [OIII] line ratio. The fifth column lists the electron density obtained from the [SII] line ratio.

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<th>Name</th>
<th>OH (Te)</th>
<th>OH (P)</th>
<th>OH (P50)</th>
<th>$T_e$([OIII]) [K]</th>
<th>$n_e$([SII]) [cm$^{-3}$]</th>
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<td>18700$^{+140}_{-130}$</td>
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<td>9700$^{+80}_{-70}$</td>
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<td>13200$^{+48}_{-50}$</td>
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</table>
Table A.5: The physical quantities for each O3EW galaxy. The second column lists the oxygen abundance, in the units of $12 + \log(O/H)$, derived with the direct method. The third column lists the oxygen abundance, in the units of $12 + \log(O/H)$, derived with the strong-line method proposed by Pilyugin & Thuan (2005). The fourth column lists the median estimate of the oxygen abundance, in the units of $12 + \log(O/H)$, extracted from the MPA-JHU Catalog. The fourth column lists the electron temperature obtained from the [OIII] line ratio. The fifth column lists the electron density obtained from the [SII] line ratio (Continued).

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<th>Name</th>
<th>OH (Te)</th>
<th>OH (P)</th>
<th>OH (P50)</th>
<th>$T_e([\text{OIII}])$ [K]</th>
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<td>7.92$^{+0.02}_{-0.02}$</td>
<td>...</td>
<td>8.06</td>
<td>14900$^{+100}_{-100}$</td>
<td>10</td>
</tr>
<tr>
<td>J1012+1220</td>
<td>8.12$^{+0.02}_{-0.02}$</td>
<td>7.62</td>
<td>8.09</td>
<td>12400$^{+80}_{-80}$</td>
<td>60 ± 20</td>
</tr>
<tr>
<td>J0910+0711</td>
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<td>...</td>
<td>8.03</td>
<td>14200$^{+120}_{-130}$</td>
<td>80$^{+20}_{-30}$</td>
</tr>
<tr>
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<td>8.06$^{+0.04}_{-0.04}$</td>
<td>...</td>
<td>8.03</td>
<td>13300$^{+80}_{-100}$</td>
<td>180 ± 20</td>
</tr>
<tr>
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<td>8.07$^{+0.04}_{-0.04}$</td>
<td>...</td>
<td>8.13</td>
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<td>260 ± 30</td>
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<tr>
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<td>7.46$^{+0.08}_{-0.08}$</td>
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<td>7.87</td>
<td>20100$^{+120}_{-200}$</td>
<td>290 ± 50</td>
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<tr>
<td>J0807+3414</td>
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<td>17400$^{+180}_{-200}$</td>
<td>10</td>
</tr>
<tr>
<td>J0825+1846</td>
<td>7.76$^{+0.02}_{-0.02}$</td>
<td>7.77</td>
<td>7.82</td>
<td>16800$^{+180}_{-170}$</td>
<td>190$^{+80}_{-70}$</td>
</tr>
<tr>
<td>J1221+2822</td>
<td>8.02$^{+0.02}_{-0.02}$</td>
<td>...</td>
<td>8.04</td>
<td>14300$^{+60}_{-70}$</td>
<td>80 ± 30</td>
</tr>
<tr>
<td>J0944-0038</td>
<td>7.82$^{+0.04}_{-0.05}$</td>
<td>...</td>
<td>7.88</td>
<td>16300$^{+40}_{-70}$</td>
<td>210 ± 20</td>
</tr>
</tbody>
</table>
Appendix B

Oxygen Abundance Map
Figure B.1: Oxygen abundance maps for the galaxies J0248-0817, J0823+0313, J1044+0353, and J1238+1009. For each galaxy, the left-hand panel shows the oxygen abundance \( \log(O/H) \) (own); the right-hand panel shows the oxygen abundance \( \log(O/H) \) (fixed). For both panels, each bin is color-coded with its value of \( \log(O/H) \) (own) or \( \log(O/H) \) (fixed). The region with white color means that its \( \log(O/H) \) (own) or \( \log(O/H) \) (fixed) cannot be measured (see details in Results and Discussions section).
Figure B.2: Oxygen abundance maps for the galaxies J0248-0817, J0823+0313, J1044+0353, and J1238+1009. For each galaxy, the left-hand panel shows the oxygen abundance log(O/H) (own); the right-hand panel shows the oxygen abundance log(O/H) (fixed). For both panels, each bin is color-coded with its value of log(O/H) (own) or log(O/H) (fixed). The region with white color means that its log(O/H) (own) or log(O/H) (fixed) cannot be measured (see details in Results and Discussions section).
Bibliography


[8] Hsiang-Chih Hwang, Jorge K. Barrera-Ballesteros, Timothy M. Heckman, Kate Rowlands, Lihwai Lin, Vicente Rodriguez-Gomez, Hsi-An Pan, Bau-Ching Hsieh,


[38] Danielle A Berg, Evan D Skillman, Andrew R Marble, Liese van Zee, Charles W Engelbracht, Janice C Lee, Robert C Kennicutt Jr, Daniela Calzetti, Daniel A Dale, and Benjamin D Johnson. DIRECT OXYGEN ABUNDANCES FOR LOW-LUMINOSITY LVL GALAXIES. page 33.


