The bimodality in MZR in SDSS-MaNGA galaxy pairs

Kiyooki Christopher Omori and Tsutomu T. Takeuchi

1 Division of Particle and Astrophysical Science, Nagoya University, Furo-cho, Chikusa-ku, Nagoya 464–8602, Japan
2 The Research Centre for Statistical Machine Learning, the Institute of Statistical Mathematics, 10–3 Midori-cho, Tachikawa, Tokyo 190–8562, Japan

Received September 15, 1996; accepted March 16, 1997

ABSTRACT

Aims. Interacting galaxies show a metallicity dilution compared to similar-mass isolated galaxies in the mass-metallicity space at the global scale. We investigate the spatially resolved mass-metallicity relation (MZR) of galaxy pairs in the SDSS-MaNGA survey to confirm that the local relation between stellar mass surface density $\Sigma$ and metallicity is consistent with the MZR at the global scale.

Methods. We investigate the relationship between the stellar mass surface density and the metallicity abundance $12 + \log(O/H)$ for star-forming spaxels belonging to 297 galaxy pairs identified using visual and kinematic indicators in the SDSS-MaNGA survey. We also investigated if a) location of spaxel relative to galaxy center and b) galaxy pair separation have any effect on the local mass-metallicity relation.

Results. We find that the correlation between mass and metallicity holds for interacting galaxies at the local level. However, we find two peaks in spaxel distribution, one peak with enriched metallicity, and the other with diluted metallicity. We find that the spaxels belonging to the galaxy central regions, i.e. at lower $R/R_{\text{eff}}$, are concentrated close to the two peaks. We also find that the metallicity enriched spaxels belong to galaxy pairs with closer projected separation, and spaxels with diluted metallicity belong to galaxy pairs with greater projected separation.

Conclusions. We find two discrete peaks in the spatially resolved mass-metallicity relation for star-forming spaxels belonging to galaxy pairs. The peaks are likely related to the galaxy projected separation, or the stage of the interaction process in a galaxy pair.

Key words. galaxies: abundances - galaxies: evolution - galaxies: interactions - galaxies: fundamental parameters

1. Introduction

In the current $\Lambda$-dominated cold dark matter ($\Lambda$CDM) framework for structure formation in the Universe, hierarchical growth of galaxies through merging is the commonly agreed upon pathway for galaxy evolution. Despite galaxy interactions and mergers being a major driver of galaxy evolution, we are yet to make many quantitative conclusions on the processes and our understanding of galaxy interactions and mergers is far from complete. One example of such is the chemical evolution of interacting galaxy systems. While chemical evolution of isolated galaxies has been extensively studied, there have been comparatively less studies done on the topic for interacting galaxies.

We can improve our understanding of chemical evolution in interacting galaxies by examining the relationship between two fundamental properties of galaxies: stellar mass ($M_*$) and gas phase metallicity (hereinafter referred to as “metallicity”). Stellar mass can be an indicator of the amount of gas turned into stars during a galaxy’s life time. Metallicity can be an tracer of gas re-processed into stars or accreted due to external processes, and can be a reflection of the state of galaxy evolution. Both of these properties can change as a consequence of star formation events. The relationship between these two properties is called the mass-metallicity relation (MZR, Lequeux et al. 1979). This relationships indicates that the metallicity, in particular the oxygen abundance, of galaxies increases with increasing stellar mass (Tremonti et al. 2004; Foster, C. et al. 2012). Lower mass galaxies are more greatly affected by blowouts due to galactic winds or outflows from galactic processes, resulting in metal content leaving the galaxy, diluting the gas phase metallicity. On the contrary, higher mass galaxies are more chemically enriched. This could be due to higher mass galaxies being less affected by the above processes and having the ability to retain their metal content, or a consequence of “chemical downsizing” (Somerville & Davé 2013). At larger stellar masses, the relation bends and flattens off towards and asymptotic value. This behaviour indicates some sort of saturation value for gas phase metallicity, possibly due to galactic outflow that regulates metallicity (Tremonti et al. 2004).

Recent studies have shown that the metallicity of galaxy mergers fall below this relation, or in other words interacting galaxies have lower nuclear metallicities than those of similar mass isolated galaxies (Ellison et al. 2008; Scudder et al. 2012; Cortijo-Ferrero et al. 2017). In particular, close galaxy pairs show an offset from the MZR. A likely explanation for this is gas inflow to galaxy core regions during a merger event. Accreted lower metallicity gas from a galaxy merger will flow into a higher metallicity central region, resulting in a lower gas phase metallicity.

In this paper, we investigate the spatially resolved MZR of galaxy pairs in the integral field spectroscopy survey Mapping Nearby Galaxies at Apache Point Observatory (MaNGA, Bundy et al. 2015) survey to study the effects of interaction on a local scale. We compare the loci of the spaxels of our sample to the MZR curve derived from all starforming spaxels in the MaNGA survey, to confirm if metallicity dilutions occur for galaxy pairs. We also investigate if the distribution of spaxels of the paired sample may be affected by other parameters.

Article number, page 1 of 8
For this paper, we adopt a ΛCDM model with the following cosmological parameters: $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$, $\Omega_m = 0.7$, $\Omega_{\Lambda} = 0.3$.

This paper is structured as follows. Section 2 describes our sample and methods to obtain our properties. We highlight our results in Section 3. We discuss our results in Section 4 and our conclusion is in Section 5.

2. Data and Analysis

2.1. Sample

For this work, we use data from the integral field spectroscopic survey MaNGA, one of the three core projects of Sloan Digital Sky Survey IV (SDSS-IV, Blanton et al. 2017). It uses the 2.5 meter telescope at the Apache Point Observatory (Gunn et al. 2006), and aims to map and acquire spatially resolved spectroscopic observations of ~10,000 local galaxies, in a redshift range of $0.01 < z < 0.15$, with an average redshift of 0.037 (Law et al. 2016) by 2020. MaNGA spectra cover a wavelength range of 3,600Å–10,000Å at a resolution of $R \approx 70$ km/s/1 Mpc.

The MaNGA target selection is optimised in such a way that galaxies are selected based only on their SDSS $i$-band absolute magnitude and redshift, and the sample is unbiased based on their sizes or environments. The methodology and extensive efforts taken for this optimisation are highlighted in Wake et al. (2017). We used data from SDSS Data Release 16 (DR16), which includes the spatially resolved maps of 4675 unique MaNGA targets.

2.2. Selection

We selected our sample of galaxy pairs using a method combining visual identification of MaNGA cutout images, visual inspection of 2D kinematic maps, and relative velocity differences. We will describe the method below.

First, we visually investigated the 2D stellar kinematic maps of MaNGA galaxies. The stellar kinematic maps were obtained from the output of the data analysis pipeline (DAP) in MaNGA (Westfall et al. 2019). In the DAP, the Voronoi binning method of Cappellari & Copin (2003) is used to bin, stack, and average the spectra of adjacent spaxels, so that the target minimum signal-to-noise (S/N) ratio to obtain accurate stellar kinematics is met, which in this case is 10. The stellar continuum of each binned spectra was fitted using the penalised pixel-fitting (pPXF) method by Cappellari (2017) and hierarchically clustered MILES templates (MILES-HC, MILES stellar library; Sánchez-Blázquez et al. 2006). The stellar kinematic information (velocity and velocity dispersion) was obtained through this fitting process. From the 2D kinematic maps, we visually identified 1569 galaxies with disturbed stellar kinematics.

We next inspected whether or not these 1569 galaxies were galaxy pairs or isolated galaxies through visual confirmation of their optical images and SDSS galaxy pair data. We investigated the MaNGA image cutouts of the galaxies, and considered the galaxy a galaxy pair if it met one of the following criteria:

- A secondary galaxy was within the cutout.
- A secondary galaxy exists within the range of SDSS Neighbours Table.

We confirmed that these galaxy pairs were within a physically connected range and not projections, following the redshift difference range adopted in Patton et al. (2009). After these steps, our final sample consisted of 297 galaxy pairs.

2.3. Obtaining physical properties

After sample selection, the next step is to extract the physical properties from the spaxels of our sample galaxies. The properties of interest in this work are the stellar surface mass densities and gas phase metallicities.

2.3.1. Stellar surface mass densities

The spatially resolved stellar surface mass densities were obtained by finding the ratio between stellar mass and surface area of each spaxel.

To obtain the stellar mass, we referred to the MaNGA FIREFLY Value Added Catalogue (MaNGA FIREFLY VAC, Goddard et al. 2017), which provides spatially resolved stellar population properties for MaNGA galaxies. The MaNGA FIREFLY VAC summarizes the results of running the full spectral-fitting code FIREFLY (Wilkinson et al. 2017) on spatially resolved MaNGA spectra that are binned using the Voronoi binning method with a S/N ratio of 10 per pixel. Details on the fitting process and how the stellar population properties are obtained are detailed in Goddard et al. (2017).

After the stellar masses for each spaxel were obtained, the surface mass densities were obtained. In MaNGA data, each spaxel has a size of 0.5 arcsec. We use the small angle approximation to estimate the physical scale of the spaxel:

$$\theta = \tan^{-1} \left( \frac{d}{D} \right) \approx \frac{206,625 \text{ [arcsec]}}{1 \text{ [radian]}}, \frac{d}{D}$$

with $\theta$ the angular size of the spaxel in arcsec, $D$ the angular diameter and $d$ the diameter of the spaxel.

We approximate the distance using the Hubble law:

$$D \approx \frac{cz}{H_0}$$

with the redshift information for each galaxy available through the DAP catalogue. We obtained the physical scale $a$ of each spaxel using the small angle approximation, then converted the spaxel size from arcsec to parsec to obtain the spaxel area.

We found the ratio between stellar mass and spaxel area to obtain the surface mass density.

$$\Sigma_* = \frac{M_*}{a^2}$$

2.3.2. Gas phase metallicities

For this work, we adopted the metallicity calibrator from Marino et al. (2013). We adopt this calibrator, also used in Barrera-Ballesteros et al. (2016), a work that handles the spatially resolved MZR for MaNGA galaxies, as it is a metallicity calibrator derived from previous starforming region studies. This work determines the metallicity using the O3N2 calibrator.

$$12 + \log (O/H) = 8.533[±0.012] - 0.214[±0.012] \times \text{O3N2},$$

where the O3N2 is determined by taking the logarithmic differences between the line ratios $\log(OIII/Hbeta)$ and $\log([NII]/Halpha)$.

$$\text{O3N2} = \log \left( \frac{[OIII]J5007}{Hbeta} \cdot \frac{Halpha}{[NII]J6583} \right)$$

Once the surface mass densities and gas phase metallicities of all spaxels were obtained, we selected only the starforming
spaxels of each galaxy, as gas phase metallicity calibrators are only accurate for starforming spaxels. The selection was done by comparing the [OIII]/Hβ and [NII]/Hα line ratios in a BPT diagram (Baldwin et al. 1981). Of the starforming spaxels, we left out spaxels with a S/N \(< 3 \) in either N[II]6585 and Hα, and any other spaxels that lacked coverage, had unreliable measurements, or otherwise considered unusable for science through the MaNGA catalogue.

3. Results

Figure 1 plots the oxygen abundance of the starforming spaxels of our galaxy pair sample as a function of stellar mass surface density. The same plot for all starforming spaxels in the MaNGA survey is available in Appendix A as reference, which we used to plot the red line in Fig. 1.

We find a bimodality in metallicity distribution at higher stellar masses, indicating that there exists two populations of spaxels. Such a discrete bimodality is not present in neither the entire MaNGA population as seen in Appendix A.

One of the peaks agrees with the MZR, that is that higher stellar masses exhibit higher metallicity. This indicates that for some galaxies pairs, the MZR at the local level is in agreement with that of the global level.

There is a secondary peak located below the fit curve for all MaNGA galaxies, however in agreement with the contour lines, indicating that there are spaxels with lower metallicities than those with similar stellar masses. These diluted spaxels are similar with the conclusions of studies that investigated the MZR for galaxy pairs at a global level, e.g. (Rupke et al. 2010; Bustamante et al. 2020) which indicate that galaxy pairs show a metallicity decrement compared to isolated galaxies of similar stellar mass.

4. Discussion

In this section, we discuss the properties and possible origins of the bimodality.

There have been a number of works that discuss the MZR in interacting galaxies (Michel-Dansac et al. 2008; Rupke et al. 2010), and a further few that include star formation rate and discuss the fundamental metallicity relation (FMR) in interacting galaxies (Mannucci et al. 2010; Robotham et al. 2014; Gronborg et al. 2015; Bustamante et al. 2020), however there are no previous works that investigate the spatially resolved MZR for interacting galaxies. Our results in Fig. 1 show that while some spaxels in galaxy pairs show a dilution in gas phase metallicity, which is in agreement with the above works that investigate the MZR for galaxy pairs, there are also spaxels that do not show diluted metallicities. We search if there are any properties that may show a close relation with the locii of the spaxels. In this work we focus on two properties: a) the effective radius of each spaxel and b) separation of the galaxy pair each spaxel belongs to.

4.1. Spaxel distribution by effective radius

We plot all spaxels within 1 R_eff in Fig. 2. We find that the two peaks in Fig. 1 are similar in loci with the core regions of the galaxy. This indicates that the central regions of galaxies are contributing to the bimodality. This bimodality indicates there are two populations of galaxies in the sample, with one population with enriched metallicity and one with a dilution of metallicity. The dilution in the latter population is likely a consequence of the galaxy interactions. In a galaxy interaction, strong inflows of gas from from the paired galaxy occur, and the accreted gas flows towards the circumnuclear regions of the primary galaxy, fueling star formation (Tono et al. 2004). If the paired galaxy has outer regions that are metal poor such as in local galaxies (Shields 1990), the accreted gas will also be metal poor, resulting in lower-metallicity gas diluting the metallicity in the core region of the primary galaxy (Montuori, M. et al. 2010).

The former population, or the higher-mass, higher-metallicity spaxels belonging to galaxy core regions, can be explained by the inside-out galaxy evolution model (Kepner 1999). In this galaxy model, a negative metallicity gradient is observed, with the greatest metallicity values in the galaxy cores (Vilchez et al. 1988; Vila-Costas & Edmunds 1992).

While the effective radius indicates that there are higher metallicity and lower metallicity cores in our sample, it does not give us a sufficient understanding of the nature of the galaxies in the sample.

4.2. Galaxy pair separation

Previous studies investigating the MZR or FMR for interacting galaxies find that close galaxy pairs have a lower metallicity compared to galaxy pairs with greater projected separation (Michel-Dansac et al. 2008; Bustamante et al. 2020). It should be noted that metallicity will have a scatter, as at any given distance, a galaxy pair can be at a number of different stages of the merger process.

Figure 3 plots all spaxels within 1 R_eff color-coded by projected separation of the galaxy pair the spaxel belongs to. We find spaxels having a gas phase metallicity consistent with that of the MZR, with increased stellar mass resulting in increased metallicity, likely belong to a galaxy pair with a greater projected separation. We also find spaxels with diluted metallicity belong to galaxies with lower projected separation. In other words, closer galaxy pairs are more diluted, particularly in their nuclear regions as can be seen from the previous section. The closest galaxy pairs experiencing a dilution in metallicity is consistent with previous works that studied the MZR or FMR for galaxy pairs (Rupke et al. 2010; Bustamante et al. 2020; Gar-duno et al. 2021).

Galaxy pairs with close separation (< 5 kpc separation) can indicate a merger at a number of different stages. Galaxies can be near the first pericenter passage or approaching coalescence. At both of these stages, galaxies are experiencing metallicity dilution in circumnuclear regions. In the first case, the primary galaxy experiences inflow of low-metallicity gas from the secondary galaxy and the gas phase metallicity abundance is diluted (Tremonti et al. 2004; Torrey et al. 2012; Montuori, M. et al. 2010). In the second case, when galaxies are approaching coalescence, strong gas inflows are observed resulting in dilution of nuclear metallicities (Torrey et al. 2012).

Close galaxy pairs can also be after coalescence and are experiencing enrichment from supernovae ejecta (Montuori, M. et al. 2010).

Galaxy pairs with a projected separation of > 20 kpc can be at the first encounter, before first pericentre passage. At this stage, little metallicity evolution is observed (Rupke et al. 2010; Torrey et al. 2012), so it would be expected that metallicity abundance is in accordance with the MZR. The pair can also be in a state after the first pericenter passage, where star formation events enhance the nuclear metallicity (Torrey et al. 2012). However, the pair could also be after the first pericenter passage and are in the midst of separation before final coalescence, where in-
We note that the majority of our galaxies are within 20 kpc in projected separation, which would all correspond under the general term 'close pairs' and commonly placed in a single bin in previous literature. However, we find that there is a possible bimodality dependent on projected separation even with this upper limit of separation. This bimodality is consistent with the metallicity evolution in a galaxy merger.

5. Conclusions

In this work, we investigated the gas phase metallicity ($12 + \log(O/H)$) as a function of stellar mass, or the mass-metallicity relation (MZR), of star-forming spaxels in MaNGA galaxy pairs identified using visual and kinematic features. Our main findings include the following:

1. We find a bimodality, i.e. two peaks in the distribution of spaxels in the mass-metallicity space for galaxy pairs, a feature not present for the entire MaNGA sample.
Fig. 2: The distribution of oxygen abundance as a function of stellar mass surface density for all starforming spaxels in 298 galaxy pairs in the MaNGA survey, colour coded by effective radius. All spaxels over 1 $R_{\text{eff}}$ are masked.

2. The spaxels at the peaks correspond to spaxels in the cores of the galaxy pairs, indicating both metallicity enrichment and dilution in circumnuclear regions.

3. Galaxy pairs with closer separation showed a tendency to display metallicity dilution, whereas galaxy pairs with greater separation showed a metallicity enrichment. This is likely an indicator of metallicity evolution during the galaxy merger process.

Previous studies investigating the global MZR for interacting galaxies find that there is a metallicity dilution present for interacting galaxies compared to isolated galaxies of similar stellar mass. Our results show that a metallicity dilution can be observed for interacting galaxies at the local level, however there is a bimodality likely attributed to galaxy separation.

For future works, we plan to investigate the star formation rate of this galaxy sample and investigate the effects of galaxy interaction on the FMR for MaNGA galaxy pairs.

Acknowledgements. Something about funding.

References
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Fig. 3: The distribution of oxygen abundance as a function of stellar mass surface density for all star-forming spaxels in 298 galaxy pairs in the MaNGA survey, colour coded by galaxy pair separation. All spaxels over 1 $R_e$ff are masked.

Barrera-Ballesteros, J. K., Heckman, T. M., Zhu, G. B., et al. 2016, MNRAS, 463, 2513
Blanton, M. R., Bershady, M. A., Abolfathi, B., et al. 2017, AJ, 154, 28
Bundy, K., Bershady, M. A., Law, D. R., et al. 2015, ApJ, 798, 7
Bustamante, S., Ellison, S. L., Patton, D. R., & Sparre, M. 2020, MNRAS, 494, 3469
Cappellari, M. 2017, MNRAS, 466, 798
Cappellari, M. & Copin, Y. 2003, MNRAS, 342, 345
Cortijo-Ferrero, C., González Delgado, R. M., Pérez, E., et al. 2017, MNRAS, 467, 3898
Ellison, S. L., Patton, D. R., Simard, L., & McConnachie, A. W. 2008, AJ, 135, 1877
Foster, C., Hopkins, A. M., Gunawardhana, M., et al. 2012, A&A, 547, A79
Gardullo, L. E., Lara-López, M. A., López-Cruz, O., et al. 2021, MNRAS, 501, 2969
Goddard, D., Thomas, D., Maraston, C., et al. 2017, MNRAS, 466, 4731
Grénoz, A. E., Finlator, K., & Christensen, L. 2015, MNRAS, 451, 4005
Gunn, J. E., Siegmund, W. A., Mannery, E. J., et al. 2006, AJ, 131, 2332
Iono, D., Yun, M. S., & Mihos, J. C. 2004, ApJ, 616, 199
Kepner, J. V. 1999, ApJ, 520, 59
Law, D. R., Cherinka, B., Yan, R., et al. 2016, AJ, 152, 83
Lequeux, J., Peimbert, M., Rayo, J. F., Serrano, A., & Torres-Peimbert, S. 1979, A&A, 500, 145
Mannucci, F., Cresci, G., Maiolino, R., Marconi, A., & Gnerucci, A. 2010, MNRAS, 408, 2115–2127
Marino, R. A., Rosales-Ortega, F. F., Sánchez, S. F., et al. 2013, A&A, 559, A114
Michel-Dansac, L., Lambas, D. G., Alonso, M. S., & Tissera, P. 2008, MNRAS, 386, L82
Montuori, M., Di Matteo, P., Lehner, T. D., Combes, F., & Semelin, B. 2010, A&A, 518, A56
Patton, D. R., Carlberg, R. G., Marzke, R. O., et al. 2000, ApJ, 536, 153

Article number, page 6 of 8
Appendix A: MZR of all MaNGA starforming spaxels

Fig. A.1: The distribution of oxygen abundance as a function of stellar mass surface density for all starforming spaxels from all galaxies in the MaNGA survey. The colorbar indicates the number of spaxels per bin in the $\Sigma_* - Z$ space. The black curve is the best fit line following Sánchez et al. (2013).

To obtain the curve of best fit, we found the median value at differing mass density bins, and following Sánchez et al. (2013), used the following fitting function:

$$y = a + b(x - c)e^{-(x-c)}$$

(A.1)

with $y = 12 + \log (O/H)$ and $x$ the logarithm of the stellar mass surface density. From the best fit line, we find the coefficients for the above function for all starforming spaxels in the MaNGA survey to be $a = 8.65 \pm 0.01$, $b = -1.07 \pm 0.04$, and $c = -1.23 \pm 0.13$. 