Anomalously Low-metallicity Regions in MaNGA Star-forming Galaxies: Accretion Caught in Action?

Hsiang-Chih Hwang1, Jorge K. Barrera-Ballesteros1, Timothy M. Heckman1, Kate Rowlands1, Lihwai Lin2, Vicente Rodriguez-Gomez3, Hsi-An Pan2, Bau-Ching Hsieh2, Sebastian Sánchez4, Dmitry Bizyaev4,5, Jorge Sánchez Almeida6,7, David A. Thilker1, Jennifer M. Lotz1, Amy Jones9, Preethi Nair9, Brett H. Andrews10,11,12, and Niv Drory13

1 Department of Physics & Astronomy, Johns Hopkins University, Baltimore, MD 21218, USA
2 Institute of Astronomy & Astrophysics, Academia Sinica, Taipei 10617, Taiwan
3 Instituto de Astronomía, Universidad Nacional Autónoma de México, A.P. 70-264, C.P. 04510, México, D.F., Mexico
4 Apache Point Observatory, P.O. Box 59, Sunspot, NM 88349, USA
5 Sternberg Astronomical Institute, Moscow State University, Moscow, Russia
6 Instituto de Astrofísica de Canarias, E-38205 La Laguna, Tenerife, Spain
7 Departamento de Astrofísica, Universidad de la Laguna, E-38205 La Laguna, Tenerife, Spain
8 Space Telescope Science Institute, 3700 San Martin Drive, Baltimore, MD 21218, USA
9 Department of Physics and Astronomy, The University of Alabama, Tuscaloosa, AL 35487, USA
10 Department of Physics and Astronomy, University of Pittsburgh, Pittsburgh, PA 15260, USA
11 Department of Astronomy, The Ohio State University, Columbus, OH 43210, USA
12 Center for Cosmology and Astro-Particle Physics, The Ohio State University, Columbus, OH 43210, USA
13 McDonald Observatory, The University of Texas at Austin, Austin, TX 78712, USA

Received 2018 October 1; revised 2018 November 27; accepted 2018 December 6; published 2019 February 19

Abstract

We use data from 1222 late-type star-forming galaxies in the SDSS IV Mapping Nearby Galaxies at Apache Point Observatory survey to identify regions in which the gas-phase metallicity is anomalously low compared to expectations from the tight empirical relation between metallicity and stellar surface mass density at a given stellar mass. We find anomalously low-metallicity (ALM) gas in 10% of the star-forming spaxels and in 25% of the galaxies in the sample. The incidence rate of ALM gas increases strongly with both global and local measures of the specific star formation rate and is higher in lower mass galaxies and in the outer regions of galaxies. The incidence rate is also significantly higher in morphologically disturbed galaxies. We estimate that the lifetimes of the ALM regions are a few hundred Myr. We argue that the ALM gas has been delivered to its present location by a combination of interactions, mergers, and accretion from the halo, and that this infusion of gas stimulates star formation. Given the estimated lifetime and duty cycle of such events, we estimate that the time-averaged accretion rate of ALM gas is similar to the star formation rate in late-type galaxies over the mass range $M_*$ $\sim$ 10$^8$–10$^{10.5}$ $M_\odot$.

Key words: galaxies: abundances – galaxies: evolution – galaxies: statistics – surveys – techniques: imaging spectroscopy

1. Introduction

Gas accretion has long been known to play a crucial role in galaxy formation and evolution (Rees & Ostriker 1977; White & Rees 1978). Indeed, the growth in the stellar masses of galaxies over cosmic time occurs mainly through the accretion of gas from the environment, rather than through galaxy mergers (Dekel et al. 2009; Papovich et al. 2011; Behroozi et al. 2013; Rodriguez-Gomez et al. 2016). Moreover, if there were no gas replenishment from the outside, the observed rate of star formation is so high that most star-forming galaxies in the present-day universe would soon run out of gas and cease to form stars (Kennicutt & Evans 2012). Our own Milky Way is a good example. It currently has a star formation rate (SFR) of about 2 $M_\odot$ yr$^{-1}$ (Robitaille & Whitney 2010; Chomiuk & Povich 2011; Licquia & Newman 2015) with a roughly constant star formation history over the past 8 Gyr (Snaith et al. 2014). This SFR would consume all of the available gas within a few Gyr if there were no gas inflow. As the star formation activity in galaxies is strongly related to their gas content (Kennicutt 1998), gas accretion is therefore at the center of our understanding of galaxy growth and quenching.

However, direct observation of accreting gas is challenging, and it is even more difficult to directly determine the accretion rates. The immediate source of such gas in star-forming galaxies is the circumgalactic medium (CGM) or the intergalactic medium (IGM; Sánchez Almeida et al. 2014), which consists of ionized gas and neutral hydrogen. For our Galaxy, the accretion rate is dominated by the Magellanic Stream (4 $M_\odot$ yr$^{-1}$) with only 0.4 $M_\odot$ yr$^{-1}$ from the other high-velocity clouds (Putman et al. 2012). Such estimates are very hard to derive for extragalactic samples. Also, the accreted gas does not necessarily become the fuel for star formation because gas clouds may get heated up by shocks when they fall onto the disks, preventing them from cooling and forming stars.

The chemical abundances (metallicities) in the interstellar medium (ISM) can serve as an indirect tool to study the gas circulation between a galaxy and its surroundings. Inflows from the CGM, IGM, or satellite galaxies can provide low-metallicity gas for galaxies. After the gas is processed by nucleosynthesis in stars, metals are released to the ISM via stellar winds and supernovae. If star formation activity is strong enough, it is able to launch a galactic outflow (Heckman et al. 1990, 2002). The outflow takes metals away from galaxies to enrich the CGM. This process and its consequences can be studied using absorption-line spectroscopy of the CGM using background quasars (Chen et al. 2010; Lehner et al. 2013;
Rubin et al. 2014; Heckman et al. 2017; Lan & Fukugita 2017). The ejected metals may reaccrete onto the disks on a dynamical timescale (Oppenheimer et al. 2010). Consequently, the metallicity in the ISM is produced by the interplay among star formation, inflow, and outflow.

Over the past decade, we have learned a great deal about the systematic relationships between ISM metallicity and galaxy properties. Single-fiber spectroscopic surveys have shown that the central oxygen metallicity increases with galaxy stellar mass: the so-called global $M-Z$ relation (Lequeux et al. 1979; Garnett & Shields 1987; Vila-Costas & Edmunds 1992; Tremonti et al. 2004). The relation can be explained in part by mass-dependent metal loss because of the shallower potential wells in low-mass galaxies and/or by the inflow of metal-poor gas. The global $M-Z$ relation may have an additional dependence on global SFR such that galaxies with higher SFRs have lower metallicity at a fixed stellar mass $M_*$ (Ellison et al. 2008a). The form of the relation between galaxy stellar mass, metallicity, and SFR may be independent of redshift, and therefore it is called the fundamental metallicity relation (Lara-Lopez et al. 2010; Mannucci et al. 2010). Whether or not this additional dependence on SFR is due to observational systematics like single-aperture bias (Sánchez et al. 2013, 2017; Barrera-Ballesteros et al. 2017), the nature of the metallicity calibrators used (Kashino et al. 2016), and whether or not its form is really independent of redshift (Steidel et al. 2014) has been debated. Also, rather than SFR, the global $M-Z$ relation may have a stronger dependence on other properties like gas fraction (Bothwell et al. 2013; Hughes et al. 2013) and stellar age (Lian et al. 2015).

Single-aperture spectroscopy limits the metallicity study to galactic centers, while metallicity is known to have significant spatial variation. Long-slit spectroscopy and integral field units (IFU) observations have shown the radial dependence of gas-phase metallicity in late-type galaxies with metallicity decreasing outwards, i.e., negative metallicity gradient (Searle 1971; Vila-Costas & Edmunds 1992; Zaritsky et al. 1994; Moran et al. 2012; Sánchez et al. 2012, 2014; Belfiore et al. 2017; Poetrodjojo et al. 2018). Furthermore, the azimuthal variations imprinted on the radial gradients suggest that the local chemical evolution may be influenced by local enrichment and dilution caused by spiral density waves (Ho et al. 2017).

Indeed, evidence is now growing that the global relations between mass, metallicity, and arguably SFR may emerge from relations at local scales. On $\sim$kpc scales, local metallicity tightly correlates with the local stellar surface mass density ($\Sigma_*$-$Z$ relation; Moran et al. 2012; Rosales-Ortega et al. 2012). This local relation can reproduce both the global $M-Z$ relation and radial metallicity gradients (Barrera-Ballesteros et al. 2016). The local metallicity also correlates with both the local gas-mass fraction and local escape velocity (Barrera-Ballesteros et al. 2018), as expected in simple models for chemical evolution that incorporate accretion and outflows. Metallicity inhomogeneities associated with enhanced SF activity have been observed in some galaxies. Extremely metal-poor galaxies tend to have a large lopsided star-forming region of low metallicity (e.g., Sánchez Almeida et al. 2013, 2015). There also seems to be a tendency for the star-forming regions of larger SFRs to have lower metallicity (Cresci et al. 2010; Richards et al. 2014; Sánchez Almeida et al. 2018). These metallicity drops are usually attributed to recent gas accretion events triggering star formation.

While the existence of these excellent empirical correlations between local galaxy properties and the local ISM metallicity provide important insights into galaxy evolution, in this paper we will take a very different approach. In particular, we use these empirical correlations to identify anomalous regions whose metallicity is significantly lower than expected. We will then compare the global properties of the galaxies that contain such regions to those that do not. We will also compare the local properties of the regions with anomalously low metallicity (ALM) to regions with normal metallicity. Based on this analysis, we will argue that these regions likely trace the sites of the recent accretion of gas that has stimulated ongoing star formation. By constraining the lifetimes of low-metallicity regions, we will try to estimate the frequency of such accretion events and the implied accretion rates and thereby assess their implications for galaxy evolution.

The paper is structured as follows. In Section 2, we will describe the observational data set, our sample selection, and our measurements of metallicity and other local and global properties. In Section 3, we will present our results linking the low-metallicity regions with both global and local galaxy properties. In Section 4, we will discuss the possible sources for the low-metallicity gas and quantify the properties of the accretion. We summarize our conclusions in Section 5. Throughout, we use an $h = 0.7$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$ cosmology. We use lower-case “$z$” for redshifts and capital “$Z$” for metallicity.

2. Observations and Data Reduction

2.1. Mapping Nearby Galaxies at Apache Point Observatory (MaNGA) Overview

MaNGA (Bundy et al. 2015) observes galaxies in the local universe ($z \lesssim 0.15$) using IFUs as part of Sloan Digital Sky Survey (SDSS)-IV (Blanton et al. 2017). MaNGA provides wavelength coverage from 3600 to 10300 Å with a spectral resolution of $R \sim 2000$ (Smee et al. 2013) and a reconstructed point spread function (PSF) of $\sim$2.5 arcsec in FWHM (Law et al. 2016). The MaNGA IFUs consist of bundles of 19, 37, 61, 91, and 127 fibers, providing effective coverage over radii from 5.45 to 14.54 arcsec (Drory et al. 2015; Yan et al. 2016a). Started in 2014, the MaNGA survey will observe $\sim$10,400 galaxies in 6 yr using the Sloan 2.5 m telescope (Gunn et al. 2006). For more details about the MaNGA observing strategy and spectrophotometry calibration, we refer to Law et al. (2015) and Yan et al. (2016b).

The MaNGA galaxy sample comprises the Primary sample, Secondary sample, Color-Enhanced sample, and objects for ancillary programs. As shown in Figure 1, the Primary and Secondary samples are targeted to have IFU areal coverage out to $\sim$1.5 and $\sim$2.5 $R_*$, respectively, with a roughly uniform stellar mass distribution (Wake et al. 2017). The Color-Enhanced sample is designed to select galaxies with IFU coverage similar to the Primary sample ($\sim$1.5 $R_*$), but which are underrepresented because of their colors (especially high-mass blue galaxies, low-mass red galaxies, and green-valley galaxies). As the Primary and Color-Enhanced samples have the same targeted IFU coverage of 1.5 $R_*$, their combination is referred to as the Primary+ sample. To cover all galaxies out to
similar effective radii, massive (large) galaxies are observed at redshifts higher than low-mass (small) galaxies (Figure 1).

In this study, the galaxy sample comes from the MaNGA Product Launches 6 (MPL6), an internal collaboration release comprising 4682 galaxies. The raw observed data are calibrated and sky-subtracted by the Data Reduction Pipeline v2.3.1 (Law et al. 2016), providing processed data cubes with spaxel sizes of 0.5 arcsec. We use the measurements of emission lines (Gaussian fluxes and equivalent widths) and relevant stellar continuum indices (D4000) from the MPL6 Data Analysis Pipeline v2.1.3 (Westfall et al. 2019). Galaxy global properties such as redshift, total stellar mass, axis ratio from elliptical Petrosian fitting \((b/a)\), broadband photometry (NUV and \(r\) in this paper), and effective radius are drawn from the NASA-Sloan catalog v1.0.1 (Blanton et al. 2011).

2.2. Sample Selection

Our goal is to identify and investigate regions of anomalously low gas-phase metallicities. These metallicities are measured using emission lines arising in gas photoionized by massive stars. We therefore focus on late-type star-forming galaxies (in which the gas-phase metallicities can be measured over much of the galaxy). The SDSS pipeline fits galaxies with a de Vaucouleurs profile and an exponential profile, and provides the quantity \(fractdeV\), which is the fraction of fluxes contributed from the de Vaucouleurs profile. Therefore, pure de Vaucouleurs early-type galaxies have \(fractdeV = 1\), and pure exponential late-type galaxies have \(fractdeV = 0\). We follow Zheng et al. (2015) and select late-type galaxies as those having \(fractdeV < 0.7\) in the \(r\)-band, where \(fractdeV = 0.7\) roughly corresponds to Sa spiral galaxies (Masters et al. 2010). In the rest of the paper, late-type galaxies will refer to galaxies selected using \(fractdeV < 0.7\). High galaxy inclination makes deprojected quantities more uncertain, so we exclude galaxies having \(b/a < 0.3\) from our sample, corresponding to an inclination of \(72.5^\circ\). In case some \(b/a\) ratios are not reliable due to foreground stars or other image artifacts, we also use the MaNGA MPL-7 catalog of highly inclined galaxies, which are visually identified by P. Nair following the procedure described in Nair & Abraham (2010). For the full highly inclined sample in this catalog, the median \(b/a\) is 0.3 and the mean is 0.31 with a standard deviation of 0.12. The distributions of redshift and spatial coverage for the resulting late-type galaxy sample are shown in Figure 1.

Emission lines can be produced by different ionization sources, like short-lived massive stars born from recent star formation, active galactic nuclei (AGNs), and evolved stars. To distinguish among these ionization sources, spaxels are classified based on their line ratios of \([\text{N} \text{II}]/\text{H}\alpha\) and \([\text{O} \text{III}]/\text{H}\beta\), the so-called Baldwin, Phillips, and Terlevich (BPT; Baldwin et al. 1981) diagram. Specifically, based on the location in the BPT diagram, spaxels are classified as either AGNs/LINERs (above the Kewley et al. 2001 demarcation line), pure star-forming (below the Kauffmann et al. 2003b line), or composite spaxels (between the two aforementioned lines) where multiple ionization sources are present. Only pure star-forming spaxels enter our sample because the metallicity calibrators we use do not apply to other ionization sources. We will describe this in detail in Section 2.6.1. We apply a signal-to-noise ratio \((S/N)\) cut of 10 to each of the emission lines used for the BPT diagram and metallicity calibrators, including \(\text{H}\alpha; \text{H}\beta; [\text{O} \text{III}]\lambda5007; [\text{O} \text{II}] \lambda3726, 9; \text{and [N II]}\lambda6584\). As detailed in Section 2.6.2, because we use the local stellar surface mass density to estimate the expected metallicities, we only consider spaxels with deprojected stellar surface mass density \(>10^7 \, M_\odot\, \text{pc}^{-2}\).

We will refer to those late-type galaxies having star-forming regions as star-forming galaxies. Motivated by the size of the PSF, we require that star-forming galaxies have at least 20 pure star-forming spaxels because the angular area of a typical MaNGA PSF (\(\sim 2.5\, \text{arcsec}\), or \(\sim 1.5\, \text{kpc} \text{at } z = 0.03\) is \(\sim 19.6\) spaxels. With these selection criteria, out of a total of 4784 MaNGA galaxies, there are 1685 late-type galaxies with stellar masses \(M_\star > 10^9 \, M_\odot\), and our final star-forming galaxy sample constitutes 1222 sources with 526,613 star-forming spaxels. As detailed later in Section 2.6.2, we identify ALM regions in 307 of these 1222 star-forming galaxies.

2.3. Galaxy Physical Quantities

The local stellar surface mass density is measured by the PIPE3D pipeline v2.3.1 (Sánchez et al. 2016a, 2016b). In short, spaxels are spatially binned so that the continua reach a target \(S/N\) ratio of 50. PIPE3D performs two analysis iterations to derive the underlying stellar properties like surface mass...
density. In the first one, PIPE3D uses a MUISCAT simple stellar population (SSP) library (Vazdekis et al. 2012) with a limited number of templates (covering four ages and three metallicities), and it is used just to analyze the kinematic properties of the stellar populations and the dust attenuation, and to remove the contamination by the emission lines. After removing the contamination from the emission lines, PIPE3D performs a second more detailed modeling of the stellar population, adopting the GSD156 SSP library (Cid Fernandes et al. 2013) that comprises 156 templates covering 39 stellar ages (from 1 Myr to 14.1 Gyr), and four metallicities (Z/Z_{\odot} = 0.2, 0.4, 1, and 1.5). These templates have been extensively used within the CALIFA collaboration (e.g., Pérez et al. 2013; González Delgado et al. 2014) and for other surveys (e.g., Ibarra-Medel et al. 2016; Sánchez-Menguiano et al. 2017). Its current implementation for the MaNGA data set is described in Sánchez et al. (2019).

The projected surface mass density is further derived assuming the Salpeter (Salpeter 1955) initial mass function (IMF). Following Barrera-Ballesteros et al. (2016), we deproject the observed surface mass densities using $b/a$ ratios to take inclination into account:

$$\Sigma_* = \Sigma_{*\text{obs}} \times (b/a),$$  \hspace{1cm} (1)

where $\Sigma_{*\text{obs}}$ is the observed, projected surface mass density derived by PIPE3D, and $\Sigma_*$ is the deprojected surface mass density. The SFR per unit area ($\Sigma_{\text{SFR}}$) is also deprojected in the same way. In the text hereafter, the stellar surface $\Sigma_*$ and $\Sigma_{\text{SFR}}$ always refer to the deprojected quantities.

SFRs are measured from extinction-corrected H$\alpha$ luminosity. Emission lines, including H$\alpha$ and those used for metallicity calibrators, are corrected for dust extinction using the Balmer decrement, assuming the star-forming extinction law of Calzetti et al. (2000) with $R_V = 4.05$. For the Balmer decrement, we assume a theoretical flux ratio of H$\alpha$/H$\beta = 2.86$ (Osterbrock & Ferland 2006). For spaxels with H$\alpha$/H$\beta < 2.86$, we do not correct for extinction. After extinction correction, SFRs are computed from the H$\alpha$ luminosity (Kennicutt 1998). Using the Cardelli et al. (1989) extinction law with $R_V = 3.1$ only results in a 3% difference in H$\alpha$ luminosity (Catalán-Torrecilla et al. 2015).

In this paper, both SFRs and surface mass densities are derived using the Salpeter IMF. Compared to a Chabrier IMF (Chabrier 2003), the Salpeter IMF produces SFRs that are higher by 0.2 dex and stellar masses that are higher by 0.22 dex (Belfiore et al. 2018). The specific star formation rate (sSFR) is the ratio between SFR and stellar mass, and so the difference between using either the Salpeter or Chabrier IMF to derive sSFR is negligible.

2.4. Galaxy Morphology Indicators

Several quantitative morphology indicators have been developed for galaxies. To search for ongoing interactions, the asymmetry index ($A$; Schade et al. 1995; Abraham et al. 1996; Bershadly et al. 2000; Conselice et al. 2000) is designed to look for disturbed morphology. For a similar purpose, the Gini coefficient together with the second moment of a galaxy’s brightest regions ($M_{20}$) is used to search for mergers, especially for high-redshift samples (Lotz et al. 2004). The shape asymmetry index (Pawlik et al. 2016) and outer asymmetry index (Wen et al. 2014) are revisions of the asymmetry index that are more sensitive to low-surface-brightness structures.

The clumpiness index (Conselice 2003) is used to look for clumpy structures like compact star-forming clusters (Isserstedt & Schindler 1986; Takamiya 1999). The prominence of bulges (e.g., bulge-to-disk ratios) can be inferred by either the model-dependent Sérsic index or the non-parametric concentration index (C: Abraham et al. 1994, 1996; Bershadly et al. 2000).

In this paper, we use the model-independent morphology indicators of concentration ($C$) and asymmetry ($A$). They are measured on the $i$-band images from the Panoramic Survey Telescope and Rapid Response System Data Release 1 (Chambers et al. 2016; Flewelling et al. 2016). With a mean point source 5σ depth of 23.1 (AB mag) in stacked images and a median PSF of 1.11 arcsec in the $i$-band, PanSTARRS provides deeper images and higher angular resolution than the SDSS, resulting in more reliable morphology measurements.

The asymmetry index $A$ is measured by comparing the original image with one rotated by 180°:

$$A = \frac{\sum_{i,j}|I(i,j) - I_{180}(i,j)|}{\sum_{i,j}|I(i,j)|} - A_{\text{bg}},$$  \hspace{1cm} (2)

where $I$ is the original image and $I_{180}$ is the one rotated by 180° about the galaxy’s center, which is chosen to minimize $A$. $A_{\text{bg}}$ is the asymmetry measured in the 32 × 32 pixel background where no structure is detected. The asymmetry index is computed over all pixels of a galaxy within 1.5 $R_p$, where $R_p$ is the circular Petrosian radius (Petrosian 1976). For a completely symmetric case, $A = 0$, or it could be slightly negative due to the subtraction of positive $A_{\text{bg}}$. Typically, galaxies with $A \geq 0.2$ are considered morphologically disturbed.

The concentration index is derived using the radii that enclose 80% ($R_{80}$) and 20% ($R_{20}$) of the galaxy’s total flux. Specifically,

$$C = 5 \log \left( \frac{R_{80}}{R_{20}} \right).$$  \hspace{1cm} (3)

We use the definition of the total flux as the flux enclosed within 1.5 $R_p$ from the galaxy’s center. A higher concentration index means the light is more centrally concentrated. This correlates with the bulge-to-total-light ratios in late-type galaxies (Conselice 2003).

The morphology measurements were performed with the statmorph v0.2.0 code (Rodriguez-Gomez et al. 2019). When the morphology measurements are used, we only include galaxies where the S/N per pixel >4 in the $i$-band image. We also have removed galaxies with flag $= 0$, which indicates that there was a problem with the basic measurements, for example, the presence of foreground stars and image artifacts.

2.5. Classification of Interaction Stages

The asymmetry index is mainly sensitive to the disturbed morphology at the first passage and the final coalescence during the interaction (Lotz et al. 2008). However, galaxies in interaction spend most of the time in close pairs without strong morphological disturbance, while inflows may have played a role in shaping the metallicity distribution since this stage (Ellison et al. 2008b). Therefore, taking different interaction
stages into account is crucial to understanding how interactions drive the inflows.

We classify galaxies into three interaction categories: mergers, close pairs, and isolated galaxies. Mergers here refer to those interacting systems at the final coalescence stage. In the literature, mergers are often identified using morphology indicators, such as CAS (concentration, asymmetry, clumpiness; Conselice 2003), and Gini–$M_{20}$ coefficients (Lotz et al. 2004). To avoid irregular galaxies and to be more sensitive to low-surface-brightness signature, we adopt the classification of the interaction via visual inspection.

The visual classification of the interaction stages is performed by H.-A. Pan et al. 2018, (in preparation) for interacting galaxies selected from the MaNGA MPL6 sample. They selected the interacting candidates by meeting one of three criteria: (1) spectroscopic close pairs with a projected separation of 50 kpc ($h = 70$) and line-of-sight velocity difference of $<500\text{ km s}^{-1}$ (Lin et al. 2004; Keenan et al. 2014) selected from the NASA-Sloan Atlas (NSA)\textsuperscript{15} matched to the MaNGA MPL6 sample; (2) $f_{m} > 0.4$, where $f_{m}$ is the “weighted-merger-vote fraction” based on the citizen classifications in the Galaxy Zoo project (Darg et al. 2010; Lintott et al. 2011); (3) galaxies having a companion within the same MaNGA bundle. This selection results in $\sim$1300 interacting candidates, which are further visually classified into five classes:

1. Class 0: non-interacting galaxies or a potential paired galaxy without a spec-z confirmation for its companion.
2. Class 1: well-separated pairs not showing any morphology distortion, including very close pairs without distortions (i.e., just before the first passage).
3. Class 2: well-separated pairs showing strong signs of interaction, such as tails, bridges, etc. (after the first passage).
4. Class 3: well-separated pairs showing a weak morphology distortion.
5. Class 4 (final coalescence): two components strongly overlapping with each other and showing a strong morphology distortion.

We consider Class 4 as merging galaxies, Class 1–3 as close pairs, and other galaxies except Class 0 as isolated galaxies because Class 0 still has potential paired galaxies. Out of the sample of 1222 star-forming galaxies, 55 (4.5%) are mergers, 161 (13.2%) are in close pairs, and 929 (76.0%) are classified as isolated galaxies.

2.6. Metallicity

2.6.1. Metallicity Indicators

The oxygen abundance in the ISM can be measured using electron temperature-sensitive line ratios between nebular and auroral lines (e.g., [O III]$\lambda$5007 and [O III]$\lambda$4363), known as the direct method (e.g., Izotov et al. 2006). However, auroral lines are $\sim$100 times fainter than nebular lines, making the direct method challenging in typical S/N spectra. Alternatively, various strong-line methods have been developed on the basis that the flux ratios between strong lines also contain information on metallicity. Commonly used strong-line combinations include ([O III]$\lambda$3927.9 + [O III]$\lambda$4959 + [O III]$\lambda$5007]/H$\beta$ (R23; Pagel et al. 1979; Tremonti et al. 2004), ([O II]$\lambda$3727/H$\beta$) $\alpha$ ([N II]$\lambda$6584/H$\alpha$) (O3N2; Pettini & Pagel 2004; Marino et al. 2013), [O II]$\lambda$3927.9/[N II]$\lambda$6584 (O2N2; Kewley & Dopita 2002; Dopita et al. 2013), and a Bayesian-based method that takes multiple lines into account (Blanc et al. 2015). Some strong-line methods are calibrated by the direct method, while others are calibrated through photoionization models. The absolute oxygen abundances from different metallicity calibrators can differ by $\sim$0.4 dex (Kewley & Ellison 2008). Since our analysis depends only on the relative values of metallicities, the accuracy of the absolute values of the metallicity calibrators is not the main concern.

However, strong-line flux ratios also depend on other physical conditions in the ISM and not just the metallicity. Specifically, one needs to distinguish among the effects of metallicity, ionization parameter, and the hardness of ionizing spectra (Kewley et al. 2013). These properties may also be physically correlated, e.g., lower metallicity regions tend to have higher ionization parameters (Dopita et al. 2013; Morisset et al. 2016). Using line ratios that depend strongly on the ionization parameter or the hardness of the ionizing radiation can complicate the interpretation of the derived metallicities. The photoionization models show that [O III]/H$\beta$ is also sensitive to ionization parameter (Dopita et al. 2013). Also, the ionization potential to produce doubly ionized oxygen (35.1 eV) is much higher than for singly ionized hydrogen, nitrogen, and oxygen (13.6, 14.5, and 13.6 eV, respectively). For these reasons, neither the R23 nor the O3N2 metallicity calibrators are ideal for the purpose of this study.

In this paper, metallicity is estimated using the [O II]/[N II] ratio. We use the pyqz code v0.8.4 (Dopita et al. 2013; F. P. A. Vogt et al. 2018, in preparation) with the MAPPINGS V model grid of [O III]/[O II] versus [O II]/[N II] (Sutherland & Dopita 1993; Allen et al. 2008; R. S. Sutherland et al. 2018, in preparation). The main idea is similar to what is described in Dopita et al. (2013), where they used the MAPPINGS IV model grid, but MAPPINGS V has upgraded some input atomic physics, the depletion of heavy elements onto dust, and the methods of solution (Dopita et al. 2016). We use models with the abundance pattern and depletion fractions as described in Dopita et al. (2016) and Nicholls et al. (2017). As shown in Figure 2, [O II]/[N II] is mainly sensitive to metallicity while [O III]/[O II] is sensitive to the ionization parameter. The effect of the non-Maxwellian $\alpha$-distributed electrons (Nicholls et al. 2012; Pierrard & Lazar 2010) is small on the model grid in the [O III]/[O II]–[O II]/[N II] space (Dopita et al. 2013). We note that a recent study shows that the electron energy distributions in H II regions closely follow the Maxwell–Boltzmann distribution (Draine & Kreisch 2018). Also, the ionization potentials are very similar for [N II] and [O II], so the hardness of the ionizing spectra plays a minor role in the resulting flux ratios.

We adopt the model grid assuming a Maxwellian electron distribution and an ISM pressure log$(P/k) = 5.5$ in spherical H II regions. Using different ISM pressures mainly affects the measured ionization parameters but leaves the estimated metallicities nearly unchanged. For spaxels located inside the grid, we derive their metallicities and ionization parameters from the model grid using cubic interpolation. For spaxels outside the grid, we extrapolate these quantities for them but discard those located more than 0.3 dex away from the grid boundary.

Figure 2 shows the distributions of pure star-forming spaxels in MaNGA late-type galaxies in the extinction-corrected [O III]/[O II]–[O II]/[N II] space, overlaid with the model grid

\textsuperscript{15} http://nsatlas.org/
described above. The majority of pure star-forming spaxels have ionization parameters of $\log q \sim 7.25^{16}$, slightly tilting to higher ionization parameters at the low-metallicity end ($12 + \log (O/H) < 8.5$). It is consistent with previous works that H II regions with lower gas-phase metallicities on average have higher ionization parameters (Dopita et al. 2013; Morisset et al. 2016).

Although we attempt to select a calibrator that is most suitable for our purpose, the reality is that every metallicity calibrator has its pros and cons. We choose an O2N2-based metallicity calibrator here because it has a weak dependence on the ionization parameter. However, its main weakness is that the wider wavelength range of the emission lines used makes it more sensitive to dust extinction. Also, the photoionization models for this indicator assume a relation between the $O/\text{H}$ and $N/O$ abundance ratios (Dopita et al. 2016). Therefore, while we select the O2N2-based calibrator carefully for the aforementioned reasons, we also reproduce our key results using many other metallicity calibrators in the Appendix. The conclusions of this paper do not change with different calibrators, and the O2N2-based calibrator we choose turns out to be representative among all calibrators we test (see the Appendix). Therefore, in the rest of the paper, we present the results using the O2N2-based metallicity calibrator.

2.6.2. Definition of Anomalously Low-metallicity (ALM) Regions

We identify ALM regions by comparing the observed metallicity to the expected metallicity based on existing empirical correlations. The central oxygen abundance increases with galaxy stellar mass and gradually saturates at the high-mass end (Tremonti et al. 2004). A similar correlation is found at ~kpc scales: the local metallicity is also correlated with $\Sigma_*$, the local stellar surface mass density (Moran et al. 2012; Rosales-Ortega et al. 2012). The local $\Sigma_*-Z$ relation may explain the global $M-Z$ relation, but the local $\Sigma_*-Z$ relation in low-mass ($\lesssim 10^{10.5} M_\odot$) galaxies systematically deviates to lower metallicities (Barrera-Ballesteros et al. 2016). Therefore, to predict the local metallicity, at least two parameters are required: the total stellar mass and the local stellar surface mass density.

For every star-forming spaxel, the expected metallicity is computed based on the correlations with total stellar mass and local surface mass density. As shown in Figure 3, for each stellar mass bin, we correlate the local metallicity with the local stellar surface mass density. Specifically, for late-type galaxies in a certain stellar mass bin, we select the pure star-forming spaxels that have measured metallicities. Then for each surface mass density bin of these spaxels, we compute the “mode” of the metallicity distribution. We use the mode because the distribution has a low-metallicity tail (like Figure 5) such that the median values are offset from the peaks. The “mode” of the
metallicity distribution is derived using the peak of a fitted skewed Gaussian profile which takes the low-metallicity tail into account. The “modes” in each stellar mass bin and surface mass bin are present as circles in Figure 3. The step of the stellar mass bin is 0.5 dex, except for the bin of $10^{10.1-12} M_{\odot}$, because fewer galaxies have masses $>10^{10.5} M_{\odot}$ and because the relation between metallicity and surface mass density does not vary significantly in this mass range.

The shape of the $\Sigma_{\text{metal}}-Z$ relation depends on the metallicity calibrated used. For example, using the O3N2 calibrator from Marino et al. (2013) gives a flatter $\Sigma_{\text{metal}}-Z$ relation on the high surface mass density end (Barrera-Ballesteros et al. 2016). But, as detailed later, because we are computing the metallicity difference at a fixed surface mass density, the overall shape of the $\Sigma_{\text{metal}}-Z$ relation does not affect our result. Some key results using different calibrators are shown in the Appendix.

We do not restrict our sample to non-interacting galaxies when we derive the $\Sigma_{\text{metal}}-Z$ relation in Figure 3. In fact, the result is nearly the same if we exclude them. This is because (1) interacting galaxies (mergers and close pairs) only constitute 18% of the star-forming galaxies, and (2) we use the “modes” to construct the $\Sigma_{\text{metal}}-Z$ relation. While the mean values are easily affected by outliers, the “mode” of the distribution is determined by the entire population so it remains almost unchanged.

The expected metallicity $(12 + \log(O/H))_{\text{exp}}$ is computed via the interpolation of both stellar mass and surface mass density from the symbols in Figure 3. For a given galaxy, we first interpolate the expected local $\Sigma_{\text{metal}}-Z$ relation for its total stellar mass. During the interpolation, each stellar mass bin represents the central value of its range. For example, the local $\Sigma_{\text{metal}}-Z$ relation for the stellar mass bin $10^9-10^{9.5} M_{\odot}$ represents the relation for a $10^{9.25} M_{\odot}$ galaxy. The exception is the most massive bin of $10^{10}-10^{12} M_{\odot}$, which represents a $10^{10.25} M_{\odot}$ galaxy (since most galaxies in this bin are in the range of $10^{10}-10^{10.5} M_{\odot}$). The bin of $10^{8.5}-10^{9} M_{\odot}$ is only used for interpolation, and we do not further analyze the galaxies in this bin. In the stellar mass bin $10^8-10^9$ and $10^9-10^{9.5} M_{\odot}$, galaxies do not cover the high surface density end ($>10^{8.8} M_{\odot} kpc^{-2}$), and we assume the same metallicities as their highest surface density bins for the uncovered bins during the interpolation. Therefore, the local $\Sigma_{\text{metal}}-Z$ relation for a galaxy of a specific total stellar mass is interpolated from these points. With the local $\Sigma_{\text{metal}}-Z$ relation for this galaxy, the metallicity expected for every spaxel is derived based on its surface mass density using interpolation.

The metallicity deviation is computed as $\Delta \log(O/H) = (12 + \log(O/H))_{\text{obs}} - (12 + \log(O/H))_{\text{exp}}$. Figure 4 presents the metallicity deviation as a function of stellar mass. It shows that there is no dependence on stellar mass over the range $10^9-10^{11} M_{\odot}$, which is the stellar mass range of interest in this paper.

The blue histogram in Figure 5 shows the distribution of metallicity deviation for the entire sample of spaxels. Because of the use of “modes” instead of medians in individual bins, the
Figure 7. Examples of galaxies having ALM regions. MaNGA plate IFU ID from top: 8252-9102, 9883-3701, 8466-12702, 8945-12705, and 8551-3701. From left to right: SDSS optical images, Hα maps, and metallicity deviation maps where $\sigma_Z = 0.07$ dex. Some galaxies are associated with strong interaction, while some are isolated. The size of the spaxels is 0.5 arcsec on each side. Spaxels without metallicity measurement are either not purely star-forming regions or have emission lines below the adopted S/N ratio cuts.
peak of the distribution is well located at ~0 as expected. The
distribution is notably asymmetric, with a tail extending to low
metallicity and no corresponding feature on the high-metallic-
city side.

We fit the metallicity deviation distribution in Figure 5 with
two components: ALM spaxels, whose metallicities are
lowered by some mechanisms, and “normal” spaxels, whose
metallicities follow the local $\Sigma_d-Z$ relation very well. There-
fore, the positive side of the metallicity deviation distribution is
dominated by “normal” spaxels. We determine $\sigma_Z$, the standard
deviation for “normal” spaxels, by fitting a Gaussian profile to
the positive side and an assumed symmetric negative side. The
best fit is shown as the dashed orange profile in Figure 5, giving
$\sigma_Z = 0.07$. The positive side of the metallicity deviation is well
described by the best-fit Gaussian profile.

The term $\sigma_Z$ contains several effects: possible mechanisms
that affect the metallicities, the intrinsic scatter of the
metallicity calibrator, uncertainty in the interpolations, all
measurement errors including $b/a$ ratios, total stellar mass,
surface mass density, flux ratios, and extinction correction.
Therefore, by using $\sigma_Z$ as a criterion, we consider that this
effectively takes these uncertainties into account.

To quantify the ALM spaxels in Figure 5, we derive the residual
(the black solid line) by subtracting the fitted Gaussian
profile of the normal spaxels from the total. The residual
intersects with the fitted Gaussian profile at $\Delta(O/H) = -0.13$.
Motivated by this, we define the low-metallicity spaxels as those
in which the observed metallicities are lower than the expected
ones by more than $2\sigma_Z = 0.14$, or $\Delta \log(O/H)/\sigma_Z < -2$.
Hereafter, we will use the term ALM to refer to those spaxels
where $\Delta \log(O/H) < -2\sigma_Z$.

With this criterion for ALM spaxels, here we further define
the galaxies having ALM regions. The definition is motivated
by the size of the PSF and by the requirement that these low-
metallicity spaxels need to constitute at least a certain fraction
of the pure star-forming spaxels in a galaxy. Specifically, with
a typical PSF of 2.5 arcsec (~1.5 kpc at $z = 0.03$) in FWHM and
0.5 arcsec for the size of a spaxel, the angular area of the PSF
corresponds to ~19.6 spaxels. Therefore, we require that
galaxies defined as having ALM regions have at least 20 ALM
spaxels. To decide how to define the subset of galaxies with
ALM spaxels, we use two other arguments. First, if the
metallicity deviation of normal spaxels is a perfect Gaussian
profile with a standard deviation of $\sigma_Z$, statistically, there is
~2.1% of normal spaxels satisfying the criterion for ALM
spaxels. Second, in Figure 6 we show the distribution for the
fraction of star-forming spaxels in a galaxy that are classified as
ALM, which we call the “ALM covering fraction.” The peak at
0 in late-type galaxies means that the majority of galaxies do
not have ALM spaxels. The distribution then drops steeply
from a fraction of 0%–4%, and then levels off, indicating an
additional component.

Based on these two factors, we introduce a cut of 4% as our
criterion. Afterwards, we visually inspect the candidate
galaxies having ALM regions, and exclude the galaxies whose
ALM spaxels are randomly distributed and therefore no
convincing ALM regions are identified. In conclusion, galaxies
having ALM regions are defined such that they have at least 20
ALM spaxels and that these ALM spaxels constitute more than
4% of the star-forming spaxels in the galaxy.
3. Results

Before any quantitative analysis, we begin this section by showing images that represent common examples of galaxies having ALM regions (in Figure 7). Such regions can be found in a variety of galaxies: interacting and non-interacting galaxies, both with and without bars. In the maps of metallicity deviation in Figure 7, blue and purple spaxels represent ALM gas. Spaxels without a metallicity deviation measurement in the maps have either low S/N ratios in some emission lines, are not purely star-forming regions based on the BPT diagram, or have bad data quality flagged in the pipeline. A simple inspection of these examples shows that the ALM regions can cover relatively large parts of some interacting galaxies (8252-9102 and 9883-3701), while in other galaxies, the ALM regions are smaller and can be located in both the inner (8551-3701) and outer disk (8466-12702).

Figure 9. Left: the fraction of star-forming galaxies having ALM regions (i.e., the occurrence rate) with respect to global properties. Right: the fraction of star-forming spaxels classified as ALM (the ALM covering fraction) in ALM galaxies. The x-axis error bars indicate the range of the bins. The y-axis error bars are the Poisson errors (left) and the standard deviation of the mean (right). The positions of the dots represent the median values in the bins.
and 8945-12705). Sometimes, especially in non-interacting galaxies, corresponding structures can be identified in the optical images, for example 8466-12702 and 8945-12705 in Figure 7. These structures include blue regions of ongoing star formation and faint structures, which might be accreting dwarf galaxies. In the following sections, we quantify these results and determine which global and local properties correlate most strongly with the presence of ALM regions.

### 3.1. Correlations with Global Properties

In Figure 8, we correlate the presence of ALM regions with the global properties of galaxies, including the total stellar mass, $M_*$, and $r$ colors, asymmetry, and concentration. Compared to the star-forming sample, galaxies having ALM regions tend to be less massive, have bluer $r$ colors, and higher asymmetry indices, but are not significantly different in terms of the concentration. We perform the Kolmogorov–Smirnov (K-S) test to quantify the significance of the difference between the star-forming sample and the galaxies having ALM regions. The $p$-values, the probability that the two distributions are sampled from the same parent distribution, are $1 \times 10^{-6}$, $2 \times 10^{-29}$, $2 \times 10^{-10}$, and 0.3 for total stellar mass, $M_*$, $r$ colors, asymmetry index, and concentration, respectively. Therefore, the differences are significant in $M_*$, $r$ colors, and asymmetry index, but not in concentration.

**Figure 10.** Fraction of ALM spaxels among all star-forming spaxels, with the normalized distributions of star-forming and ALM spaxels at top. The fraction of ALM spaxels rises steeply with decreasing $D_n4000$, increasing sSFR and EW(Hα), while it slightly increases at larger galactocentric radii.
In Figure 9, we further investigate the occurrence rate of galaxies having ALM regions as a function of stellar mass, NUV−r color, and the asymmetry index. The fraction of star-forming galaxies with ALM regions drops strongly with increasing stellar mass, from nearly 30% at $10^9 M_\odot$ to nearly 0% at $10^{11} M_\odot$. A complementary view is provided by Figure 9 in the right panels. Here we select only the ALM galaxies, and then plot the fraction of star-forming spaxels that are classified as ALM in these galaxies as a function of the stellar mass. We define this as the “ALM covering fraction.” This shows that the ALM covering fraction drops from about 30% at $10^9 M_\odot$ to about 10% above $10^{10.5} M_\odot$. This means that ALM regions tend to cover a larger fraction of SF regions in less massive galaxies.

On average, galaxies with ALM regions are bluer in NUV−r colors by 0.5 mag (Figure 8). Among the bluest galaxies (NUV−r < 1.5), roughly 70% have ALM regions (Figure 9). This fraction drops to only about 10% for galaxies redder than NUV−r ∼ 3.0. The results establish a connection between low-metallicity regions and higher global sSFRs. Also, the ALM covering fraction drops from about 35% for galaxies bluer than NUV−r = 1.8 to about 25% for the rest.

Figure 9 shows that the fraction of ALM galaxies rises with increasing asymmetry index: from only about 10% at asymmetry ∼ 0, to ∼50% for asymmetry > 0.2 (strongly disturbed). Similarly, the ALM covering fraction in ALM galaxies is higher for strongly disturbed galaxies. All of these results are consistent with the conclusions in Reichard et al. (2009) based on SDSS central fiber data that more metal-poor galaxies are more lopsided at fixed mass (see also Michel-Dansac et al. 2008). However, the majority of ALM galaxies actually do not have a strongly disturbed morphology. Specifically, 82% of galaxies with ALM regions have an asymmetry index less than 0.2. In other words, while highly asymmetric galaxies are much more likely to have ALM regions, the majority of galaxies with ALM regions are not highly asymmetric. Some may be in interacting systems at early stages without strong morphological disturbance, or experiencing minor mergers with satellite galaxies. We will discuss this further in Section 3.3.

Finally, Figure 8 shows that there is no apparent difference in the concentration index between star-forming galaxies with and without ALM regions (with a p-value of 0.3 from the K-S test). The concentration index is a measure of bulge-to-disk ratios and the Hubble types of late-type galaxies (Conselice 2003). Therefore, the presence of low-metallicity regions is nearly independent of the relative strength of the bulge for late-type galaxies. However, we are pre-selecting star-forming galaxies, which will tend to have smaller bulges. Therefore, the lack of a trend could be due to the relatively small range of the concentration index.

### 3.2. Correlations with Local Properties

In this section, we will examine whether spaxels containing ALM gas differ systematically in terms of their other local properties. To probe a connection to the star formation, we will use two local parameters. The first is the amplitude of the 4000 Å break or $D_n4000$ (the ratio of continuum fluxes on either side of the 4000 Å break caused by long-lived low-mass stars). This is an indicator of the specific SFR (sSFR) over timescales of $\sim 10^8$ to $10^9$ yr (Kauffmann et al. 2003a). We will also use the extinction-corrected $H\alpha$ emission-line luminosity.

---

**Figure 11.** Metallicity deviation versus specific SFR (top), EW(Hα) (middle), and $D_n4000$ (bottom) for star-forming spaxels, where $\sigma_2 = 0.07$ dex. The circles indicate the median values, and the error bars show the standard deviation. The blue dots are the ALM spaxels, and the red dots are the rest of the spaxels. Spaxels having higher sSFR, higher EW(Hα), and lower $D_n4000$ deviate more to the lower metallicity.
to calculate the local SFR per unit area ($\Sigma_{\text{SFR}}$), and divide this by the local stellar surface mass density ($\Sigma_*$) to determine the local sSFR ($= \Sigma_{\text{SFR}}/\Sigma_*$). This measures the sSFR over much shorter timescales than $D_e$4000. We also use the equivalent width of $\text{H} \alpha$ (EW($\text{H} \alpha$)), which is a non-parametric indicator of sSFR. Although the relation between sSFR and EW($\text{H} \alpha$) is very tight (Sánchez et al. 2013; Belfiore et al. 2018), we decide to present the results for both of them because while sSFR has a more direct physical meaning, EW($\text{H} \alpha$) is independent of stellar population models and free from the error propagation caused by the measurement of the stellar surface mass density.

Figure 10 shows the kiloparsec-scale local properties of low-metallicity regions. The error bars are Poisson errors, and when we compute them, we divide the number of spaxels in each bin by 20 because the size of the PSF means that not all spaxels are independent. The fraction of ALM spaxels among all star-forming spaxels as a function of sSFR, EW($\text{H} \alpha$) is independent of this particular choice. This is shown in Figure 11, where we plot the metallicity deviation of star-forming spaxels as a function of sSFR, EW($\text{H} \alpha$), and $D_e$4000. There are clear and systematic trends for larger metallicity deviations for young (more strongly star-forming) regions in both plots that are independent of any specific definition of ALM.

The strong connection between ISM metallicity and a young stellar population suggests that the star formation in the ALM regions may be triggered by the arrival of low-metallicity gas. The young stellar ages in low-metallicity regions also constrain the lifetime of these regions. We will return to this point in Section 4.2 below.

### 3.3. Interactions and Interaction Classes

In Section 3.1, we found that galaxies having a higher asymmetry index tend to have ALM regions, suggesting that galaxy interactions play an important role in producing these ALM regions. Since the asymmetry index is mainly sensitive to the strongest morphological disturbances and later interaction stages, and does not reflect the entire interaction process, we further consider the visual classification of three interaction classes: mergers, close pairs, and isolated galaxies (see details in Section 2.5).

In our star-forming galaxy sample, 52% (29/55) of mergers and 30% (49/161) of close pairs have ALM regions, while only 23% (229/1006) of isolated galaxies have them. The higher occurrence rate in stronger interacting systems suggests that interaction may be able to trigger ALM regions.

Figure 12 demonstrates how ALM regions are distributed radially in the ALM galaxies. In each radial annulus, we collect all star-forming spaxels for a certain class of ALM galaxies and compute the median metallicity deviation and the standard deviation of the mean (represented as vertical bars in the left panel of Figure 12). When computing the standard deviation of the mean, we take the PSF into account by dividing the total $1 R_e$ to 17% outside $2 R_e$. It means that ALM regions slightly prefer the outer regions. We will show in Section 3.3 that the radial distribution of ALM regions is related to the interaction stage.

We note that although we have chosen a specific metric to define ALM regions (a metallicity deviation of more than $2\sigma_Z$, equivalent to an offset of more than 0.14 dex in O/H), the connection of metallicity deviation and star formation is independent of this particular choice. This is shown in Figure 11, where we plot the metallicity deviation of star-forming spaxels as a function of sSFR, EW($\text{H} \alpha$), and $D_e$4000. There are clear and systematic trends for larger metallicity deviations for young (more strongly star-forming) regions in both plots that are independent of any specific definition of ALM.

The strong connection between ISM metallicity and a young stellar population suggests that the star formation in the ALM regions may be triggered by the arrival of low-metallicity gas. The young stellar ages in low-metallicity regions also constrain the lifetime of these regions. We will return to this point in Section 4.2 below.

**Figure 12.** Metallicity deviation (left) and covering fraction of ALM spaxels (right) versus galactocentric distances for galaxies having ALM regions. The metallicity deviations in the left panel show the median, and the error bars show the standard deviation of the mean. The horizontal segments show the median FWHM of the PSF in units of $R_e$. Spaxels in mergers deviate to lower metallicity the most in the inner regions, and the covering fraction of the ALM gas shows little radial variation. In close pairs and isolated galaxies, both the amplitude of the metallicity deviation and the covering fraction of ALM spaxels increase with increasing radius.
Here we exclude a close pair galaxy, 8312-12701, because it has an unreliable effective radius measurement in the NSA catalog. Figure 12 shows that different interaction classes have distinct radial distributions of ALM gas and different ALM covering fractions. Mergers have lower metallicity deviations over all radii, particularly in the inner regions ($<0.5 \, R_e$). In close pairs, the absolute metallicity deviations increase monotonically with radius, both in terms of the median deviation and the covering fraction of ALM spaxels. The radial distributions in mergers and close pairs suggest that, during the interaction, inflows lower the metallicity more significantly in the outer regions at the early stage, and then the low-metallicity material flows into the innermost region at the final coalescence phase. Thorp et al. (2019) study the...
metallicity profiles in post-merger galaxies (see also Ellison et al. 2018), showing similar results that these galaxies tend to have widespread regions having lower metallicities.

One can argue that the ALM regions identified in interacting systems are due to the inward radial transport of outer disk gas (which is more metal-poor), instead of the accretion of gas from outside the galaxy. While this scenario is possible, it is at odds with our finding that ALM regions are more likely to be found in the outskirts in close pairs and isolated galaxies.

In isolated galaxies, the metallicity deviation as a function of galactocentric radii is similar to that in close pairs, with larger deviation in the outer regions $\gtrsim 1 R_\odot$, while the amplitude is weaker than close pairs on average. This similarity hints that the ALM regions in isolated galaxies might be related to weaker interaction, like accreting satellite galaxies or CGM/IGM gas.

In addition to radial variations, some close pairs have intriguing azimuthally asymmetric metallicity distributions. Figure 13 presents two of the clearest examples, 8454-12703 (left) and 8313-12702 (right). They have projected separations of 45 and 17 kpc ($h = 0.7$), respectively, from their companions. The regions of ALM are found mainly in the outer regions ($>0.5 R_\odot$) in both cases. Most interestingly, the metallicity deviations are much stronger on the sides closer to their companions. This azimuthal dependence can also be seen in the measured metallicity, as shown in the bottom row of Figure 13, where the x-axes are the azimuthal angles corrected for inclination, with $0^\circ$ pointing toward the companions.

The fact that the side closer to the companion has a lower metallicity suggests that these azimuthally asymmetric metallicity distributions may originate from the interaction with the companion. In 8454-12703 and 8313-12702, the low-metallicity regions have sizes on galactic scales. If they were from the infalling satellite galaxies, the galactic-scale infalling structures would have been seen in the optical images, and the morphologies of 8454-12703 and 8313-12702 would be strongly disturbed. However, 8454-12703 and 8313-12702 do not show any such discrete structures, and their disks are not strongly disturbed. Therefore, they may be the most convincing cases that their ALM regions are due to the metal-poor gas inflow, instead of accreting satellite galaxies or minor mergers. Out of the 48 close pairs with ALM regions, we find that six of them, including the two in Figure 13, show such azimuthal metallicity dependences. The occurrence of such metallicity distributions may depend on the interaction configurations, mass ratios, primary or secondary galaxy in close pairs, and/or gas content.

While the majority of galaxies with ALMs are not strongly interacting or merging systems, they may be interacting with small satellite galaxies that do not significantly perturb their morphology. As an example, we consider here the isolated ALM galaxy 8931-12702 (Figure 14). The galaxy has a strong bar and two distorted spiral arms. In addition, a faint third arm appears northwest to the galaxy without any symmetric counterpart on the other side. Furthermore, the third arm has a much lower metallicity than the rest of the galaxy. A much deeper optical image from DECaLS DR7 shows that there is a faint “great circle” structure around the galaxy. This structure is similar to the tidal streams like the Sagittarius stream around the Milky Way (Belokurov et al. 2006) and NGC 5907 (Martinez-Delgado et al. 2008). N-body simulations show that such tidal streams are due to the disruption of a satellite galaxy in the past 6–10 Gyr (Law et al. 2005; Johnston et al. 2008). The ALM region is connected to the great circle structure, suggesting they share the same origin.
3.4. Metal-poor Outer Rings

We found above that the strongest radial trends for ALM regions are that they are more prevalent in the outer disks of isolated massive star-forming galaxies. Here we show some examples of the morphology of these outer ALM regions. Figure 15 shows objects that have ALM regions in their outskirts, forming an outer “ring” (see their [O III] maps). All of these galaxies are isolated and non-interacting, and they have higher stellar mass (>10^{10} M_☉), older stellar population at the centers, with ongoing star-forming regions on the edges of the stellar disks.

4. Discussion

4.1. The Sources of Low-metallicity Gas

First, we note that our methodology searches for low-metallicity outliers, so it is mainly sensitive to individual events that have significantly lowered the ISM metallicity relative to expectations. Examples of such events would include enhanced radial inflow induced by interactions, accretion of dwarf galaxies, and infalling gas clouds from CGM and IGM. On the other hand, if there is gas inflow feeding galaxies constantly and spatially uniformly, its effect on metallicity would be incorporated into the local Σ_*–Z relation, and these regions would not be identified as ALM regions with our method.
Previous work on gas-phase metallicity mainly focused on the properties of the general population of star-forming spaxels. Some studies show that there is no strong correlation between the local $\Delta \log(O/H)$ with local SFRs (Sánchez et al. 2013; Barrera-Ballesteros et al. 2018), while some report such a relation (Sánchez Almeida et al. 2015, 2018). In terms of radial distribution, the metallicity gradients of MaNGA star-forming galaxies are reported in Belfiore et al. (2017). Similarly, the correlation between metallicity and local stellar surface mass density has been presented in several studies (Moran et al. 2012; Rosales-Ortega et al. 2012; Barrera-Ballesteros et al. 2016). While it is still under debate whether galactocentric distance or surface mass density is more fundamental to the metallicity distribution (e.g., Pilyugin et al. 2017), empirically, the local stellar surface mass density is strongly related to the distance (for a given stellar mass). Thus, when we select ALM spaxels by using the local surface mass density, we are effectively incorporating the radial dependence of metallicity. Our approach is different from these aforementioned studies, as we focus on the ALM outliers rather than the mean. Because ALM spaxels only constitute $\sim10\%$ of the star-forming spaxels, they make very little contribution to the correlations seen for the entire star-forming population and may be easily missed. Here we are specifically targeting them to study their properties and origin.

What is the origin of this ALM gas? One important clue is that the incidence rate and spatial distribution of this material is significantly larger in strongly asymmetric galaxies. This can be seen in Figures 8 and 9, as well as in Figure 12. This implies that in these cases, the low-metallicity inflow occurs as a result of strong interactions. This is further supported by the difference in the radial distributions of the ALM material in close pairs versus mergers (Figure 12). This implies that during the early stages of the interaction, the ALM material has been delivered to the outer part of the galaxy. During the subsequent merger, the ALM material is redistributed throughout the galaxy. The delivery of this gas leads to enhanced star formation on local and global scales in these systems.

However, it is important to emphasize that most of the galaxies with ALM regions are not in strongly interacting systems. While in principle this gas could have an entirely different origin, the most straightforward interpretation is that it is delivered by qualitatively similar (but smaller-scale) mechanisms, such as the capture of small satellite galaxies (see Figure 14) or accretion of gas clouds from the CGM or IGM. This is consistent with the association between ALM gas and strong star formation that we see on local and global scales in the whole sample (not just mergers and close pairs). The CGM is a plausible source for such material: CGM clouds have a mean metallicity about three times lower than the ISM and comprise at least as much gas mass as the ISM (Tumlinson et al. 2017 and references therein).

### 4.2. Timescales

In order to understand how frequently gas is accreted by galaxies, we begin by attempting to constrain the lifetime of the ALM regions we have identified. Below, we will consider several constraints: the lifetime of massive stars responsible for most of the oxygen in the ISM, the mixing timescales of low-metallicity gas, and the self-enrichment of the gas by metal-rich stellar ejecta.

The strong local connection between low-metallicity regions and lower $D_n(4000)$ in Figure 11 suggests that the young stellar population is recently born from the low-metallicity gas. Therefore, the stellar age serves as a clock in the low-metallicity regions. With a median $D_n(4000)$ of 1.2 for low-metallicity spaxels, the corresponding stellar age is $\sim 250$ Myr (Kauffmann et al. 2003a), providing a timescale for the lifetime of low-metallicity regions. The presence of low-metallicity gas is also correlated with the global specific SFR (based on NUV $-r$). On global scales, a simple causality argument implies that the SFR cannot vary significantly on timescales much shorter than a galaxy crossing time (of order a hundred Myr). This is consistent with the timing constraints based on the local stellar population.

We can also consider how long it would take low-metallicity material to physically mix with the surrounding (higher-metallicity) ISM. Locally, typical non-circular velocities in the ISM are of order $10$ km s$^{-1}$, so gas would mix on spatial scales of a few kiloparsec on timescales of a few hundred Myr. Differential rotation will lead to shear and radial mixing on timescales of a galaxy rotation period (few hundred Myr); see, for example, Davé & Ferrara (2018). The azimuthally asymmetric metallicity distribution seen in close pairs (Figure 13) also suggests that the mixing timescale is at least half of the rotation periods. Based on their stellar velocities, $8454–12703$ and $8313–12702$ have rotation periods of $\sim 200$ Myr, implying a mixing timescale of at least $\sim 100$ Myr. This is in agreement with our previous estimates. Numerical simulations based on the mixing driven by supernova (de Avillez & Mac Low 2002) and thermal instabilities (Yang & Krumholz 2012) are also consistent with these timescales.

Finally, we can consider how long it will take, once star formation begins, until the resulting metal-rich stellar ejecta self-enrich the ISM and erase the signature of the low-metallicity gas. Almost all oxygen in the ISM is produced by massive stars ($\gtrsim 8 M_\odot$). Their lifetimes are short ($\lesssim 30$ Myr), so oxygen from the nucleosynthesis in massive stars can enrich the ISM via supernovae very quickly. If we consider a simple closed-box model given a gas depletion time $\tau_{SF}$ and a constant SFR (so $\Sigma_* = \Sigma_{SFR} \times t$), the mass fraction of oxygen in ISM $X_O(t)$ is

$$X_O(t) = \frac{\Sigma_{oxygen}}{\Sigma_{gas}} = \frac{P \times \Sigma_*}{\Sigma_{SFR} - \Sigma_*} = \frac{P \times t}{\tau_{SF} - t},$$

where $P$ is the dimensionless oxygen yield integrating over the IMF, and $t$ is the time since the onset of star formation. Assuming $P = 0.007$ (Kobayashi et al. 2006; Zahid et al. 2012) and the Salpeter IMF, the time it takes for the ISM to reach solar metallicity from an initial half-solar metallicity is $0.17 \tau_{SF}$. Based on this simple closed-box model, we have an order-of-magnitude timescale for massive stars to enrich the ISM with oxygen. With the Kennicutt–Schmidt relation (Schmidt 1959; Kennicutt 1998; Bigiel et al. 2008), we estimate $\tau_{SF} \sim 1$ Gyr in the ALM regions, so this gas will be self-enriched on a timescale of a few hundred Myr.

We conclude that all of these arguments yield consistent lifetimes for the ALM regions of a few hundred Myr.

### 4.3. Masses and Accretion Rate

ALM regions are commonly found across the population of late-type galaxies. While they are more common in the lower mass galaxies, they can be found across the whole mass range. Moreover, they do not show any apparent dependence on
concentration, a proxy for bulge-to-disk ratios and hence the Hubble types of late-type galaxies (Conselice 2003). The ubiquity of these ALM regions suggests that they are part of the normal life cycle of typical late-type galaxies. If indeed accretion events causing the low-metallicity regions happen occasionally for all late-type galaxies, then the fraction of late-type galaxies having low-metallicity regions indicates the duty cycle for such accretion events. Based on the occurrence rate of having ALM regions in the star-forming galaxies, the overall duty cycle is $\sim$25% (307/1222). With the lifetime of ALM regions being a few hundred Myr, this implies that there is an accretion event once every $\sim$Gyr.

We now make an order-of-magnitude estimate of the mass involved and the implied accretion rate. Let us consider a typical MaNGA galaxy with ALM regions. For the typical stellar mass of $10^9$ to $10^{10} M_{\odot}$, the typical ISM (atomic and molecular) gas mass will be a few $\times 10^9 M_{\odot}$ (Catinella et al. 2018). Based on the covering fraction of ALM spaxels in ALM galaxies over this mass range, the implied mass of metal-poor gas in such a galaxy would be $10^9 M_{\odot}$. With one event per Gyr, the accretion rate per late-type galaxy would be $\sim 1 M_{\odot}$ yr$^{-1}$.

We can now compare this to the rate at which gas is converted into stars. In the local universe, the star-forming sequence has a mean SFR ranging from $\sim 0.3 M_{\odot}$ yr$^{-1}$ for $10^9 M_{\odot}$ to $\sim 1 M_{\odot}$ yr$^{-1}$ for $10^{10} M_{\odot}$ galaxies (Schiminovich et al. 2007). Therefore, an accretion rate of $1 M_{\odot}$ yr$^{-1}$ is able to supply gas for these low-mass late-type galaxies at a rate sufficient to offset their star formation. Of course, using ALM regions as sign posts may miss some of the accretion, especially if it happens more smoothly (rather than in events that are discrete in time, space, and chemical composition).

5. Conclusions

In this paper, we have used MaNGA data to identify regions of ALM in the ISM in 1222 local star-forming late-type galaxies. We have chosen to use the [O III]/[N II]-based oxygen metallicity calibrator in order to minimize the effect of the ionization parameter on the estimates. Only pure star-forming spaxels are analyzed so that this metallicity calibrator can be used. Based on the tight empirical relation between metallicity and local stellar surface mass density at fixed stellar mass, ALM regions are identified by those spaxels with observed metallicity lower than the expected value by more than 0.14 dex. We find few spaxels whose metallicities are higher than expected by this amount. By investigating the global properties of galaxies having ALM regions and their local properties, we present the following findings:

1. ALM regions are found in about 25% of the MaNGA star-forming galaxies. The low-metallicity spaxels comprise about 10% of the total number of star-forming spaxels over this same mass range.

2. The incidence rate of ALM regions decreases systematically with increasing stellar mass, from about 30% at $10^9 M_{\odot}$ to nearly zero at $10^{11} M_{\odot}$. The incidence rate is also much higher for bluer NUV$-r$ colors (and therefore higher global specific SFRs), reaching about 70% for galaxies bluer than NUV$-r = 1.5$. Roughly 50% of the strongly disturbed galaxies (asymmetry $>0.2$) have ALM regions, compared to only 25% of the less-disturbed galaxies. Nevertheless, the majority of ALM galaxies (82%) are not strongly disturbed. We find no strong trends with concentration (a proxy for Hubble type).

3. On local kiloparsec scales, the ALM regions have higher sSFRs and younger stellar populations. Specifically, the ALM incidence rate rises steeply as a function of $D_s$, reaching over 50% for the youngest and most actively star-forming regions.

4. The locations of ALM regions are strongly related to galaxy interaction. ALM regions can be found at all radii (including the centers) of mergers, while they tend to be located in the outer disk in close pairs and isolated galaxies.

5. Interesting morphologies of ALM regions are found. Some close pairs have an azimuthally asymmetric metallicity distribution, with lower metallicities on the sides closer to the companions. Also, low-metallicity outer rings are seen in the more massive galaxies ($>10^9 M_{\odot}$).

6. We have proposed that these ALM regions trace the sites of accretion of gas with a metallicity significantly less than that of the pre-existing ISM. This could be mass transfer or inflow in mergers or strong interactions, but their existence in non-interacting galaxies suggests that the accretion of gas from the CGM, IGM, and/or from gas-rich dwarf satellites can also be important.

7. Several independent lines of evidence suggest that the duration of the ALM regions is a few hundred Myr. Interpreting the incidence rate of 25% as a duty cycle, this would correspond to one accretion event per Gyr. The implied time-averaged accretion rate of this metal-poor gas is $\sim 1 M_{\odot}$ yr$^{-1}$, similar to the SFR of late-type galaxies over the stellar mass range $10^9$ to $10^{10} M_{\odot}$. Therefore, fed by bursty accretion events, local galaxies on the star-forming sequence can continue their star formation without running out of gas.

H.C.H. would like to acknowledge the helpful discussion with Christy Tremonti, Michael Dopita, and Frédéric Vogt. The authors are grateful to the anonymous referee for constructive suggestions.

Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS website is www.sdss.org.

SDSS-IV is managed by the Astrophysical Research Consortium for the Participating Institutions of the SDSS Collaboration including the Brazilian Participation Group, the Carnegie Institution for Science, Carnegie Mellon University, the Chilean Participation Group, the French Participation Group, Harvard-Smithsonian Center for Astrophysics, Instituto de Astrofísica de Canarias, The Johns Hopkins University, Kavli Institute for the Physics and Mathematics of the Universe (IPMU)/University of Tokyo, the Korean Participation Group, Lawrence Berkeley National Laboratory, Leibniz Institut für Astrophysik Potsdam (AIP), Max-Planck-Institut für Astronomie (MPIA Heidelberg), Max-Planck-Institut für Astrophysik (MPA Garching), Max-Planck-Institut für Extraterrestrische Physik (MPE), National Astronomical Observatories of China, New Mexico State University, New York University, University of Notre Dame, Observatório Nacional/MCTI, The Ohio State University, Pennsylvania State University, Shanghai Astronomical Observatory, United Kingdom Participation Group, Universidad Nacional...
Appendix

We have used a specific metallicity indicator in this paper. To show that our results are insensitive to this choice, we present here some of our most crucial results using different metallicity indicators. In doing so, we tried to select a diversity of metallicity calibrators: some use [O III], some use [S II]; some based on empirical methods anchored to the direct method, while some based on photoionization model. Our main conclusions do not change using these different metallicity calibrators.

We first summarize the metallicity calibrators we use.

Appendix A.1

Summary of Metallicity Calibrators

A.1.1. O3N2 (PP04)

This is a hybrid calibrator that uses the direct method for low-metallicity (12 + log(O/H) \( \lesssim \) 8.7) H II regions and photoionization models for high-metallicity (12 + log(O/H) \( \gtrsim \) 8.7) H II regions. The calibrator we use is Equation (3) of Pettini & Pagel (2004),

\[
12 + \log(O/H) = 8.73 - 0.32 \times \text{O3N2},
\]

where O3N2 = log \( \frac{[\text{OIII}]}{[\text{NII}]} \times \frac{\lambda_{5007}/H_{\beta}}{\lambda_{6584}/H_{\alpha}} \).

(5)

It is valid for \(-1 < \text{O3N2} < 1.9\). Since the wavelength of H\(\alpha\) is close to [N II] and H\(\beta\) is close to [O III], O3N2 calibrators are insensitive to dust extinction.

A.1.2. O3N2 (Marino+13)

It is calibrated using the direct method for the H II regions in the CALIFA survey. The calibrator is Equation (2) of Marino et al. (2013),

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

with O3N2 defined in Equation (5). The calibrator is valid for \(-1.1 < \text{O3N2} < 1.7\). Again, it is insensitive to dust extinction.

A.1.3. Calibrators from PG16

This is calibrated using the counterpart method anchored to the direct method. Pilyugin & Grebel (2016) provide two types of calibrators. One uses [O II] and the other one uses [S II], which are called “R calibration” and “S calibration,” respectively, in Pilyugin & Grebel (2016). Here we follow their notations for the flux ratios:

\[
R_2 = [\text{OII}] \lambda 3727, 9/H_\alpha,
R_3 = [\text{OIII}] \lambda 4959, 5007/H_{\beta},
N_2 = [\text{NII}] \lambda 6548, 84/H_{\beta},
S_2 = [\text{SII}] \lambda 6717, 31/H_{\beta}.
\]

(7)

The R and S calibrations consist of two equations for two metallicity ranges. The upper branch (log \( N_2 \gtrsim -0.6\)) of the R calibration, their Equation (4), is

\[
12 + \log(O/H) = 8.589 + 0.022 \log(R_3/R_2) + 0.399 \log N_2 + (-0.137 + 0.164 \log(R_3/R_2) + 0.589 \log N_2) \times \log R_2.
\]

(8)

and the R calibration for the lower branch (log \( N_2 < -0.6\)) is

\[
12 + \log(O/H) = 7.932 + 0.944 \log(R_3/R_2) + 0.695 \log N_2 + (0.970 - 0.291 \log(R_3/R_2) - 0.019 \log N_2) \times \log R_2.
\]

(9)

The calibration explicitly takes the excitation parameter \( P = R_3/(R_2 + R_3) \) into account, the spirit of which is similar to the [O III]/[O II] ratios we use to derive the metallicity from the model grid in Section 2.6.1. Because the dependence on the excitation parameter at the high-metallicity end is weak, the upper branch calibration (Equation (8)) can be reduced to a function of \( N_2 \) and \( R_2 \) only (see their Equation (8)). The reduced form only uses [O II], [N II], and H\(\beta\), making it similar to O2N2-based calibrators, although it does not explicitly depend on the [O II]/[N II] flux ratio. Only 0.4% of our SF spaxels are in the lower branch, but we still choose to use the full form (Equations (8) and (9)) to derive the metallicity.

The S calibration for the upper branch is Equation (6) in Pilyugin & Grebel (2016),

\[
12 + \log(O/H) = 8.424 + 0.030 \log(R_3/S_2) + 0.751 \log N_2 + (-0.349 + 0.182 \log(R_3/S_2) + 0.508 \log N_2) \times \log S_2,
\]

(10)

and the S calibration for the lower branch (log \( N_2 < -0.6\)) is

\[
12 + \log(O/H) = 8.072 + 0.789 \log(R_3/S_2) + 0.726 \log N_2 + (1.069 - 0.170 \log(R_3/S_2) + 0.022 \log N_2) \times \log S_2.
\]

(11)

Similar to the R calibration, the reduced form for the upper branch is also available (see their Equation (9)).

A.1.4. R23 (Tremonti+04)

This is calibrated by using Bayesian statistics to fit several emission lines (H\(\alpha\), H\(\beta\), [O III], [O II], [N II], and [S II]) to the theoretical models. Based on this, Tremonti et al. (2004) also provided the calibration for R23 in their Equation (9):

\[
12 + \log(O/H) = 9.185 - 0.313x - 0.264x^2 - 0.321x^3,
\]

(12)

where \( x = \log(R23) = \log([\text{OII}]3927.9 + [\text{OIII}]4959 + [\text{OIII}]5007)/H_{\beta} \). This R23 calibration is valid for the upper branch of the double-valued R23–metallicity relation. [N II]/[O II] ratios can be used to separate the upper and lower branches for R23 (Kewley & Ellison 2008). Only 0.002% of our SF spaxel sample are in the lower branch (log \( \frac{[\text{NII}]}{[\text{OII}]}) < -1.2\), so we apply Equation (12) for the entire sample without special treatment for the lower branch spaxels.
each calibrator, we reproduce Figures 3–5. \( \sigma_Z \) is set to the standard deviation of the best-fit Gaussian profile in each alternative version of Figure 5. Typically, the residual (the black line in Figure 5) intersects with the fitted Gaussian at around \(-2\sigma_Z\). Some exceptions are O3N2 (PP04) and O3N2 (Marino+13), whose intersections are \(-1.7\sigma_Z\). Following Section 2.6.2, we define spaxels deviating more than \(-2\sigma_Z\) as ALM spaxels.

Figure 16 presents our key results using these metallicity calibrators. The overall trend is the same, in that the fraction of ALM spaxels rises significantly with increasing sSFR and EW(H\(\alpha\)). At low sSFR and EW(H\(\alpha\)), all metallicity calibrators give similar ALM fractions, with 5% at EW(H\(\alpha\)) = 20 Å and <10% at sSFR <10\(^{-10}\) yr\(^{-1}\). The rising amplitudes differ from calibrator to calibrator. ALM fractions from two O3N2 calibrators (PP04 and Marino+13) rise the most steeply toward the higher EW(H\(\alpha\)) and sSFR. The ALM fraction can even reach 90% in the highest bin of EW(H\(\alpha\)). The R calibration (PG16) and the O2N2-based calibrator we use in this paper also show significant increasing ALM fractions toward the higher end of EW(H\(\alpha\)) and sSFR, but not as strong as the two O3N2 calibrators. R23 (Tremonti+04) also shows a similar trend. Interestingly, calibrators involving [S II] give a weaker trend. The S calibration has a similar amplitude to the R23 calibrator.

We emphasize that we select a variety of metallicity calibrators. The O3N2 calibrators are insensitive to extinction correction, supporting the fact that extinction plays a minor role in our results. Also, some use [O III] (two O3N2 and R23) while some do not, and some are calibrated through the direct method (two O3N2 and the two from PG16) while others are based on the photoionization models. Some explicitly take the ionization parameter (or excitation parameter) into account, like the R and S calibration from PG16 (empirical method) and the O2N2-based calibrator we use in this paper (photoionization model). The O2N2-based calibrator has a moderate trend, making it a good representative to present the results throughout the paper. Therefore, our results and conclusions in this paper do not change with different metallicity calibrators.

ORCID iDs

Hsiang-Chih Hwang @ https://orcid.org/0000-0003-4250-4437
Jorge K. Barrera-Ballesteros @ https://orcid.org/0000-0003-2405-7258

Timothy M. Heckman @ https://orcid.org/0000-0001-6670-6370
Lihwai Lin @ https://orcid.org/0000-0001-7218-7407
Hsi-An Pan @ https://orcid.org/0000-0002-1370-6964
Bau-Ching Hsieh @ https://orcid.org/0000-0001-5615-4904
Dmitry Bizyaev @ https://orcid.org/0000-0002-3601-133X
S. J. J. Z. Almeida @ https://orcid.org/0000-0003-1123-6003
David A. Thilker @ https://orcid.org/0000-0002-8528-7340
Jennifer M. Lotz @ https://orcid.org/0000-0003-3130-5643
Brett H. Andrews @ https://orcid.org/0000-0001-8085-5890
Niv Drory @ https://orcid.org/0000-0002-7339-3170

References

Abraham, R. G., Tanvir, N. R., Santiago, B. X., et al. 1996, MNRAS, 279, L47
Abraham, R. G., Valdes, F., Yee, H. K. C., & van den Bergh, S. 1994, ApJ, 433, 75
Allen, M. G., Groves, B. A., Dopita, M. A., Sutherland, R. S., & Kewley, L. J. 2008, ApJS, 178, 20
Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5
Barrera-Ballesteros, J. K., Heckman, T., Sanchez, S. F., et al. 2018, ApJ, 852, 74
Barrera-Ballesteros, J. K., Heckman, T. M., Zhu, G. B., et al. 2016, MNRAS, 463, 2513
Barrera-Ballesteros, J. K., Sanchez, S. F., Heckman, T., Bla, G. A., & Team, M. 2017, ApJ, 844, 80
Behroozi, P. S., Wechsler, R. H., & Conroy, C. 2013, ApJ, 770, 57
Belfiore, F., Maiolino, R., Bundy, K., et al. 2018, MNRAS, 477, 3014
Belfiore, F., Maiolino, R., Tremonti, C., et al. 2017, MNRAS, 469, 151
Belokurov, V., Zucker, D. B., Evans, N. W., et al. 2006, ApJ, 642, L137
Bershady, M. A., Jangren, A., & Conselice, C. J. 2000, AJ, 119, 2645
Bigiel, F., Leroy, A., Walter, F., et al. 2008, AJ, 136, 2846
Blanton, M. R., Kewley, L. A., Vogt, F. P. A., & Dopita, M. A. 2015, ApJ, 798, 99
Blanton, M. R., Bershady, M. A., Abolfloati, B., et al. 2017, AJ, 154, 28
Blanton, M. R., Kainz, E., Muna, D., Weaver, B. A., & Price-Whelan, A. 2011, AJ, 142, 31
Bothwell, M. S., Maiolino, R., Kennicott, R., et al. 2013, MNRAS, 433, 1425
Bundy, K., Bershady, M. A., Law, D. R., et al. 2015, ApJ, 798, 7
Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682
Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245
Catalán-Torrecilla, C., Gil de Paz, A., Castillo-Morales, A., et al. 2015, A&A, 584, A87
Catinella, B., Saintonge, A., Janowiecki, S., et al. 2018, MNRAS, 476, 875
Chabrier, G. 2003, PASP, 115, 763
Chambers, K. C., Magnier, E. A., Metcalfe, N., et al. 2016, arXiv:1612.05560
Chen, H.-W., Helsby, J. E., Gauvri, J.-R., et al. 2010, ApJ, 714, 1521
Chomiuk, L., & Povich, M. S. 2011, AJ, 142, 197
Cid Fernandes, R., Pérez, E., García Benito, R., et al. 2013, A&A, 557, A86

Figure 16. Figure 10 reproduced using different metallicity calibrators. The trend remains the same, only differing in amplitude. The O2N2 metallicity calibrator we used throughout this paper is representative for all calibrators tested here.
Wake, D. A., Bundy, K., Diamond-Stanic, A. M., et al. 2017, AJ, 154, 86
Wen, Z. Z., Zheng, X. Z., & An, F. X. 2014, ApJ, 787, 130
Westfall, K. B., Cappellari, M., Bershady, M. A., et al. 2019, arXiv:1901.00856
White, S. D. M., & Rees, M. J. 1978, MNRAS, 183, 341
Wild, V., Kauffmann, G., Heckman, T., et al. 2007, MNRAS, 381, 543
Yan, R., Bundy, K., Law, D. R., et al. 2016a, AJ, 152, 197

Yan, R., Tremonti, C., Bershady, M. A., et al. 2016b, AJ, 151, 8
Yang, C.-C., & Krumholz, M. 2012, ApJ, 758, 48
Zahid, H. J., Dima, G. I., Kewley, L. J., Erb, D. K., & Dave, R. 2012, ApJ, 757, 54
Zaritsky, D., Kennicutt, R. C. J., & Huchra, J. P. 1994, ApJ, 420, 87
Zheng, Z., Thilker, D., Heckman, T., et al. 2015, ApJ, 800, 120