SDSS-IV MaNGA: What Shapes the Distribution of Metals in Galaxies? Exploring the Roles of the Local Gas Fraction and Escape Velocity

J. K. Barrera-Ballesteros1, T. Heckman1, S. F. Sánchez2, N. L. Zakamska1, J. Cleary1, G. Zhu1, J. Brinkmann3, and N. Drory4

THE MaNGA TEAM

1 Department of Physics & Astronomy, Johns Hopkins University, Bloomberg Center, 3400 N. Charles St., Baltimore, MD 21218, USA; jbarre3@jhu.edu
2 Instituto de Astronomía, Universidad Nacional Autónoma de México, A.P. 70-264, 04510 México, D.F., México
3 Apache Point Observatory, Sunspot, NM 88349, USA
4 McDonald Observatory, The University of Texas at Austin, 1 University Station, Austin, TX 78712, USA

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Abstract

We determine the local metallicity of the ionized gas for more than $9.2 \times 10^5$ star-forming regions (spaxels) located in 1023 nearby galaxies included in the Sloan Digital Sky Survey-IV MaNGA integral field spectroscopy unit survey. We use the dust extinction derived from the Balmer decrement and the stellar template fitting in each spaxel to estimate the local gas and stellar mass densities, respectively. We also use the measured rotation curves to determine the local escape velocity ($V_{\text{esc}}$). We then analyze the relationships between the local metallicity and both the local gas fraction ($V_{\text{H}}$) and $V_{\text{esc}}$. We find that metallicity decreases with both increasing $V_{\text{H}}$ and decreasing $V_{\text{esc}}$. By examining the residuals in these relations we show that the gas fraction plays a more primary role in the local chemical enrichment than does $V_{\text{esc}}$. We show that the gas-regulator model of chemical evolution provides a reasonable explanation of the metallicity on local scales. The best-fit parameters for this model are consistent with the metal loss caused by momentum-driven galactic outflows. We also argue that both the gas fraction and the local escape velocity are connected to the local stellar surface density, which in turn is a tracer of the epoch at which the dominant local stellar population formed.

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

1. Introduction

The observed gas-phase metal content in the interstellar medium (ISM) is the byproduct of stellar evolution, modulated by gas flows into and out of galaxies. Therefore, understanding how the metals relate to other observables provides key clues about how galaxies evolve and (more important) about the physical processes responsible for this evolution.

In simple models of chemical evolution, the metal abundance in the ISM will set by three main processes. The first is the degree of chemical evolution, which increases as more gas is converted into massive stars, which return metal-enriched gas. The second is the loss of metals through outflows driven by the feedback effects of massive stars and supernovae. The fractional metal loss is expected to be larger in low-mass galaxies with low escape velocities. The third is the inflow of lower-metallicity gas from the surrounding circumgalactic medium. Indeed, recent analytical models suggest that chemical evolution can be understood as an interplay between these gas flows and the gas reservoir available to form new stars (Lilly et al. 2013).

Over the last three decades many studies have been devoted to testing these models of galactic chemical evolution. One fundamental observational parameter in probing the chemical evolution of galaxies is their total gas fraction (i.e., the ratio between the gas and the stellar-plus gas masses). Gas-rich galaxies tend to show lower metallicity in comparison to gas-poor massive galaxies (e.g., Garnett 2002; Pilyugin et al. 2004; Bothwell et al. 2013, 2016; Hughes et al. 2013). This is qualitatively consistent with theoretical expectations.

Different authors have also noted the correlation between a galaxy’s luminosity and its oxygen abundances in samples of late-type and irregular galaxies (e.g., Lequeux et al. 1979; Vila-Costas & Edmunds 1992; Zaritsky et al. 1994; Pilyugin et al. 2004). Using reliable estimates of the stellar mass and the very large data set provided by the Sloan Digital Sky Survey (SDSS), Tremonti et al. (2004) showed a very tight relation between the stellar mass and the central gas-phase metallicity for more than 53,000 star-forming galaxies. The central metallicity increases with stellar mass, reaching a constant value for massive galaxies. This supports the idea of a mass-dependent loss of metals.

Due to the technical challenge in obtaining spatially resolved data for a large sample of galaxies, most of the studies to date have relied on integrated or central properties. In particular, the emission line fluxes used to derive metallicity are usually obtained from the central region of the target; these in turn only probe the physical processes that affect metallicity in that specific region of galaxies. However, the situation has changed significantly in recent years with the deployment of integral-field spectroscopy surveys. Thanks to them, different studies have unveiled relations at local scales that are analogous to those observed globally/centrally. Rosales-Ortega et al. (2012) found a tight relation between local metallicity and local stellar surface mass density. This relation has also been observed in large surveys such as the CALIFA survey (Sánchez et al. 2014). For a large sample of disk MaNGA galaxies (650), we were able to reproduce both the observed radial metallicity gradients and the global mass-metallicity relation using a single relationship between the local values of the...
metallicity and the stellar surface mass density (Barrera-Ballesteros et al. 2016). This result indicates that local gas-phase metallicity is a consequence of local star formation history.

As noted above, two important quantities in models of chemical evolution are the gas fraction and the escape velocity. Studies exploring the spatially resolved metallicity as a function of the gas fraction and/or the escape velocity are rather scarce. With a large, homogeneous data set from the GASS survey Moran et al. (2012) found that the metallicity in the outskirts of a sample of star-forming galaxies decreases as their total atomic gas fraction increases, suggesting that the gas fraction is fundamentally important. More recently, Carton et al. (2015) studied the metallicity gradients in a sample of 50 late-type galaxies. In order to explain the observed radial distributions, the authors used the gas fraction in a local version of a chemical model in which inflows, outflows, and star formation are in equilibrium (Lilly et al. 2013). The gradients are then explained by the radial variation of the gas fraction and the mass loading factor (the ratio of the outflow and the star formation rate (SFR)), which is in turn driven by the radial variation in the escape velocity. On the other hand, Ho et al. (2015) explained the similarity in the observed metallicity gradients of 49 late-type galaxies by assuming a model in which the mass loading factor and the ratio of the inflows and SFRs are constant. Their results suggest that at local scales the chemical evolution of galaxies is virtually the same as a closed-box model in which the metallicity depends only on the local gas fraction and very weakly on inflows or outflows.

In this paper our goal is to exploit the data from the SDSS in the field of spatially resolved spectroscopy via the MaNGA survey (Bundy et al. 2015) in order to study the impact of the local gas fraction and the local escape velocity on the local metallicity in more than 1700 star-forming galaxies. The motivation is to provide insights into the physical processes responsible for chemical evolution on local scales and to better understand the origin and meaning of the corresponding global relations. The structure of this paper is as follows: in Section 2.2 we introduce the main aspects of the MaNGA survey as well as the selection criteria for our sample; in Section 3 we derive the spatially resolved quantities that we used in the study, while in Section 4 we present the relations between these parameters; in Section 5 we compare those relations with models of chemical evolution and discuss the implications of our findings in Section 6; finally in Section 7 we present our conclusions.

2. Sample and Data

2.1. The MaNGA Sample and Datacubes

For this study we use the sample of galaxies observed by the MaNGA survey through 2016 June. The goal of this ongoing survey is to observe a sample of 10,000 nearby galaxies using an integral field spectroscopy unit (IFU; Bundy et al. 2015). The MaNGA survey is conducted at the 2.5 m Sloan Telescope at the Apache Point Observatory (Gunn et al. 2006). Observations are carried out using a set of 17 different fiber bundles (science IFUs) packed in hexagonal shapes (Drory et al. 2015). The number of fibers varies from 19 to 127 per bundle covering a field-of-view (FoV) of 12–32 arcsec, respectively. The diameter of the fibers in each of these bundles is 2.7 arcsec. These bundles feed two dual-channel spectrographs covering a large wavelength range from 3600 to 10000 Å and provide a spectral resolution of $R \sim 2000$ (Sme et al. 2013). Details of the spectrophotometric calibrations for the MaNGA survey can be found in Yan et al. (2016). The observing strategy includes a three-point dithering in order to provide homogeneous coverage of the field of view. Final datacubes are reduced by a dedicated pipeline described in Law et al. (2016). The pipeline accounts for sky subtraction, wavelength, and flux calibration, as well as the combination of the three dithered observations. The final product of this pipeline is a datacube where each element is described by two spatial coordinates x and y corresponding to the R.A. and decl. projected on the sky and the $z$ coordinate corresponding to the wavelength element. Each of the spatial elements containing individual spectra are also known as spaxels. The spatial size of each spaxel in the final datacube is 0.5 arcsec.

The targets for MaNGA observations have been selected from the extended NASA-Sloan catalog (NSA; Blanton et al. 2011). This catalog provides a large set of spectro-photometric parameters for individual targets, such as redshift ($z$), total stellar mass ($M_*$), half-light radius ($R_{\text{eff}}$), absolute $ugriz$ magnitudes, photometric position angle (PA), and photometric ellipticity ($e$). The main selection criteria for the MaNGA set of galaxies yield nearby targets with stellar masses of $M_* > 10^8 M_\odot$, a relatively flat distribution in stellar mass, and uniform radial coverage. Detailed descriptions of the selection parameters can be found in Bundy et al. (2015). To accomplish different science goals, the radial coverage of the IFU for $\sim 66\%$ of the sample is at least $1.5 R_{\text{eff}}$ (also known as the primary sample) whereas for $\sim 30\%$ the IFU FoV covers at least $2.5 R_{\text{eff}}$ (the secondary sample). For a description of the sample properties see Wake (2016). The sample from which our subsample is drawn includes 2780 galaxies at redshift $0.01 < z < 0.17$, covering a wide range of galaxy parameters (e.g., stellar mass, colors, and morphology). For internal distribution purposes, this sample is known as the MPL-5. Most of these galaxies are included in the SDSS-IV DR14 data release.

These objects provide a panoramic view of the properties of the galaxy population in the Local Universe.

2.2. Selected Sample

For this study we perform a further target selection using the following criteria: (1) galaxies with a representative number of spaxels (>10%) classified as star forming (see Section 3.1 for details) and (2) a reliable estimation of the rotation curve from their $H\alpha$ velocity field (see details in Section 3.4). This selection yields a final sample that includes 1023 galaxies. In Figure 1 we compare the distribution of the selected sample against the entire MPL-5 sample in the color-$M_*$ diagram. The mass distribution of the MPL-5 sample is relatively flat in the mass range $9.2 \lesssim \log(M_*/M_\odot) \lesssim 11.0$. The resulting mass distribution from our selection parameters mimics the MPL-5 parent flat distribution for a large range of stellar masses. Note, however, that our sample does not cover the most massive galaxy bins. This is expected since from our selection parameters we required galaxies to have a significant amount of star-forming regions, which are not likely to occur in the most massive (early-type) galaxies.

http://www.nsatlas.org

http://www.sdss.org/dr14/manga/
diagram of the MPL-5 MaNGA sample. Gray and blue
1
histograms for the MPL-5 and selected samples, respectively
( Figure 1. Color-
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and color, respectively. The color distribution from our selected sample is
The pipeline provides a simultaneous
bimodality in color distributions
we used the PIPE3D analysis pipeline
different properties of the ISM in individual datacubes. For this
sources
or assuming a constant ratio between gas column density
molecular hydrogen in our Galaxy as well as in extragalactic
common observational technique to gauge gas content in its

testing is done for each of the coadded
emission lines in the continuum-free datacube on a spaxel-by-
emission lines in the continuum-free datacube by subtracting
pipeline also creates a continuum-free datacube by subtracting
the modeled continuum from the original datacube. The stellar-
mass map is determined by assuming the same extinction and
mass-to-light ratio for all the spaxels within a given spatial bin.
We determine the surface mass density ($\Sigma_{gas}$) in each spaxel and
correct from projection effects following the same procedure as
in Barrera-Ballesteros et al. (2016).

The pipeline also fits single Gaussians to the strongest
emission lines in the continuum-free datacube on a spaxel-by-
spaxel basis. Thus for a given emission line the pipeline
produces spatially resolved maps of the flux intensity, line-of-
sight velocity, velocity dispersion, and equivalent width. For
this study we use the derived flux maps from [O III] $\lambda$5007, H$\beta$
H$\alpha$, and [N II] $\lambda$6548 as well as the velocity map from H$\alpha$. In
Figure 2 we show an example of the maps obtained using this
analysis pipeline.

We further select galaxies with star-forming spaxels. First
we select spaxels with a H$\alpha$ flux error smaller than 30%. Then
we use the classical BPT diagnostic diagram (Baldwin et al. 1981) that compares the line ratios [O III] /H$\beta$
and [N II] /H$\alpha$. We classify as star-forming those spaxels with line
ratios below the Kauffmann demarcation line (Kauffmann et al. 2003a)
and having EW(H$\alpha$) >6. These two criteria provide a reliable selection of star-forming regions allowing us
to determine the metallicity indicators using H II-region studies
as well as the SFR. As result, our sample of star-forming regions includes \~9.2 $\times$ 10$^5$ spaxels in the sample of 1023
galaxies. We use the abundance calibrator O3N2 from Pettini
& Pagel (2004). This calibrator is based on the above line
ratios,

$$12 + \log(O/H) = 8.73 - 0.32 \times \text{O3N2}, \quad (1)$$

with O3N2 = $\log([\text{O III}] / H\beta)$–$\log([\text{N II}] / H\alpha)$. The errors in
the metallicity using this calibrator are typically of the order of
\~0.06 dex.

3.2. Gas Surface Mass Densities

One of the main goals of this article is to understand the role
of gas flows and their relationship with the stellar component in
shaping the gas-phase metallicity at local scales. We require
an estimation of the total gas mass density ($\Sigma_{gas}$). The most
common observational technique to gauge gas content in its
different phases is at millimeter wavelengths. In particular, the
emission line from the ground rotational transition $J=1-0$ of
the CO molecule has been widely used as a tracer for H$_2$
molecular hydrogen in our Galaxy as well as in extragalactic
sources (for a recent review see Bolatto et al. 2013). However,
direct spatially resolved observations of cold gas emission lines
in large samples of galaxies, such as MaNGA, are technically
quite challenging.

From optical data, there are different methods or relations to
estimate $\Sigma_{gas}$. Among them, these methods include the inverse
of the well-known Kennicutt–Schmidt Law (Kennicutt 1998)
which relates the star formation surface density ($\Sigma_{SFR}$) to
$\Sigma_{gas}$; the relation with stellar mass density ($\Sigma_{*}$) and $\Sigma_{gas}$;
or assuming a constant ratio between gas column density
and dust (we discuss these relations elsewhere; J. K. Barrera-
Ballesteros 2018, in preparation). In this study we simply
adopt a full mixed distribution of gas and dust across an
effective foreground screen that includes half of the gas
column density (e.g., McLeod et al. 1993; Imara & Blitz 2007;
In this simple scenario, the total gas density is related to the optical extinction ($A_V$) via

$$\Sigma_{\text{gas}} = 30 M_\odot \text{ pc}^{-2} A_V.$$  

We obtain the dust attenuation from the Balmer decrement. We derive the dust attenuation for the H$\alpha$ emission line following Equation (1) from Catalán-Torrecilla et al. (2015) using the H$\alpha$/H$\beta$ flux ratio with its canonical Case B value of 2.86 and the extinction curve from Cardelli et al. (1989) for $R_V = 3.1$.

$$A(\text{H}\alpha) = \frac{K_{\text{H}\alpha}}{-0.4(K_{\text{H}\alpha} - K_{\text{H}\beta})} \times \log \left( \frac{F_{\text{H}\alpha}}{F_{\text{H}\beta}} \right)$$

where $F_{\text{H}\alpha}/F_{\text{H}\beta}$ is the flux ratio between these Balmer lines and $K_{\text{H}\alpha} = 2.53$ and $K_{\text{H}\beta} = 3.61$ are the extinction coefficients for the Galactic extinction curve from Cardelli et al. (1989). Catalán-Torrecilla et al. (2015) also noted that this attenuation is robust among different extinction curves and dust-to-star
geometries (e.g., \( R_V = 3.1 \) from Cardelli et al. 1989 or \( R_V = 4.05 \) from Calzetti et al. 2000). Using the above extinction curve, \( A_v \) is simply \( A_v = 0.83 A(H\alpha) \).

We plot in Figure 3 the distribution of \( \Sigma_{gas} \), the gas fraction \( (\Sigma_{gas}/\Sigma_{tot}) \), and the total gas fraction \( (\mu = \Sigma_{gas}/(\Sigma_{gas} + \Sigma_{star})) \) against the \( \Sigma_{star} \). In each panel, we overplot the median values of \( \Sigma_{gas} = \Sigma_{mol} + \Sigma_{H_2} \) for different \( \Sigma_{star} \) bins. \( \Sigma_{mol} \) comes from direct CO measurements from the EDGE survey (Bolatto et al. 2017). We assume a constant distribution of \( \Sigma_{H_2} = 10 M_\odot \text{pc}^{-2} \). In Barrera-Ballesteros et al. (2017, in preparation) we present a detailed study of the relations between molecular gas densities and spatially resolved optical properties. This comparison indicates that the effective screen method provides a reliable estimation of \( \Sigma_{gas} \) with similar values as those derived directly from CO measurements.

### 3.3. Rotation Curve from H\(_\alpha\) Velocity Fields

As a first step in determining the local escape velocity for each of the star-forming spaxels in our sample of galaxies, we estimate the maximum rotation velocity \( (V_{max}) \). To do so, we obtain the velocity curve for each of them via the velocity field from the H\(_\alpha\) emission line (see an example in the left panel of Figure 4 and details in Section 3.1). We follow a similar procedure to that introduced in García-Lorenzo et al. (2015) and applied to a sample of CALIFA disk galaxies in Barrera-Ballesteros et al. (2014). Using the H\(_\alpha\) velocity maps we determine the position of those spaxels with the maximum/minimum (receding/approaching) de-projected line-of-sight velocities compared to the systemic velocity at different de-projected distances (i.e., \( V_{rot} \) versus \( d_{depro} \), see red and blue dots in middle panel of Figure 4). We assume that the kinematic center (i.e., the position of the systemic velocity) is located at the optical nucleus. This is a reasonable assumption for disk galaxies where the location of the maximum gradient coincides in most cases with the optical nucleus (e.g., Barrera-Ballesteros et al. 2014). To de-project both the line-of-sight velocities and the distances in our sample, we assume the photometric inclination from the NSA catalog to be the kinematic inclination across the entire galaxy. Then we parameterize our rotation curve as

\[
V_{rot}(d_{depro}) = V_{max} \cdot \frac{d_{depro}}{(R_{turn} + d_{depro})^{\alpha/\alpha}},
\]

where \( R_{turn} \) is the galactocentric distance at which the rotation curve transitions from solid-body to flat (see Section 3.4). We use this parameterization to fit the observed rotation curve to determine \( V_{max} \) (see dashed-lines in Figure 4).

As a sanity check, we investigate how well we are able to reproduce the observed Tully–Fisher relation using these derived velocities under the simple assumptions used here. In Figure 5, we plot \( \log(V_{max}) \) against \( \log(M_*/M_\odot) \) for those galaxies where we have reliable estimates of \( V_{max} \) (1023 galaxies) with uncertainties from the fitting smaller than 50 km s\(^{-1}\) (gray points). We also overplot in Figure 5 with red-dashed lines the best-fit Tully–Fisher relation derived using Fabry–Perot \( H\alpha \) velocity fields from a sample of field galaxies included in the GHASP survey (Torres-Flores et al. 2011). All the medians at different stellar mass bins and most of the
individual values of $V_{\text{max}}$ lie within the Tully–Fisher relation derived from the GHASP survey. At low stellar masses ($<10^{10.5} M_\odot$) we seem to slightly underestimate $V_{\text{max}}$ (by $\sim$0.1 dex). We also note that this is a mass range in which one must consider the velocity dispersion in the budget to account for the dynamical mass (e.g., Simons et al. 2015). Despite these limitations, the great majority of stellar masses and $V_{\text{max}}$ in our sample are well described by the values from the best Tully–Fisher relation presented in Torres-Flores et al. (2011).

### 3.4. Escape Velocity Maps

The amount of gas (and metals) expelled by the kinetic energy or momentum supplied by stellar feedback should depend on the depth of the local potential well. We have therefore used the rotation curves above to estimate the local escape velocity. We follow a straightforward approach in order to build the escape velocity maps. We assume the simplest approximation of the galactic potential: a spherically symmetric two-component model and the simplification of the galactic potential: a spherically symmetric Navarro–Frenk–White (NFW) dark-matter halo. We derive the escape velocity at a given radius $r$ from the optical nucleus using the following equation:

$$V_{\text{esc}}^2(r) = \begin{cases} V_{\text{esc,in}}^2(r) + V_{\text{esc,out}}^2, & \text{if } r < R_{\text{turn}} \\ V_{\text{esc,out}}^2, & \text{if } r > R_{\text{turn}} \end{cases}$$

where

$$V_{\text{esc,in}}^2(r) = (V_{\text{max}}/R_{\text{turn}})^2 (R_{\text{vir}}^2 - r^2)$$

and

$$V_{\text{esc,out}}^2 = 2 V_{\text{max}}^2 \ln(R_{\text{vir}}/R_{\text{turn}}) + 2 V_{\text{max}}^2,$$

where the virial radius ($R_{\text{vir}}$) is obtained from its relation to the halo mass. The halo mass is in turn obtained by the matching function between the halo and the stellar mass (Behroozi et al. 2010). In the right panel of Figure 4 we plot an example of the profile of $V_{\text{esc}}$ for a particular galaxy. As expected, the escape velocity decreases with the de-projected distance. In the Appendix, we explore a more realistic model assuming that the baryonic mass is distributed in a disk-like profile and add a spherical Navarro–Frenk–White (NFW) dark-matter halo. We show that the differences in the escape velocity between this two-component model and the simplified one presented in this section are of the order of $\sim 5\%$ for a low subset of the galaxies included in our sample.

In Figure 6 we compare $V_{\text{esc}}$ against $\Sigma_\star$. We find a broad distribution of $V_{\text{esc}}$ for a given stellar density. However, the density of the distribution suggests a linear relation (in logarithmic scales) between the escape velocity and the stellar mass density in which the scaling factor depends on the total stellar mass. This is expected given that these observables are tightly related (e.g., Lelli et al. 2016). As we note in Section 3.3, to fully account for the galaxy potential from a kinematic point of view, in particular for low-mass galaxies, it is necessary to consider the velocity dispersion distribution. For simplicity, in this study we only consider the contribution of the circular velocity. In a future work, we will consider the possible relation of the velocity dispersion in the chemical enrichment at local scales.

![Figure 6](image_url)  
**Figure 6.** Distribution of $V_{\text{esc}}$ against $\Sigma_\star$ for our sample of star-forming spaxels. Our sample spans a dynamic range of roughly an order of magnitude in $V_{\text{esc}}$.

### 4. Results

#### 4.1. Gas Fraction Metallicity ($\mu$–Z) Relation

In Figure 7 we plot the distribution of the oxygen abundance as a function of the gas fraction for the star-forming spaxels in our sample of 1024 galaxies. We find a very tight relation between these two local observables; as $\mu$ decreases the metal content increases, reaching a constant abundance of $(12 + \log(O/H)) \sim 8.8$ for a low $\mu$ ($\mu \leq 0.1$). We measure the median metallicity at different gas fraction bins in the range of $-1.3 < \log(\mu) < -0.1$ within bins of log($\mu$) $\sim 0.1$. The standard deviation of the metallicity in these bins ranges between 0.03 and 0.1 dex for low and large gas fractions, respectively. In order to estimate the residuals of this relation, we fit a fourth-order polynomial function to the median values (blue circles with error bars in Figure 7).

The median residual of this relation is close to zero ($\sim -0.01$ dex, see distribution on the inset in Figure 7). The standard deviation of these residuals from this best-fitted curve confirms that this is a tight relation ($\sigma \sim 0.09$ dex). This deviation is comparable to the one observed in the residuals of the $\Sigma_\star$–Z relation for the MaNGA galaxies (\(\sigma \sim 0.06\) dex; Barrera-Ballesteros et al. 2016). Figure 7 also shows that for a given intermediate $\mu$, the metallicity seems to be skewed toward low values. In Section 4.3 we explore how the residuals of this distribution correlate with the escape velocity. We find that regions with low metallicities tend to have small escape velocities.

As we mentioned above, previous studies aimed at understanding the observed metallicity gradients in small samples of star-forming galaxies (Carton et al. 2015; Ho et al. 2015) have found similar trends to those presented in our much larger sample. Despite the tightness of the local $\mu$–Z relation for our large sample of galaxies, we must emphasize that we do not have direct estimations of the molecular or the atomic gas densities. Nevertheless, we consider that this relation is robust regardless of the proxy used to gauge the gas density.

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Barrera-Ballesteros et al.
particular, Carton et al. (2015) used a different method to estimate gas fractions but found results similar to ours. They also reported that their derived local $\mu$–Z relation was similar for the H$_2$-rich galaxies and for their control sample, suggesting that the physical processes occurring in both samples are similar. The statistical properties of our sample ensure that we cover a wide range of global parameters (e.g., stellar mass and global SFRs). This, along with the fact that the local $\mu$–Z relation reported here is almost as tight as the $\Sigma_\mu$–Z relation, indicates that $\mu$ is a key parameter in understanding the metal content of the ionized gas (as noted by Bothwell et al. 2016).

4.2. Escape Velocity and Metallicity ($V_{\text{esc}}$–Z Relation)

The escape velocity parameterizes the amount of material that can be ejected from the galaxy by momentum- or energy-driven outflows. Therefore, it could play a key role in determining the local metallicity.

In Figure 8 we plot the distribution of the metallicity as function of the local escape velocity for all the star-forming spaxels in our sample of galaxies. We measure the median metallicity at different escape velocity bins of a 60 km s$^{-1}$ width, within a range of 180 km s$^{-1} < V_{\text{esc}} < 900$ km s$^{-1}$. We find that metallicity increases as $V_{\text{esc}}$ increases, reaching a constant value of $\sim 8.8$ dex for $V_{\text{esc}} \geq 400$ km s$^{-1}$. However, the standard deviations for these bins are relatively larger than those obtained for the $\mu$–Z relation, ranging from 0.13 to 0.04 dex for small and large escape velocities, respectively. We fit to the median metallicities a curve of the form

$$12 + \log(O/H) = \frac{\alpha}{1 + (\beta/V_{\text{esc}})^{\gamma}}.$$  \hspace{1cm} (6)

The best-fitting values for our data are $\alpha = 8.85 \pm 0.3$ dex, $\beta = 165 \pm 13$ km s$^{-1}$, and $\gamma = 0.83 \pm 0.3$ (see the black solid curve in Figure 8). The median values of the residuals are close to zero ($\sim 0.01$ dex). The standard deviations of the residuals from this best-fit curve are slightly larger than the ones derived from the $\mu$–Z relation ($\sigma \sim 0.11$ dex). The distribution of these two parameters is not symmetrical with respect to the best-fit line. In particular, at low values of $V_{\text{esc}}$, the metallicity has a tail skewed toward lower values. We find that these low-metallicity spaxels have large gas fractions.

Bearing in mind these results, in the next section we investigate the impact of the escape velocity on the $\mu$–Z relation (and vice versa).

4.3. Joint Dependences on $V_{\text{esc}}$ and $\mu$

So far we have investigated how the local metallicity relates to the gas fraction and $V_{\text{esc}}$ separately. In this section we explore how $\mu$ and $V_{\text{esc}}$ can jointly regulate the local metal content in our sample of galaxies. To explore this joint dependence we first study the residuals of the $\mu$–Z relation presented in Section 4.1 as a function of $V_{\text{esc}}$. We then study how the residuals of the relation of the metallicity with $V_{\text{esc}}$ relate to the gas fraction.

In Figure 9 we plot the distribution of the residuals from the $\mu$–Z relation as a function of $V_{\text{esc}}$. Broadly speaking, there is a mild trend for residuals to increase with $V_{\text{esc}}$. Using the median metallicities at different $V_{\text{esc}}$ bins, we find that negative residuals (i.e., an overestimation of the best-fitting curve, by $\sim 0.04$ dex) are found in spaxels with $V_{\text{esc}} \leq 400$ km s$^{-1}$. For larger $V_{\text{esc}}$ the residuals seem to have a constant positive value...
is the rate at which enriched material leaves the residuals in different bins of $V_{\text{esc}}$. The circles and error bars represent the median and standard deviation of the residuals in different bins of $V_{\text{esc}}$ of a 50 km s$^{-1}$ width each, respectively. The dashed lines represent the best-fit curve in the $\mu-Z$ relation (i.e., zero scatter).

(i.e., an underestimation of the best-fitting curve) of $\Delta \log(O/H) \sim 0.03$ dex. We also note that the scatter of these residuals tends to increase as $V_{\text{esc}}$ decreases. In Section 5 we study the impact of parameterizing the expelled gas as a function of $V_{\text{esc}}$ in models of chemical evolution.

In Figure 10 we study the residuals of the $V_{\text{esc}}-Z$ relation against the gas fraction. We find a clear trend of negative residuals increasing at larger gas fractions, with an amplitude of about 0.3 dex. This implies that those spaxels where the fitted $V_{\text{esc}}-Z$ curve overestimates the observed metallicity tend to be those with larger gas fractions.

In summary, we find that the primary factor in determining the local metallicity is the local gas fraction, with the local escape velocity playing a smaller role. Bearing these results in mind, in the next section we compare the observed $\mu-Z$ relation with several simple analytic models of galactic chemical evolution. We show that in order to explain the observed local metallicities, one must take into account the fraction of metals removed from a local region, as parameterized by $V_{\text{esc}}$.

5. Analytical Modeling of the Local Metallicity

In this section we analyze two recent models of chemical evolution in order to gain insight into the most plausible physical scenario for the evolution of metals at local scales in star-forming galaxies. More specifically, we compare our MaNGA observed $\mu-Z$ relation with the predictions from these analytic models. First, we briefly explain the gas-regulator model proposed by Lilly et al. (2013) and implemented at local scales by Carton et al. (2015) (Section 5.1). We then summarize the local leaky-box model proposed by Zhu et al. (2017) (Section 5.2). For both models we parameterize outflows as a function of the local escape velocity (Section 5.3). The results of this analysis are presented in Section 5.4.

5.1. The Gas-regulator Model

The main idea in the model of chemical evolution presented by Lilly et al. (2013) relies on the postulate that the global SFR is regulated by the total mass of gas (also known as the gas reservoir) in the galaxy. In turn, any other process that affects the fraction of gas or metals in the ISM (i.e., gas transformed into long-lived stars, metal-rich material returned instantaneously from the stellar component, and gas expelled from the system) can be represented as a function of the SFR.

More recently, Carton et al. (2015) adapted this model to explain the metallicity gradients in a sample of star-forming galaxies. For this local adaptation of the global model, they apply the model in radial bins (annuli). Then for each of these bins they assume an equilibrium between inflows, outflows, and star formation. They also assume that the radial transfer of gas/stars/metals between the bins could be ignored. A detailed description of the spatially resolved gas-regulator model is given in Carton et al. (2015), whereas a full description of the global model is found in Lilly et al. (2013). Here we briefly outline the main features of the gas-regulator model presented in Carton et al. (2015). We use assumptions similar to those in Carton et al. (2015) implemented for the radial bins in their sample of galaxies.

The change in time of the gas mass in each of the spaxels is then given by

$$\dot{m}_{\text{gas}} = \dot{m}_{\text{in}} - \dot{m}_{\text{out}} - \dot{m}_{*} + \dot{m}_{\text{return}},$$

where $\dot{m}_{\text{in}}$ represents the inflow of metal-poor gas into the spaxel and $\dot{m}_{\text{out}}$ is the rate at which enriched material leaves the spaxel. Carton et al. (2015) assumed that this was due to outflows driven by from massive stars and core-collapse supernovae. They therefore considered this to be proportional
As we mentioned above, this model is based on the fact that the SFR is proportional and regulated by the gas mass. Thus
\[ \text{SFR} = \epsilon \, m_{\text{gas}}, \]
where \( \epsilon \) is the star formation efficiency. Finally, \( m_{\text{return}} \) represents the rate at which metal-enriched gas returns to the ISM from short-lived high-mass stars. The model assumes that a fraction \( R \) of the mass converted into stars returns instantaneously to the gas reservoir. Thus following Lilly et al. (2013) and Carton et al. (2015) we assume that this fraction is constant (\( R = 0.4 \)). In simple terms, Equation (7) is a representation of mass conservation: the fraction of gas that enters the system could end up as long-lived stars, be expelled by the system, or be recycled (see Figure 2 in Lilly et al. 2013). With these assumptions the change of the gas in the reservoir is given by
\[ m_{\text{gas}} = m_{\text{in}} - (1 - R + \lambda) \text{SFR}. \tag{8} \]

By defining the gas-to-stellar-mass ratio as \( r_{\text{gas}} = m_{\text{gas}}/m_{\text{st}} \), Lilly et al. (2013) show that the above equation can be expressed as
\[ m_{\text{in}} = \left( (1 - R)(1 + r_{\text{gas}}) + \lambda + e^{-1 \frac{d \ln(r_{\text{gas}})}{dt}} \right) \cdot \text{SFR}. \tag{9} \]

This equation explicitly relates the inflow rate to the SFR. We assume that this relation is valid for our sample of star-forming spaxels. The gas-to-stellar-mass ratio can be easily transformed to the gas fraction by
\[ r_{\text{gas}} = \frac{\mu}{1 - \mu}. \tag{10} \]

Similar to Equation (7), the change of metals in the reservoir is related to the inflow of metal-poor gas from the halo, the recycled metal-rich material produced by short-lived stars, the material transformed into long-lived stars, and the enriched material ejected out of the reservoir via outflows. Along with these assumptions and Equation (9), Lilly et al. (2013) find that this gas-regulator system will reach equilibrium on timescales shorter than the depletion timescale (i.e., \( \ll 1/\epsilon \)). They show that in equilibrium the metallicity of the gas-regulated system can be described as
\[ Z_{\text{eq}} = Z_0 + \frac{y}{1 + r_{\text{gas}} + (1 - R)^{-1} \left( \lambda + e^{-1 \frac{d \ln(r_{\text{gas}})}{dt}} \right)}, \tag{11} \]
where \( Z_0 \) and \( y \) are the infalling oxygen mass fraction and the yield (i.e., the oxygen mass returned per unit mass in long-lived stars), respectively. This equation explicitly correlates the metallicity with the gas fraction \( r_{\text{gas}} \). The fitting of this model to the SDSS data by Lilly et al. (2013) results in
\[ e^{-1 \frac{d \ln(r_{\text{gas}})}{dt}} \sim -0.25. \]
We set this factor to that constant value.

### 5.2. The Leaky-box Model

Recently Zhu et al. (2017) examined the local \( \Sigma_{\text{gas}}-Z \) relation observed in MaNGA galaxies (Barrera-Ballesteros et al. 2016). They assume an evolutionary model in which disk galaxies grow inside out, with metal-poor gas accreting from the halo to the outskirts of the galaxy, collapsing and eventually triggering localized star formation. They assume that there are no radial flows in the disk plane. Hence for a given region within a disk galaxy they define a total density \( \Sigma_{\text{tot}}(t) \) that does not vary with time and is set only by the accreted initial gas surface density at the time \( t_0 \Sigma_0 = \Sigma_{\text{gas}}(t_0) \). The evolution of the localized components is then given by
\[ \Sigma_{\text{tot}}(t) = \Sigma_{\text{gas}}(t) + \Sigma_{\text{out}}(t) = \Sigma_0, \tag{12} \]
where \( \Sigma_{\text{out}}(t) \) represents the density of the expelled gas that does not return to the galaxy. Similar to Lilly et al. (2013), the outflow rate is related to the SFR surface density by the mass loading factor. Under these assumptions the evolution of the metallicity is
\[ Z = Z_0 + \frac{y}{1 + \lambda} \ln \left( \frac{\Sigma_0}{\Sigma_{\text{gas}}(t)} \right), \tag{13} \]
where \( y \) is the effective yield and \( \Sigma_0 = \Sigma_{\text{gas}}(t) + (1 + \lambda) \Sigma_{\text{gas}} \). Rewriting this in terms of the total gas fraction, the observed metallicity can be described as
\[ Z = Z_0 + \frac{\ln(10) y}{1 + \lambda} \cdot \log \left( 1 + \frac{1 + \lambda}{1 - \mu} \right). \tag{14} \]
As in the case of the gas regulator model, we now have an explicit relation between the expected metallicity and the gas fraction \( \mu \). We note that Zhu et al. (2017) assumed a constant value for \( \lambda \). We relax this assumption in Section 5.3 and introduce a dependence on \( v_{\text{esc}} \).

### 5.3. Local Parameterization of the Outflows

As we mentioned above, both models described in this study correlate the gas/metal loss from outflows with the SFR via the mass loading factor (\( \lambda \)). Observations of starburst galaxies reveal that galactic-scale outflows have properties that indeed relate to the SFR and the SFR per unit area (Heckman et al. 2000; Rupke et al. 2002; Martin 2005; Grimes et al. 2009; Hill & Zakamska 2014; Heckman et al. 2015; Heckman & Borthakur 2016). The measured outflow velocities \( v_{\text{w}} \) are of the order of hundreds of \( \text{km s}^{-1} \). Simple analytic models assume that these outflows are driven by either momentum or energy. Assuming that outflows are driven by a combination of hot wind driven (thermalized ejecta of massive stars and supernovae; Chevalier & Clegg 1985) and radiation pressure (Murray et al. 2005) Heckman et al. (2015) show that for a typical starburst population the total momentum flux is given by \( \rho_w = 4.8 \times 10^{33} \text{ SFR dynes} \). For a momentum-driven outflow \( \rho_w = M_{\text{out}} v_{\text{w}} \), the mass loading factor is then given by
\[ \lambda_{\text{momentum}} = \frac{670 \text{ km s}^{-1}}{v_w}. \tag{15} \]

However, if the outflow is driven by kinetic energy from supernovae and stellar winds (Chevalier & Clegg 1985; Dekel & Silk 1986; Silk & Rees 1998; Murray et al. 2005), then the mass loading factor is described by
\[ \lambda_{\text{energy}} = \frac{2 \epsilon_{\text{eff}} \eta_{\text{SN}} E_{\text{SN}}}{v_w^2} = \left( \frac{1000 \text{ km s}^{-1}}{v_w} \right)^2, \tag{16} \]
where \( E_{\text{SN}} = 10^{51} \text{ erg} \) is the typical energy produced by a supernova, \( \eta_{\text{SN}} = 1 \times 10^{-2} \) is the number of supernovae per
solar mass, and $\epsilon_{\text{eff}} = 1$ is the efficiency in which supernovae transfer kinetic energy to the ISM. In Section 6.1 we compare the above normalizations of the mass loading factor with the results from fitting the models to the local relation. To fit the models presented in the previous sections with the data, we use a local version of the parameterization of the mass loading factor for global parameters proposed by Peeples & Shankar (2011):

$$\lambda(r) = \left( \frac{V_0}{V_{\text{esc}}(r)} \right)^\alpha + \lambda_0.$$  \hspace{1cm} (17)

In the next section we study the impact in the fitting using different selections of the values that parameterize the mass loading factor.

5.4. Fitting the Models to the Data

In both models described in Sections 5.1 and 5.2 there are three unconstrained parameters: the oxygen yield $y$ (the mass of newly created oxygen returned to the ISM, divided by the mass of long-lived stars), the metallicity (the oxygen mass fraction) of the inflowing material $Z_0$, and the mass loading factor $\lambda(V_{\text{esc}})$. As Peeples & Shankar (2011) point out, variations in the IMF as well as uncertainties in supernovae II yields lead to a rather poorly constrained yield ($0.008 \leq y \leq 0.023$). Nevertheless, these authors justify a midrange value of $y = 0.015$ by comparing different nucleosynthetic yields and IMFs (see their Figure 7). We find similar values by studying the oxygen mass loss in a synthetic galaxy modeled using STARBURST99 ($y = 0.014$, Leitherer et al. 2014). A simple empirical way to constrain the oxygen yield is to use clusters of galaxies, assuming that they are closed boxes (Renzini & Andreon 2014). In this case, nearly all the oxygen produced will be either in stars or in the hot intracluster medium (ICM). We assume that oxygen in the cold ISM is negligible in these early-type gas-poor galaxies. We can then write the following expression for the total oxygen mass:

$$M_0 = \langle Z_s \rangle M_8 + \langle Z_{\text{ICM}} \rangle M_{\text{ICM}},$$  \hspace{1cm} (18)

where $\langle Z_s \rangle$ and $\langle Z_{\text{ICM}} \rangle$ are the mean mass fractions of oxygen in the stars and the ICM, respectively. Since the stellar mass in the early-type galaxies that dominate clusters is almost entirely made up of long-lived stars and remnants, we use the present-day $M_8$ to define the yield. That is,

$$Y_0 = M_0 / M_8 = \langle Z_s \rangle + \langle Z_{\text{ICM}} \rangle (M_{\text{ICM}} / M_8).$$  \hspace{1cm} (19)

Renzini & Andreon (2014) assume as solar the mean stellar metallicity, and estimate that $M_{\text{ICM}} / M_8 = 5.6$. The radial metallicity gradients in the ICM in Mernier et al. (2017) and Simionescu et al. (2015) imply a mean metallicity of $\alpha$-elements of about 0.25 solar. The implied oxygen yield is then $0.006 + 0.0015 \times 5.6 = 0.0144$. This is gratifyingly close to the estimate from STARBURST99 and we therefore fix the yield in our models to 0.0144. With this, we select three different variations of the mass loading factor in our models: a windless scenario ($\lambda = 0$), a constant positive loading factor ($\lambda = \text{constant} > 0$), and a variable mass-loading factor that varies with $V_{\text{esc}}$ as in Equation (17). For all fits, we set $Z_0$ as a free parameter.

In Figure 11 we present the results of the fitting, allowing different parameterizations as explained above. The left panel shows the results of the fitting for both models assuming a windless scenario ($\lambda = 0$, dashed lines) and fitting the mass loading factor as a constant value (solid lines). For both models in the windless scenario the metallicity of the accreting gas is $Z_0 \sim 6 \times 10^{-4}$, while in the constant mass loading factor models it is $Z_0 \sim 3 \times 10^{-3}$. This latter value is about half of the solar oxygen abundance.

From this panel it is evident that a windless scenario provides a very poor fit to the observed $\mu$–$Z$ relation. On the other hand, when a constant mass loading factor is included in both models, the fit to the observed metallicities is significantly improved. However, the value derived for the leaky-box model ($\lambda \sim 14$) is one order of magnitude larger than the one derived from the gas-regulator model ($\lambda \sim 1.4$). As we discuss in Section 6, the large mass loading factor in the leaky-box model is not compatible with other observed properties of galaxies.

In the middle and right panels of Figure 11 we compare the observed $\mu$–$Z$ relation with the gas-regulator and leaky-box best fits from models parameterizing the local mass loading factor as in Equation (17). For both models the best fit is no longer a single line but is instead a two-dimensional distribution. This is a consequence of assuming the dependence of the mass loading factor on the local $V_{\text{esc}}(r)$. For both models the metallicity of the accreting gas is $Z_0 \sim 3 \times 10^{-3}$. Once again, the fitted values in the parameterization of the mass loading factor using Equation (17) are much larger in the leaky-box model than in the gas-regulator model.

6. Discussion

In Section 3 we presented the relation between the metallicity and the total gas fraction ($\mu$, see Figure 7). We showed that the dispersions in the residuals are similar to those observed in the local stellar surface mass density relation ($\Sigma_{\text{gas}}$–$Z$) reported for a similar sample of MaNGA galaxies (Barrera-Ballesteros et al. 2016). Thanks to the wealth of information in the MaNGA datacubes, we can also make spatially resolved estimates of the escape velocity. We found a relation between the metallicity and $V_{\text{esc}}$ (see Figure 8). The residuals of these two relations indicate the interplay of $\mu$ and $V_{\text{esc}}$ in producing the observed metallicity (see Figures 9 and 10).

From these two plots we inferred that the role of the escape velocity in the local chemical enrichment is secondary in comparison to the gas fraction. However, we also showed that including a parameterization of the mass loading factor that depended on the local escape velocity in models of chemical evolution resulted in a better description of the observed $\mu$–$Z$ relation (see Figure 11). In this section we discuss the validity of our results. First we explore the implications of the best-fitted parameters derived from the two chemical models presented in Section 5. Then we discuss the role of the SFR surface density, the surface gas density, and the escape velocity in the $\mu$–$Z$ relation.

6.1. Chemical Evolution Models

In Section 5 we compared the derived metallicity from different models of chemical evolution to the observed metallicity in order to understand the physical scenario that explains the local $\mu$–$Z$ relation and the role of $V_{\text{esc}}$. Specifically, we compared local adaptations of the gas-regulator (see
Section 5.1 and the leaky-box models (see Section 5.2). The gas-regulator model (Lilly et al. 2013), adapted for local scales by Carton et al. (2015), assumes that all the processes that can enrich the ISM (i.e., the SFR and flows) are directly related to the gas reservoir in each of the regions (or spaxels) included in the host galaxy (see Equation (7)). Carton et al. (2015) note that the main parameters that affect the determination of the metallicity gradients in their sample are the local gas fraction and the mass ejected out of the host galaxy (i.e., the mass-loading factor $\lambda$). The other chemical scenario that we use, the leaky-box model, assumes that the total surface mass density in a given region of a galaxy (plus the mass ejected) is set by the accreted initial gas density ($\Sigma_0$). In this model, the metallicity is constrained mainly by $\lambda$ and $\mu$ (see Equation (14)). We note that these are simplified models of the chemical evolution of the ISM that ignore other possible effects that can alter the chemical evolution (e.g., radial flows in the disk).

Our results show that the simple prescription provided by a windless scenario ($\lambda = 0$) at local scales provides a poor fit to the observed metallicity (see dotted lines in left panel of Figure 11) in both of the models. In other words, the gas fraction alone and the assumption of the instantaneous recycling of metals from long-lived stars to the ISM are not sufficient to explain the observed local metallicity. On the other hand, a positive constant mass loading factor improves the fit to the observed local $\mu$–$Z$ relation in both models. However, the best-fitted parameters we obtain for each model are different ($\lambda \sim 1$ and 14 for the gas-regulator and the leaky-box models, respectively).

The large mass loading factor of the leaky-box model is not tenable for several reasons. First, from molecular and atomic gas studies in nearby galaxies (e.g., Leroy et al. 2008) the gas depletion time ($t_{\text{delp}}$), which is defined as the ratio $\Sigma_{\text{gas}}/\Sigma_{\text{SFR}}$, is relatively constant for most nearby galaxies, with a value of $\sim 10^9$ years. Assuming that there is no replenishment of accreted gas, for the leaky-box model all the observed gas will be consumed and/or expelled in $t_{\text{delp}}/15$, or less than 100 Myr. This is implausibly short. Second, the mass loading factors would require that about 10 times more metals are outside of galaxies than are inside. This is inconsistent with observations, as well as the metal mass budget that could have been created in stars (Peeples et al. 2014). Finally, the amount of momentum needed to drive the very high mass outflow rates in the leaky-box model exceeds the total available amount by roughly an order of magnitude, as we now show.

In Section 5.3 we parameterized the loss of enriched gas in terms of the local escape velocity (Equation (17)) and fit our model to the data using this parameterization (see middle and right panels of Figure 11). We found different sets of best-fitted parameters for the two models of chemical evolution. In Figure 12 we compare the mass loading factor as a function of $V_{\text{esc}}$ using the best-fitted parameters derived in Section 5.4 for both the gas-regulator and the leaky-box models (blue and red lines, respectively). As noted in the paragraph above, the $\lambda(V_{\text{esc}})$ derived from the best fitting of the leaky-box model is one order of magnitude larger than the one derived from the gas-regulator model. We also compare our best-fitted $\lambda$ for local $V_{\text{esc}}(r)$ with theoretical models of supernova winds driven by momentum and energy as described in Section 5.3 (dashed and dotted-dashed lines in Figure 12). While the leaky-box model yields a best-fit slope consistent with a momentum-driven outflow, the normalization is about an order of magnitude too low. On the other hand, the gas-regulator model is in agreement with a momentum-driven outflow in terms of both the normalization and the slope. Energy-driven winds predict a large overestimation of $\lambda$ and a steeper slope compared to the best fits to either the gas-regulator or the leaky-box model. Finally, the dashed curve in Figure 12 shows $\lambda$ for the chemical evolution model presented by Peeples & Shankar (2011). We plot the best-fitting parameters derived for the model calibrated used in this study (i.e., P004O3N2; Pettini & Pagel 2004). For comparison, we assume that $v_w$ = 3$V_{\text{vir}}$. Despite the difference between the methods used to derive the escape velocity, scales (local versus global), and parameterization, the local $\lambda(r)$ from the gas-regulator model is consistent with the one derived by Peeples & Shankar (2011).

In the chemical models used in this study, we implicitly assumed that the metallicity of the expelled gas due to outflows
is similar to ISM metallicity \((Z_{\text{ISM}})\). Peeples & Shankar (2011) fit a metallicity-weighted mass loading factor \(\lambda_Z = [Z/\text{ZISM}] \lambda\) to the global parameters. In this model the metallicity of the outflow could be larger than the surrounding ISM. Their best-fitting parameters yield in general a steeper \(\lambda_Z\) in comparison to the simple analytical models we have considered.

However, the results presented here from spatially resolved data, and assuming a local version of the gas-regulator model, suggest that outflows driven by feedback from massive stars are likely to be momentum driven across the disk of the galaxy.

For simplicity, most models of chemical evolution assume the metallicity of the accreted gas to be zero. However, the metallicity of the intergalactic medium (IGM) \(Z_{\text{IGM}}\) is not zero at the current epoch. There are indications that the IGM has been enriched since early epochs \((z > 3)\); e.g., Songaila & Cowie 1996; Ellison et al. 2000; Schaye et al. 2003. In the chemical models used in this study we set as a free parameter the metallicity of the accreted material, \(Z_0\) (see Section 5). Regardless of the parameterization of the mass loading factor for both models, we find \(Z_0 \sim 3 \times 10^{-3}\) corresponding to \(Z_0 \sim 10^{-0.30} Z_\odot\). Although there are major uncertainties in the amount of metals expelled at high redshift and in recycling timescales to deliver these back to galaxies, this value is similar to recent estimates of the metallicity of the circumgalactic medium at low redshift: \(Z_{\text{IGM}} \sim 10^{-0.51} Z_\odot\) (Prochaska et al. 2017).

In conclusion, we used the local adaptation of two chemical models (gas regulator and leaky box) in order to understand the observed local \(\mu-Z\) relation derived from the MaNGA survey. From the fitting of these models we find that the gas-regulator model provides a better description of the observed parameters. In particular, we find that in this model the best parameterization of the mass loading factor as a function of local escape velocity is in good agreement with models of momentum-driven outflows powered by feedback from massive stars and supernovae.

### 6.2. The Role of Star Formation

We have shown that there is a strong local inverse correlation between the total gas fraction \(\mu\) and the oxygen abundance \((Z)\). Since regions of high gas fraction will have higher SFRs, we may expect there to be a local correlation between \(Z\) and the specific SFR \((sSFR = \Sigma_{\text{SFR}}/\Sigma_g)\) or \(\Sigma_{\text{SFR}}\). On the other hand, we have recently used MaNGA data to show that on global scales there is no significant correlation between the SFR or the sSFR and the residuals in the global \(M_\text{esc}-Z\) relation (Barrera-Ballesteros et al. 2017).

To better understand the interrelationships between \(\mu\), SFR, and \(Z\) in Figure 13, we plot the residuals in the best-fit \(\mu-Z\) relation (Figure 7) as a function of both local sSFR and \(\Sigma_{\text{SFR}}\). In the case of the sSFR there is only a very weak trend \((0.04 \text{ dex over a range of } 1.2 \text{ dex in sSFR})\). There is no systematic trend in the case of \(\Sigma_{\text{SFR}}\). These results on local scales are consistent with the results on global scales presented in Barrera-Ballesteros et al. (2017).

These results have a simple interpretation. The local ISM metallicity is most strongly dependent on the gas fraction (and secondarily on the local escape velocity). Once these quantities are specified, the degree of local star formation does not play a significant role in terms of predicting the metallicity. Any apparent correlation between \(Z\) and star formation is a nonphysical one induced by the mutual correlations of \(\mu\) with both star formation and \(Z\).

### 6.3. The Role of Local Stellar Surface Density

In this paper we have examined the local dependence of the ISM metallicity \((Z)\) on the total gas-mass fraction \(\mu\) and the escape velocity \((V_{\text{esc}})\). We have focused on these two specific parameters because they can be most easily related to the parameters and processes invoked in simple models of the chemical evolution of galaxies. As we have shown above, at least one such model (a local version of the Lilly et al. (2013) gas-regulator model) does provide a statistically good and physically reasonable fit to our data.

In our previous paper (Barrera-Ballesteros et al. 2016) we found a very strong empirical local correlation between \(Z\) and the stellar surface density \((\Sigma_*\)) as well. Indeed, as we noted above, the scatter in this correlation is smaller than either the \(\mu-Z\) or the \(V_{\text{esc}}-Z\) relations presented in this paper. We also determine that for the galaxies with large global sSFR values, the local metallicity derived from the best fitted \(\Sigma_*-Z\) relation was larger than the observed metallicity. This is consistent with our recent study (Ellison et al. 2018), where we show that for the most efficient star-forming galaxies at global scales the radial gradient of the metallicity residuals from the \(\Sigma_*-Z\) relation is positive. To close out this paper, we briefly explore the connections between the \(\Sigma_*-Z\) relation and the results we have presented here.

It is well established empirically that the star formation history of galaxies (e.g., the luminosity-weighted mean age of the local stellar population) depends very strongly on \(\Sigma_*\). For
example, (Kauffmann et al. 2003b) used the amplitude of the 4000 Å break to show that the stellar age measured in the SDSS fiber correlated more strongly with the global-average value of $\Sigma_{b}$ than with any other global property of the galaxy. Zheng et al. (2013) used multiband imaging data to reach similar conclusions on a local scale. More recently, González Delgado et al. (2014) found a tight correlation between $\Sigma_{b}$ and the mean age of the stellar population at kpc scales in galaxies included in the CALIFA survey. High values of $\Sigma_{b}$ are characteristic of massive galaxies and the central regions of galaxies. Models of galaxy evolution (see Somerville & Davé 2015) find both that the progenitors of more massive galaxies form earlier and that the centers of galaxies form first (e.g., the inside-out picture of galaxy formation). This then suggests a picture in which $\Sigma_{b}$ is a proxy for the redshift at which the dominant stellar population at that location formed or was assembled. In this picture, these early-forming dense regions were predestined to have low present-day gas fractions (the gas was mostly used up much earlier) and high escape velocities characteristic of the central regions of more massive galaxies. This suggests that the correlation between $Z$ and $\Sigma_{b}$ is so good because $\Sigma_{b}$ encodes information about both $\mu$ and $V_{esc}$.

7. Conclusions

Thanks to the SDSS-IV MaNGA IFU survey, we have been able to study the spatially resolved properties for more than $9.2 \times 10^5$ star-forming spaxels in a sample of 1023 galaxies. Our goal was to use these data to test, on local scales, the general premises of models of chemical evolution in which the ISM metallicity is primarily set by the gas fraction (measuring the degree of chemical evolution) and the local escape velocity (which will regulate the rate at which gas and metals can be expelled by feedback from massive stars).

The main conclusions and results from this study are:

1. We presented the local relation between the gas fraction ($\mu$) and metallicity ($\mu-Z$ relation) This tight relation ($\sigma \sim 0.09$ dex) indicates that metallicity increases as gas fraction decreases.

2. We constructed maps of the local escape velocity ($V_{esc}$) based on modeling of the galaxy rotation curve. With a larger scatter than the $\mu-Z$ relation, we found that local metallicity also scales with $V_{esc}$: spaxels with low escape velocity tend to be metal poor.

3. We found weak but statistically significant systematic residuals in the $\mu-Z$ relation as a function of $V_{esc}$. We found stronger systematic residuals in the $V_{esc-Z}$ relation as a function of $\mu$. We concluded that the gas fraction is the most important parameter in setting $Z$ but that the local escape velocity also contributes.

4. We fit local adaptations of the gas-regulator and leaky-box models of chemical evolution to the observed $\mu-Z$ relation. The best-fit leaky-box model required unphysically large values for the mass loading factor of the outflow. The best-fitting parameters from the gas-regulator model suggest that local chemical composition is consistent with local outflows driven by the momentum supplied by massive stars and supernovae.

5. The scatter of the $\mu-Z$ relation is similar to the one reported previously for the surface mass density–metallicity ($\Sigma_{b}-Z$) relation. This latter quantity is a measure of the time of formation of the mass-dominant stellar at a given location, suggesting that the local metallicity, gas fraction, and escape velocity at the present epoch are predetermined at much earlier times.
Our results indicate that both the resolved gas fraction and the ionized gas metallicity are the result of galaxy evolution occurring at local scales. This study also highlights the impact of local momentum-driven outflows on shaping the internal metallicity of star-forming galaxies.

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Appendix

In Section 3.4 we assume a spherically symmetric galactic potential for our sample of star-forming galaxies. In this appendix we estimate the error introduced into the escape velocity from this assumption by using a more sophisticated dynamical model of a disk galaxy composed of an axisymmetric stellar disk within a spherical dark-matter halo. For this particular example, we use a galaxy observed in the 127-fiber bundle setup to have a good spatial coverage, a Sérsic index of $n < 2$, and an axial ratio of $0.25 < b/a < 0.75$ to avoid inclination effects. In the left panel of Figure 14 (see blue points) we plot the rotation curve derived using the same procedure as described in Section 3.3.

These rotation curves were then fit using a model rotation curve composed of an axisymmetric disk and a spherical halo. The disk component was assumed to contain all of the baryonic matter and to have an exponentially decreasing surface density:

$$\Sigma(R) = \frac{M_d}{2\pi R_d^2} e^{-R/R_d},$$

where $M_d$ is the total mass of the disk and $R$ is the radius in the plane of the disk (Binney & Tremaine 2008). The disk mass in each case was taken from the NSA catalog. The NSA half-life radius of each galaxy was used to obtain the disk scale radius by assuming a constant mass-to-light ratio and that the surface brightness and surface mass density each follow the same $\rho(R/R_d)$ form. On the other hand, the halo component was modeled as a spherical NFW profile:

$$\rho(r) = \frac{\rho_0}{(r/R_h)(1 + r/R_h)^2},$$

where $r$ is the spherical radius (Navarro et al. 1996). The parameters $\rho_0$ and $R_h$ are taken as free parameters in our model. Both of these density profiles have analytically solvable potentials. The potential of the disk is given by Binney & Tremaine (2008):

$$\Phi_d(R) = -\frac{GM_d y}{R_d} (I_0(y)K_0(y) - J_1(y)K_0(y)), \quad y = \frac{R}{2R_d},$$

where $I_n$ and $K_n$ are modified Bessel functions of the first and second kind, respectively. The potential of the halo is (Binney & Tremaine 2008):

$$\Phi_h(r, \rho_0, R_h) = -4\pi G \rho_0 R_h^2 \ln(1 + r/R_h)/r/R_h.$$

These potentials were then used to calculate the rotation curves $v_d(R)$ produced by the disk and the $v_h(r, \rho_0, R_h)$ produced by the halo. We considered rotation curves and escape velocities within the plane of the disk where $r = R$. In addition to the disk and halo contributions, the model rotation curve also included a systemic velocity term to allow for errors in the systematic velocities used in deriving the rotation curve. Thus the final model that was fit to our data is

$$v(R, \rho_0, R_h, v_{sys}) = \sqrt{(v_d^2(R) + v_h^2(R, \rho_0, R_h)) + v_{sys}}.$$

Once the halo and disk parameters were obtained from the best fit, the escape velocity to $R = \infty$ and the halo mass $M_{100}$ (defined as the halo mass within 100 kpc) were calculated. In the right panel of Figure 14 we show the comparison between the escape velocity derived using this two-component dynamical model (red dashed line) and the one described in Section 3.4 (blue points). According to this comparison, the simplest model described in Section 3.4 tends to overestimate the escape velocity in comparison to the two-component model. However, the difference of the order of $\sim 10$ km s$^{-1}$ at different radii is a factor of $<5\%$ of the estimated escape velocity from the single-component dynamical model in Section 3.4. This difference is similar in other disk galaxies with characteristics similar to the one presented in this example.
Determination of the escape velocity using a two-component dynamical model for a disk-like galaxy included in our sample. Left panel: blue points represent the rotation curve determined using the same procedure as described in Section 3.3. The black solid line represents the best fit from the two-component dynamical model while the green and cyan dotted lines represent the individual contributions to the rotational curve from the axisymmetrical stellar disk and the spherical dark-matter halo, respectively. Right panel: the blue points show the radial profile of the escape velocity as derived in Section 3.4 while the red dashed line represents the escape velocity from the best-fit parameters using the two-component dynamical model. The green and cyan dashed lines represent the individual contributions to the escape velocity from the axisymmetric stellar disk and the spherical dark-matter halo, respectively. In this example, the difference between the red line and blue points is ~10 km s\(^{-1}\).

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