A VARIANT STELLAR-TO-NEBULAR DUST ATTENUATION RATIO ON SUBGALACTIC AND GALACTIC SCALES

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\textbf{ABSTRACT}

The state-of-the-art geometry models of star/dust suggest that dust attenuation toward nebular regions ($A_{V,\text{gas}}$) is always larger than that of stellar regions ($A_{V,\text{star}}$). Utilizing the newly released Integral Field Spectroscopic data from the MaNGA survey, we investigate whether and how the $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio varies from subgalactic to galactic scales. On subgalactic scale, we report stronger correlation between $A_{V,\text{star}}$ and $A_{V,\text{gas}}$ for more active H\textsc{ii} regions. The local $A_{V,\text{star}}/A_{V,\text{gas}}$ is found to have moderate non-linear correlations with three tracers of diffuse ionized gas (DIG) as well as indicators of gas-phase metallicity and ionization. DIG regions tend to have larger $A_{V,\text{star}}/A_{V,\text{gas}}$ compared to classic H\textsc{ii} regions excited by young OB stars. Metal-poor regions with higher ionized level suffer much less nebular attenuation and thus have larger $A_{V,\text{star}}/A_{V,\text{gas}}$ ratios. A low-$A_{V,\text{gas}}$ and high-$A_{V,\text{star}}/A_{V,\text{gas}}$ sequence, which can be resolved into DIG-dominated and metal-poor regions, on the three BPT diagrams is found. Based on these observations, we suggest that besides geometry of star/dust, local physical conditions such as metallicity and ionized level also play an important role in determining the $A_{V,\text{star}}/A_{V,\text{gas}}$. On galactic scale, the global $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio has strong correlation with stellar mass, moderate correlations with SFR and metallicity, and weak correlations with inclination and sSFR. Galaxies with larger $M_*$, higher SFR, and being more metal-rich tend to have smaller $A_{V,\text{star}}/A_{V,\text{gas}}$ ratios. Such correlations form a decreasing trend of $A_{V,\text{star}}/A_{V,\text{gas}}$ along the star-forming main sequence and mass-metallicity relation. The dust growth process accompanied with galaxy growth might be one plausible explanation of our observations.

\textit{Keywords:} dust, extinction — galaxies: evolution — galaxies: ISM — galaxies: star formation
1. INTRODUCTION

Almost one half of optical emission is shielded by dust and reach us in the form of infrared (IR) radiation (Dole et al. 2006), especially for stellar light from star-forming galaxies (SFGs) that contribute to the cosmic infrared background up to about 95% (Viero et al. 2013). This so-called dust extinction/attenuation effect prevents us from measuring some important galactic properties accurately, such as star formation rate (SFR), stellar mass ($M_*$), and so on. Dust is produced from the late stage of stellar evolution, namely supernovae (SN) and stellar winds of asymptotic giant branch stars (e.g., Dwek 1998; Aoyama et al. 2017; Gjergo et al. 2018), grows in the interstellar medium (ISM), especially in dense molecular cloud (e.g., Hirashita & Voshchinnikov 2014), and is destroyed by SN shocks (e.g., Aoyama et al. 2017). Such dust processes substantially alter the dust abundance and the size distribution of dust grains (e.g., Asano et al. 2013; Aoyama et al. 2017; Hirashita & Aoyama 2019) and hence affect the absorption and scattering of light (see Galliano 2018 for a review). Therefore, to better understand the formation and evolution of galaxies, we should know how and how much stellar light is reproduced by the dust extinction/attenuation effect.

Besides the dust properties, the geometry between dust and stars is also believed to be an important factor for dust attenuation in terms of variations in the shape of the dust attenuation law (Salmon et al. 2016; Narayanan et al. 2018a) and the IRX-β relation (Popping et al. 2017; Narayanan et al. 2018b). Particularly, it is thought of as the main origin of the different level of dust attenuation between stellar light and emission lines (e.g., Price et al. 2014; Reddy et al. 2015; Koyama et al. 2019). Plenty of observations on both local (e.g., Calzetti 1997; Kreckel et al. 2013; Zahid et al. 2017; Koyama et al. 2019) and high-redshift (e.g., Garn et al. 2010; Wuyts et al. 2011, 2013; Price et al. 2014; Pannella et al. 2015; Theios et al. 2019) SFGs reveal that nebular emission lines tend to suffer more dust attenuation compared to stellar continuum. Such extra attenuation can be explained by a widely used two-component dust model (Charlot & Fall 2000; Wild et al. 2011; Chevallard et al. 2013) in which dust inside a galaxy consists of a diffuse, optically-thin component and a denser optically thick one (the birth cloud) that relates with star-forming regions. Thus, emission from ionized gas travel through the outer envelope of the birth clouds and then the ambient ISM, while the majority of stellar light propagates only the ambient ISM and suffer less dust reddening compared to emission lines (Charlot & Fall 2000).

By utilizing the observation of local starburst galaxies and bright star-forming regions, Calzetti (1997) present the relation between color excess $E(B-V)$ of star and gas as $E(B-V)_{\text{star}} = 0.44E(B-V)_{\text{gas}}$, i.e., the reddening of stellar light is only nearly one half of the one toward nebular regions. A similar relation based on V-band attenuation ($A_V$) was reported by spatially resolved study of Kreckel et al. (2013) in which they found $A_V= 0.47 \pm 0.006A_V$, assuming $R_V = 3.1$ for several relatively face on local galaxies. More recent studies also suggest that $A_V/\langle A_V \rangle$ may be not a constant for all type of galaxies (Wild et al. 2011; Koyama et al. 2015; Zahid et al. 2017; Koyama et al. 2019). It is found to be correlated with $M_*$ (Koyama et al. 2015; Zahid et al. 2017; Koyama et al. 2019), specific star formation rate (sSFR; Wild et al. 2011; Koyama et al. 2015, 2019), and inclination (Wild et al. 2011).

High-redshift studies also revealed a wide diversity of the stellar-to-nebular reddening ratio, varying from 0.44 (Wuyts et al. 2011) to $\sim 1$ (Pannella et al. 2015; Puglisi et al. 2016), as well as the dependences of $A_V/\langle A_V \rangle$ on physical properties of galaxies (Price et al. 2014; Reddy et al. 2015; Puglisi et al. 2016).

However, most of the aforementioned studies focused on dust attenuation on global scale, deriving the $A_V/\langle A_V \rangle$ using the integrated fluxes of galaxies. With the development of integral field unit (IFU) technique, spatially resolved spectra were observed for thousands of galaxies in several IFU surveys, such as SAMI (using the Sydney-Australian Astronomical Observatory Multi-object Integral Field Spectrograph; Croom et al. 2012), CALIFA (Calar Alto Large Integral Field Area; Sánchez et al. 2012), MaNGA (Mapping Nearby Galaxies at Apache Point Observatory; Bundy et al. 2015). Taking advantage of these dataset, we are able to study the dust attenuation on subgalactic scale that would help us obtain a more comprehensive understanding of dust effects. However, only a few of works paid attention to the subgalactic dust attenuation until now.

On the basis of spatially resolved spectra of several local galaxies, Kreckel et al. (2013) showed that the dust attenuation ratio within individual galaxy exhibit a dependence on the $\lambda \alpha E6717$-to-H$\alpha$ line ratio which is believed to be a tracer of the transition between diffuse ionized gas (DIG) and HII regions (e.g., Hoopes & Walterbos 2003). Adopting a critical $\lambda \alpha E6717$/H$\alpha$ ratio of 0.2, they found an $A_V/\langle A_V \rangle$ ratio of 0.7 and 0.5 for DIG-dominated and HII-dominated regions, respectively. Recently, using the high-resolution IFU observations of NGC 5626, a lenticular galaxy with a redshift of 0.023, Viaene et al. (2017) found that the continuum attenuation is independent from the ionized gas attenuation in this early-type galaxy. This observation raises the question of whether the dust attenuation of stellar
continuum and ionized gas indeed correlate tightly with each other, and whether the correlation could be broken under certain conditions.

On the other hand, adopting the ultraviolet (UV) slope $\beta$ as an indicator of stellar attenuation, Calzetti et al. (1994) observed a linear correlation between $\beta$ and the nebular attenuation, indicating a tight and monotonic relation between the stellar dust attenuation and nebular dust attenuation. Based on this property, the widely used dust attenuation law of Calzetti et al. (2000) was constructed. More recent works following the same methodology to derived the attenuation law either in local Universe (e.g., Battisti et al. 2016; Battisti et al. 2017) or at high redshift (e.g., Reddy et al. 2015) also rely on this relation. Therefore, it is important to verify the applicability of this finding to a broader range of galaxies than those used in previous studies.

Making use of IFU data, this work aims at investigating whether the dust attenuation of stellar continuum and ionized gas correlate with each other and, if so, whether their ratio correlates with local and global properties for H\textsc{ii} regions. This paper is organized as follows. In Section 2, we give a brief overview on the data and sample selection. We present results of correlations between the reddening ratio and local physical properties in Section 3. We further analyze how $A_{V,\text{star}}/A_{V,\text{gas}}$ vary with global properties of galaxies in Section 4. Finally, we summarize in Section 5. Throughout this paper, we adopt a flat $\Lambda$CDM cosmology with $H_0 = 71$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_\Lambda = 0.73$, $\Omega_m = 0.27$, and a Salpeter (1955) initial mass function (IMF).

2. DATA AND SAMPLE SELECTION

2.1. MaNGA Survey and Pipe3D Value Added Catalog

MaNGA, as one of the major spectroscopic programs of the Sloan Digital Sky Survey IV (SDSS-IV; Blanton et al. 2017), plans to observe $\sim 10,000$ nearby galaxies with a redshift range of 0.01–0.15, spanning a wide range of $M_*$, SFR, and environment (Bundy et al. 2015; Y\text{"a}n et al. 2016). Spectral observations of the MaNGA survey cover a wavelength range of 3600–10300 Å with a spectral resolution of $R \sim 2000$ and a spatial resolution, i.e., the full-width at half maximum (FWHM) of the reconstructed point spread function (PSF), of 2.5″ (Law et al. 2016). In this work, we make use of MaNGA data from the SDSS DR15 (Aguado et al. 2019), which includes 4824 datacubes.

Our main data is from the MaNGA value added catalog (VAC) of the Pipe3D pipeline (Sánchez et al. 2018), which is released as one part of the SDSS DR15\textsuperscript{1}. This pipeline is designed to implement full spectral fitting with stellar population models for IFU spectra. Details and algorithms can be found in Sánchez et al. (2016a,b). Here, we provide a brief summary of the procedure of the stellar continuum fitting. A spatial binning is performed for each datacube to achieve a nominal continuum signal-to-noise ratio (SNR) of 50 before fitting. A set of 156 simple stellar population (SSP) templates from Cid Fernandes et al. (2013) accounting for 39 stellar ages (from 1 Myr to 13 Gyr) and 4 metallicities ($Z/Z_\odot = 0.2, 0.4, 1$, and 1.5) is used to model the coadded spectra of each spatial bin. Fitting procedure includes two steps: first, a fitting is performed to extract the non-linear parameters such as velocity, velocity dispersion, and dust attenuation, assuming an extinction curve of Cardelli et al. (1989) and a selective extinction of $R_V = 3.1$; then a robust modeling is applied on the corrected spectra after accounting for the non-linear effects derived from the previous step, via a linear combination of the 156 SSPs with the Monte-Carlo method to obtain the coefficients of the best fitted model and the corresponding uncertainties.

After the continuum modeling, the pipeline rescale the best fitted SED of one spatial bin by the V band flux of each spaxel within that bin and take it as the best fitted model of each spaxel. This resulting “fake” spectrum is then subtracted from the observed one to generate a pure emission line spectrum. Individual emission line is fitted spaxel by spaxel with a single Gaussian profile. It is noteworthy that the continuum modeling is implemented for spatial bins, whereas the ionized gas analysis is performed for individual spaxel. Finally, the Pipe3D VAC provides dataproducts for 4815 galaxies including both the results of the analyses of stellar continua and emission lines (Aguado et al. 2019).

2.2. Reanalysis of Emission Lines

Given the aim of this study, we need dust attenuation of both stellar continuum and emission lines, while the former one is provided for spatial bins and the latter one is given for individual spaxel in the Pipe3D VAC. To reconcile the spatial scale of these two parameters, we determine to use spatial bins to study and reanalyze the emission lines on the same spatial scale. This choice can also prevent the oversampling of low SNR spectra for which the stellar properties should be the same if they belong to the same spatial bin, as well as avoid any potential uncertainties from the V band flux-based

\footnote{https://www.sdss.org/dr15/manga/manga-data/manga-pipe3d-value-added-catalog/}
assignment of the underlying stellar contribution. For simplicity, in the follows the term "spaxel" refers to a given spatial element regardless of the number of spaxels within it.

We reconstruct the best fitted spectra for each spaxel using the weights of 156 SSP templates from the Pipe3D VAC. The resulting spectra are in good agreement with the coadded observed spectra, and then are subtracted to create pure emission line spectra for further emission line analysis. We fit each emission line with one single Gaussian function using the Python version of MPFIT\(^2\) software (Markwardt 2009). The SNRs of emission lines are calculated via the method introduced in Ly et al. (2014). We use the Balmer decrement to correct the galactic internal attenuation. Under the assumption of the Case B recombination, we employ an intrinsic flux ratio of H\(\alpha\)/H\(\beta\) = 2.86 (Storey & Hummer 1995), an extinction curve of Cardelli et al. (1989), and a \(R_V\) = 3.1 to do the dereddening. In short, we redo the analysis of ionized gas but on the spatial bin scale.

2.3. Sample Selection

To ensure a reliable estimate of the dust attenuation of gas (\(A_{V,\text{gas}}\)), we limit our analysis to spaxels with SNR of H\(\alpha\) and H\(\beta\) greater than 5 and SNR of [O\(\text{III}\)]\(\lambda\)5007, [N\(\text{II}\)]\(\lambda\)6584, and [S\(\text{II}\)]\(\lambda\)6717 greater than 3. Setting lower SNR cuts should not change our results (see Appendix A for a detailed discussion). Given that the spatial binning scheme performed by the Pipe3D requires not only a SNR goal but also a continuity criterion, many of the spatial bins cannot reach the set SNR of 50 due to the balance between these two requirements (Sánchez et al. 2016b). Therefore, an additional continuum SNR cut, which we set to 10, is also needed to ensure an unbiased estimate of stellar attenuation (\(A_{V,\text{star}}\); Sánchez et al. 2016a). The distribution of these selected spaxels on the standard Baldwin-Phillips-Terlevich (BPT) diagram (Baldwin et al. 1981), which is widely used to remove contamination of active galactic nucleus (AGN) from star-forming regions, is shown in Figure 1. We further select star-forming spaxels based on the Kauffmann et al. (2003) demarcation. The quality control\(^3\) provided by the Pipe3D VAC is also considered, only galaxies flagged as 0 (i.e., do not find any problem) are included in our sample. The above criteria result in more than 450,000 spaxels from 2975 galaxies that is taken as our final sample. The median and 68% range of the physical size of these spaxels is 0.20\(^{+0.54}_{-0.12}\) kpc\(^2\).

\(^2\) https://code.google.com/archive/p/astrolibpy/
\(^3\) https://data.sdss.org/datamodel/files/MANGAPIPE3D\nMANGADRP_VER/PIPE3D_VER/QC_MaNGA.html

Figure 1. BPT diagram of the selected spaxels. The dashed black curve represents the theoretical maximum starburst line of Kewley et al. (2001), the solid black curve shows the demarcation between the pure star-forming region and the AGN region from Kauffmann et al. (2003). The gray region shows the density distribution of all the selected spaxels, while the blue contours are drawn at the 68%, 95%, and 99% of the star-forming spaxels only, respectively. The black errorbar denotes the median uncertainties of all star-forming spaxels.

Recent IFU studies show that there is a sub-galactic main sequence (SGMS) relation between the stellar mass surface density (\(\Sigma_*\)) and the SFR surface density (\(\Sigma_{\text{SFR}}\)) held down to sub-kpc scale (e.g., Wuyts et al. 2013; Cano-Díaz et al. 2016; Hsieh et al. 2017; Liu et al. 2018). SFR is computed from the dust-corrected H\(\alpha\) luminosity based on the conversion of Kennicutt (1998b). We find that our spaxels form an evident SGMS that shows remarkable agreement with another two SGMSs (Hsieh et al. 2017; Liu et al. 2018) derived from the MaNGA data of SDSS DR14, which suggests that our sample well represents the population of sub-galactic star-forming regions.

The stellar dust attenuation \(A_{V,\text{star}}\), which is a product of the continuum modeling process described in Section 2.1, is taken from the Pipe3D VAC. Its statistical uncertainty propagated from the uncertainties of the observed spectrum is derived by the Monte-Carlo approach during the continuum modeling, and is estimated to have a typical value of 0.007 mag. Therefore, the total uncertainty should be dominated by the systematic uncertainty. According to our SNR criterion, we expect a nearly unbiased \(A_{V,\text{star}}\) estimation with a dispersion better than 0.26 mag (Sánchez et al. 2016a). The nebular dust attenuation \(A_{V,\text{gas}}\) is a byproduct of the emission line dereddening in which the uncertainty propaga-
tion is carefully performed. Under the aforementioned assumptions, the median and 1-σ dispersion of the statistical uncertainty of $A_{V_{\text{gas}}}$ is estimated be 0.08 $\pm$ 0.07 mag.

The stellar and nebular attenuation are both derived on the basis of the Cardelli et al. (1989) extinction curve. The choice of extinction/attenuation curve might affect the resulting attenuation values. However, for $A_{V_{\text{star}}}$, Sánchez et al. (2016a) claimed that no major differences were found when the Cardelli et al. (1989) extinction curve is replaced by the Calzetti et al. (2000) attenuation law or a $\lambda^{-1.3}$ extinction curve due to the small differences between these extinction/attenuation law in optical wavelength range. The replacement of extinction/attenuation curve in the calculation of $A_{V_{\text{gas}}}$ only introduces a constant scaled factor. For these reasons, the choice of extinction/attenuation curve could alter the absolute values of $A_{V_{\text{star}}}/A_{V_{\text{gas}}}$, but the relative values, as well as most of our following results, should remain almost unchanged.

3. RELATION BETWEEN $A_{V_{\text{star}}}/A_{V_{\text{gas}}}$ AND LOCAL PROPERTIES

3.1. Correlate or not?

We first examine whether the $A_{V_{\text{gas}}}$ correlation with $A_{V_{\text{star}}}$ for the whole spaxel population, the Pearson linear and Spearman’s rank correlation coefficients are 0.40 and 0.34, respectively. However, if the spaxels are divided into bins of $\Sigma_{H\alpha}$, we find that the correlation coefficients of the binned subsamples strongly change with the $\Sigma_{H\alpha}$.

We show how the Pearson ($r$) and Spearman’s rank ($\rho$) correlation coefficients between the $A_{V_{\text{star}}}$ and $A_{V_{\text{gas}}}$ vary with $\Sigma_{H\alpha}$ in Figure 2. Obviously, both correlation coefficients display a substantial increase from $r < 0.1$ at low-$\Sigma_{H\alpha}$ end to $r \approx 0.8$ at high-$\Sigma_{H\alpha}$ end. Thus, the nebular attenuation indeed correlates with the stellar attenuation, although the strength of this correlation strongly correlates with the level of local star formation.

3.2. Correlation Analysis

In this subsection we consider how the $A_{V_{\text{star}}}/A_{V_{\text{gas}}}$ ratio correlate with local physical properties, such as $H\alpha$ luminosity (i.e., local SFR) and its surface brightness ($\Sigma_{H\alpha}$, i.e., $\Sigma_{SFR}$), stellar mass within each spaxel ($M_{\text{star,spaxel}}$) and its surface density ($\Sigma_{*}$), local specified SFR (ssSFR) and its observational indicator - equivalent width of $H\alpha$ (EW$_{H\alpha}$), stellar age tracer $D4000$ (Bruzual A. 1983), and several emission line indices.

The O3N2 and N2 indices, which are defined as

$$\text{O3N2} \equiv \log\left( \frac{[\text{O iii}]\lambda5007}{H\beta} \times \frac{H\alpha}{[\text{N ii}]\lambda6584} \right)$$

and

$$\text{N2} \equiv \log([\text{N ii}]\lambda6584/\text{H} \alpha),$$

respectively, are widely used as diagnostic of gas-phase metallicity (e.g., Pettini & Pagel 2004; Kewley & Ellison 2008; Marino et al. 2013). Moreover, N2O2, defined as

$$\log([\text{N ii}]\lambda6741 /[\text{O ii}]\lambda3727),$$

is also considered as an excellent metallicity tracer (e.g., Dopita et al. 2000, 2013), especially when the DIG may have a non-negligible contribution to emission lines (Zhang et al. 2017). However, the empirical calibrations between these indices and oxygen abundance are different among previous works, leading to discrepancies up to $\Delta[\text{log(O/H)}] = 0.7$ dex (Kewley & Ellison 2008). Lin et al. (2017) also reported an inconsistency between metalicities derived from O3N2 and N2 even the calibrations were derived based on the same dataset. For these reasons, here we directly use O3N2, N2, and N2O2 as indicators of metallicity but do not apply any empirical calibrations.

Given that the status of ionized gas may play an important role in determining the $A_{V_{\text{star}}}/A_{V_{\text{gas}}}$ ratio (Kreckel et al. 2013), we also include DIG indicators in the analysis. Besides the $[\text{S ii}]\lambda6717/\text{H} \alpha$

\footnote{Due to the limited spectral resolution of MaNGA, all $[\text{O ii}]\lambda3727$ mentioned in this work represents the sum of the $[\text{O ii}]\lambda3726, 3729$ doublet.}
ratio, $\Sigma_{\text{H}\alpha}$ (Zhang et al. 2017) and EW$_{\text{H}\alpha}$ (Lacerda et al. 2018) are also used to separate H II-dominated and DIG-dominated regions. Furthermore, as suggested by Lin MY et al. (2019, in preparation), [N II]/H$\alpha$ vs. [S II]/H$\alpha$ diagram can be a useful tool to infer the ionization source of DIGs. Thus, we define $S2 \equiv \log([\text{S II}]\lambda 6717/\text{H}\alpha)$ and $N2S2 \equiv \log([\text{N II}]\lambda 6584/[\text{S II}]\lambda 6717)$, and add these two indices in our correlation analysis, together with $O32 \equiv \log(\langle \text{O III} \rangle\lambda 5007/\langle \text{O II} \rangle\lambda 3727)$ to distinguish differences in ionization parameter (Baldwin et al. 1981; Dopita et al. 2013). Figure 3 shows the Spearman’s rank correlation coefficients ($\rho$) between the $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio and all the above parameters.

The DIG indicator of N2S2 gives the strongest correlation with the $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio. However, its physical meaning is not clear at present, we defer discussion of this index to Section 3.5. Other two DIG tracers of S2 and $\Sigma_{\text{H}\alpha}$ also present moderate ($|\rho| > 0.4$) correlations with the attenuation ratio, which suggest that emission line regions with smaller $\Sigma_{\text{H}\alpha}$ (more diffuse) and higher [S II] $\lambda$6717-to-H$\alpha$ ratio (smaller ionization parameter, e.g., Haffner et al. 2009) would have larger $A_{V,\text{star}}/A_{V,\text{gas}}$ values. In other word, at fixed $A_{V,\text{star}}$, DIG regions tend to suffer less nebular attenuation with respect to classical H II regions. Such correlations are in good agreement with the result of Kreckel et al. (2013), and can be explained by the two-component dust model of Charlot & Fall (2000). In this model, the H II-dominated regions embedded in dense and dustier clouds in which massive stars born, surrounding by diffuse ISM where most of the DIG-dominated regions locate. Irrespective of what provide the ionizing photons of the DIG, leaky H II regions (e.g., Haffner et al. 2009) or hot low-mass evolved stars (e.g., Flores-Fajardo et al. 2011; Zhang et al. 2017), the possible excitation mechanisms of DIG imply that these regions should be more uniformly mixed with the diffuse ISM.

However, EW$_{\text{H}\alpha}$ (and sSFR), which is also considered as an alternative DIG indicator by Lacerda et al. (2018), contrary to other three DIG tracers, shows much weaker correlation with the attenuation ratio. As elucidated in Zhang et al. (2017), the dependence of EW$_{\text{H}\alpha}$ on metallicity makes it a poor tracer of DIG in some cases, resulting in an almost flat distribution together with a very large scatter on the EW$_{\text{H}\alpha}$ (sSFR) vs. $A_{V,\text{star}}/A_{V,\text{gas}}$ plane for our sample. By comparison, we present the contour of spaxel density on the $\Sigma_{\text{H}\alpha}$-$A_{V,\text{star}}/A_{V,\text{gas}}$ plane in Figure 9. Obviously, the dispersion of spaxels significantly decreases with increasing $\Sigma_{\text{H}\alpha}$, suggesting the $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio converge to a constant that close to the value of Calzetti (1997) at high-$\Sigma_{\text{H}\alpha}$ end. The different behavior between $\Sigma_{\text{H}\alpha}$ (or $L_{\text{H}\alpha}$) and EW$_{\text{H}\alpha}$ implies that the dust attenuation of local star-forming region is more sensitive to the current star formation activity rather than the past one, which is also implied by the weaker correlation between the $A_{V,\text{star}}/A_{V,\text{gas}}$ and $M_{\text{gas}}$ (or $\Sigma_{\text{gas}}$).

Moderate correlations are also found for emission line indices of both metallicity and ionization. Given the positive (negative) relation between oxygen abundance and N2, N2O2 (O3N2) index (e.g., Kewley & Ellison 2008; Marino et al. 2013; Dopita et al. 2013), the correlations presented in Figure 3 imply that the ratio between $A_{V,\text{star}}$ and $A_{V,\text{gas}}$ tends to be smaller in more metal-rich regions. Moreover, regions with a higher ionized level (larger O32) tend to have larger $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio. We will return to these two parameters with a more detailed discussion in Section 3.3. $D4000$ shows the weakest correlation, suggesting that the $A_{V,\text{star}}/A_{V,\text{gas}}$ is stellar age-insensitive on the physical scale of our spaxels.

The Pearson correlation coefficients between the $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio and these properties are also calculated. However, all of them are found to be smaller than the corresponding Spearman’s rank correlation coefficients, indicating weaker linear correlations between the $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio and the explored parameters.

![Figure 3. Spearman’s rank correlation coefficients between the $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio and several local properties. The hatched magenta bars presents positive correlation coefficients, while the cyan bars indicate the absolute value of negative correlation coefficients. The order of these parameters are sorted by the absolute value of their correlation coefficients.](image-url)
3.3. Correlate with Physical Condition of Ionized Gas

As mentioned in Section 3.2, the physical condition of ionized gas such as metallicity and ionized level may help us determine the dust attenuation ratio. However, it is hard to draw reliable conclusions from Figure 3 alone due to the small correlation coefficients. On the one hand, although we find moderate correlations between the $A_{\text{V,star}}/A_{\text{V,gas}}$ ratio and metallicity indicators, the relation with metallicity still has large uncertainty because of the non-negligible role of ionization in emission line ratios (Dopita et al. 2013). For example, Mao et al. (2018) suggested that the radial gradients of O3N2 and N2 indices across H II regions can attribute to the variations of ionized level rather than the metallicity. On the other hand, there is a contradiction that larger $A_{\text{V,star}}/A_{\text{V,gas}}$ ratio is preferred for highly ionized gas (i.e., large O32 index) as well as DIG for which a smaller ionization parameter compared to classic H II regions is always suggested (e.g., Haffner et al. 2009). To better understand the role of metallicity and ionization parameter in determining the $A_{\text{V,star}}/A_{\text{V,gas}}$ ratio and reconcile the seemingly conflicting observations, the connection between these two parameters should be disentangled.

3.3.1. N2O2 vs. O32 Diagram

We first explore how the DIG tracer ($\Sigma_{\text{H}\alpha}$) distributes in the metallicity-ionization parameter space. The median map of $\Sigma_{\text{H}\alpha}$ on the N2O2 vs. O32 diagram for all spaxels is shown in Figure 4, overlapping with density contour in black solid lines. In addition, we also plot the grid of ionization model of spherical H II region with $\kappa = \infty$ from Dopita et al. (2013) in which emission-line fluxes at different metallicities $Z$ and different ionization parameters $\log(q)$ are computed. This diagram clearly separates the metallicity from the ionization parameter, and will be suitable for examining the respective effect of abundance or ionization when the other is fixed. As we expected, most of the selected spaxels are covered by the theoretical grid of H II region, except for a branch perpendicular to the main star-forming cloud at the upper right corner, which is identified as AGN sequence (Dopita et al. 2013). At the metal-poor end, there is a trend that the median $\Sigma_{\text{H}\alpha}$ increases with increasing ionization. However, the trend inverts apparently at the metal-rich end possibly due to the contamination from AGN-dominated spaxels.

We further separate all spaxels into H II-dominated and DIG-dominated populations adopting the criterion of Zhang et al. (2017), i.e., H II-dominated spaxels with $\Sigma_{\text{H}\alpha} > 10^{39}$ erg s$^{-1}$ kpc$^{-2}$ and DIG-dominated spaxels with $\Sigma_{\text{H}\alpha} < 10^{39}$ erg s$^{-1}$ kpc$^{-2}$. Kreckel et al. (2013) adopted [S ii] $\lambda 6717$/H$\alpha = 0.2$ to separate spaxels into these two populations, which is based on observations in Milky Way (Madsen et al. 2006). However, due to the beam smearing effect resulted from the low spatial resolution of MaNGA (Zhang et al. 2017), as well as the metallicity-dependence of the [S ii] $\lambda 6717$/H$\alpha$ ratio, this simple boundary cannot be directly applied to the MaNGA data.

According to the $\Sigma_{\text{H}\alpha}$ criterion, the fractions of spaxels that classified as H II-dominated and DIG-dominated regions are 68.2% and 31.8%, respectively. Two DIG-

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5 Here, the $\kappa$ describes how the energy distribution of electrons in H II regions departs from a standard Maxwell-Boltzmann equilibrium energy distribution, while $\kappa = \infty$ represents the Maxwell-Boltzmann distribution (Nicholls et al. 2012; Dopita et al. 2013).

6 The distribution of all DIG-dominated spaxels on the BPT diagram might extend across the Kaufrman et al. (2003) boundary (Zhang et al. 2017), and covers the composite or even the AGN regime of Figure 1, where is already excluded by our selection of star-forming spaxels. Thus, the DIG-dominated population in this work is incomplete. The following analysis of DIG-dominated spaxels is restricted to this subsample that resides in the star-forming regime.
dominated loci are found in Figure 4, one is at the low-$Z$, low-$q$ regime, the other is the AGN sequence. The distributions of de-projected galactocentric distances of spaxels in both loci span a wide range, and peak at $\sim 1.5$ kpc and $\sim 2.5$ kpc for the AGN sequence and the low-$Z$, low-$q$ locus, respectively. In combination with the properties of the underlying low-SNR & low-$\Sigma_{H\alpha}$ population shown in Appendix A, we argue that these loci should be predominantly attributed to Li(N)ER-like regions or DIG excited by hot, low-mass, evolved stars. The coverage of the star-forming cloud is in good agreement with the distribution of SDSS galaxies from Kewley et al. (2006) shown in Dopita et al. (2013), and extends from the low-$Z$, high-$q$ end to the high-$Z$, low-$q$ end.

3.3.2. Dust attenuations on the N2O2 vs. O32 Diagram

To see how dust attenuation (and ratio) vary with $Z$ and $q$, we present the median map of $A_{V,\text{star}}/A_{V,\text{gas}}$, $A_{V,\text{gas}}$, and $A_{V,\text{star}}$ for all, H ii-dominated, and DIG-dominated spaxels in Figure 5, over-plotting with the theoretical grid of star-forming regions from Dopita et al. (2013). The medians and the 68% limits of $A_{V,\text{star}}/A_{V,\text{gas}}$ are 0.55$^{+0.68}_{-0.26}$, 0.48$^{+0.32}_{-0.22}$, and 0.93$^{+0.79}_{-0.56}$ for all, H ii-dominated, and DIG-dominated spaxels, respectively. As a comparison, Kreckel et al. (2013) found the $A_{V,\text{star}}/A_{V,\text{gas}}$ ratios of 0.5 and 0.7 for their selected H ii-dominated and DIG-dominated regions, respectively, which are consistent with ours.

Although the ionization level of DIG regions is found to be systematically lower compared to that of H ii regions, the large overlap of the contours of both subsamples with the theoretical grid in Figure 5 indicates that both of them cover a similar and wide range in parameter space of either metallicity or ionization. Comparing the subplots in Figure 5 column by column, the overall features are very similar for all the three populations except for the systematic shift of absolute value between them. Comparing the subplots row by row, it is evident that the overall trend of the $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio is dominated by that of the $A_{V,\text{gas}}$, while the $A_{V,\text{star}}$ maps exhibit a relatively uniform distribution on the N2O2 vs. O32 diagram (i.e., the metallicity-ionization parameter grid), regardless of the population.

The roles of gas-phase metallicity and ionization level in determining $A_{V,\text{star}}/A_{V,\text{gas}}$ are more obvious on this plot. For the $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio, all the three populations show significantly higher value at the low-$Z$, high-$q$ corner, leading to the moderate correlations between $A_{V,\text{star}}/A_{V,\text{gas}}$ and metallicity, ionization parameter found in Section 3.2. As for the $A_{V,\text{gas}}$, spaxels occupied the low-$Z$, high-$q$ corner suffer smaller dust attenuation, indicating that $A_{V,\text{gas}}$ decreases with $Z$ ($\log q$) being lower (higher). This trend might be a geometric result if the low-$A_{V,\text{gas}}$ spaxels are in the outer disks of their host galaxies. We adopt N2O2 < 0 & O32 > −0.5 to select the low-$A_{V,\text{gas}}$ regime and use the de-projected galactocentric distances normalized by the effective radii of host galaxies (i.e., $r/R_e$) to measure their location on the disks. We find that the $r/R_e$ distribution of the low-$A_{V,\text{gas}}$ subsample is similar to that of the whole sample. However, spaxels in this low-$A_{V,\text{gas}}$ regime tend to reside in less massive galaxies compared to the whole sample. Therefore, the trend of the low-$A_{V,\text{gas}}$ subsample with lower metallicity and higher ionization parameter dose not result from the geometric effect, and is mainly due to the smaller $M_*$ of their host galaxies.

Intriguing, the low-$Z$, high-$q$ corner of DIG-dominated spaxels have a $A_{V,\text{star}}/A_{V,\text{gas}}$ larger than 1, indicating that the stellar light is more attenuated than emission lines. Spaxels in this regime only account for nearly 16% of the DIG-dominated population. Comparing with the H ii-dominated spaxels in the same regime, these DIG-dominated spaxels have comparable $A_{V,\text{star}}$ but smaller $A_{V,\text{gas}}$, suggesting that $A_{V,\text{star}}/A_{V,\text{gas}} > 1$ mainly results from a smaller $A_{V,\text{gas}}$. The distributions of these spaxels on several emission line diagrams are consistent with the model predictions of leaky H ii regions presented in Zhang et al. (2017) (their Figure 18). Meanwhile, D4000 and EW_Halpha of these DIG-dominated spaxels are also comparable to normal star-forming regions. Taking into account the relatively higher ionization level of these spaxels, we argue that these DIG might be attributed to the leaky H ii region scenario in which ionized gas leaks from the dusty H ii regions, while the stellar continuum is dominated by the background stellar populations that are physically unassociated with the leaky H ii regions, leading to $A_{V,\text{star}} > A_{V,\text{gas}}$.

In summary, the smaller value of ionization parameter of DIG regions with respect to H ii regions is a systematic effect within which there still have a large dispersion in this parameter, resulting in a large scatter of the local $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio. Furthermore, the influences of metallicity and ionization level are independent of the classification of spaxels. Metal-poor regions with large log $q$ tend to have smaller nebular attenuation and thus larger $A_{V,\text{star}}/A_{V,\text{gas}}$ values for either H ii-dominated or DIG-dominated subsample. These two effects may originate from different aspects of dust attenuation, while the former reflects the different star/dust geometry for H ii-dominated and DIG-dominated populations (Kreckel et al. 2013), and the latter implies the difference in dust properties (e.g., the size distribution of dust grains; Relaño et al. 2018) or the dust-to-gas ratio ($D/G \equiv m_{\text{dust}}/m_{\text{gas}}$; Engelbracht et al. 2008; Galliano
Figure 5. Median maps of $A_{V,\text{star}}/A_{V,\text{gas}}$ (top), $A_{V,\text{gas}}$ (middle), and $A_{V,\text{star}}$ (bottom) on the N2O2 vs. O32 diagram. In each case (row), we plot results for all spaxels (left), HII-dominated regions (middle), and DIG-dominated regions (right). The overlapping $Z$-$q$ grid is the same as Figure 4. The contours over-plotting in the bottom row enclose 68%, 95%, and 99% of the spaxels on each diagram. The typical uncertainties of N2O2 and O32 for each population are shown at the upper right corner of the top row.

et al. 2011; Rémy-Ruyer et al. 2014) in different local environments.

### 3.3.3. Possible Reason for Correlations between $A_{V,\text{star}}/A_{V,\text{gas}}$ and Physical Conditions

Although most of previous works attributed the integrated $A_{V,\text{star}}/A_{V,\text{gas}}$ to geometry effect (e.g., Price et al. 2014; Reddy et al. 2015; Koyama et al. 2019), the conclusions drawn from Figure 5 imply that the local physical conditions of ionized gas may also have significant effect on the $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio. The dust attenuation at wavelength $\lambda$ ($A_\lambda$) along the line of sight $s$ can be written as

$$A_\lambda = 1.086 \tau_\lambda^{\text{att}} = 1.086 \times \int_s \kappa_\lambda^{\text{att}} \rho_{\text{dust}}(s) \, ds$$

$$= 1.086 \times \int_s \kappa_\lambda^{\text{att}} \rho_{\text{gas}}(s) \cdot D/G \, ds,$$

in which $\tau_\lambda^{\text{att}}$ is the attenuation optical depth at wavelength $\lambda$, $\kappa_\lambda^{\text{att}}$ is the corresponding total opacity (including the absorption and scattering effects), $\rho_{\text{dust}}(s)$ and $\rho_{\text{gas}}(s)$ are the mass density of dust and gas along the line of sight, respectively. In fact, the term of “extinction” should be distinguished from “attenuation.” The former one always refers to dust effects for individual point-like sources and includes absorption and scattering out of the line of sight, whereas the latter one represents the net loss of light for extended emitters, including extinction and scattering into the line of sight in which the star/dust geometry play an important role (see Calzetti 2001 for a review). Therefore, the $\tau_\lambda^{\text{att}}$ we used here is something like an effective optical depth rather than the center-to-edge optical depth of a cloud which describes the amount of dust, and the $\kappa_\lambda^{\text{att}}$ depends on not only the dust properties but also the star/dust geometry.

Here we further express $A_\lambda$ as a function of $\rho_{\text{gas}}$ and $D/G$. In the case of $A_{V,\text{star}}$ and $A_{V,\text{gas}}$, the differences between them that can be explained as geometry effect due to the two-component dust model (Charlot & Fall...
model of spherical H II region with \( \kappa = \infty \) from Dopita et al. (2013) are also plotted for all the three diagnostic diagrams. Although the \([\text{N II}]/H\alpha-[\text{O III}] /H\beta\) BPT diagram (hereafter \([\text{N II}]-[\text{O III}]\) diagram), combining with the Kauffmann et al. (2003) boundary, is used to exclude spaxels with possible AGN contribution, we still find a small amount of spaxels lay beyond the Kewley et al. (2006) boundaries of star-forming regions on both \([\text{S II}]/H\alpha\) vs. \([\text{O III}]/H\beta\) and \([\text{O I}]/H\alpha\) vs. \([\text{O III}]/H\beta\) diagrams (hereafter \([\text{S II}]-[\text{O III}]\) and \([\text{O I}]-[\text{O III}]\) diagram, respectively).

It is very interesting to find that the dust attenuation (and ratio) show some patterns on the BPT diagrams. Similar to the N2O2 vs. O32 diagram, the maps of \(A_{V,\text{star}}\) on all the three diagrams are fairly smooth, so that the overall trends of the \(A_{V,\text{star}} /A_{V,\text{gas}}\) ratio are dominated by those of the \(A_{V,\text{gas}}\), regardless of the diagrams. Notably, there is an intriguing low-\(A_{V,\text{gas}}\) regime and a consequent but more distorted high-\(A_{V,\text{star}} /A_{V,\text{gas}}\) sequence on each diagnostic diagram. The low-\(A_{V,\text{gas}}\) and high-\(A_{V,\text{star}} /A_{V,\text{gas}}\) regime occupies the low-[\text{N II}]/H\alpha region on the \([\text{N II}]-[\text{O III}]\) diagram, the Kewley et al. (2006) boundary on the \([\text{S II}]-[\text{O III}]\) diagram, and the upper right region, which also extends across the Kewley et al. (2006) boundary, on the \([\text{O I}]-[\text{O III}]\) diagram. On the one hand, the closer locations of the low-\(A_{V,\text{gas}}\) sequences to the Kewley et al. (2006) boundaries on both the \([\text{S II}]-[\text{O III}]\) and \([\text{O I}]-[\text{O III}]\) diagrams imply that the excitation sources of these spaxels may be other than massive young stars, so that they would be more DIG-like and be mixed well with the diffuse ISM. On the other hand, observations from either the Milky Way (Madsen et al. 2006) or nearby galaxies (e.g., Hoopes & Walterbos 2003; Kaplan et al. 2016; Zhang et al. 2017; Lacerda et al. 2018) revealed enhancement of \([\text{S II}]/H\alpha\) and \([\text{N II}]/H\alpha\) ratios in DIG regions compared to classical H II regions, indicating a lower ionization level of DIG. Although this low-\(A_{V,\text{gas}}\) population indeed extends to the regime with high-[\text{S II}]/H\alpha ratio, it seems to exhibit a smaller \([\text{N II}]/H\alpha\) ratio. The location of the sequence on the \([\text{N II}]-[\text{O III}]\) BPT diagram differs from that of DIG-dominated regions selected by either low-\(\Sigma_{H\alpha}\) (Zhang et al. 2017) or low-\(E_{H\alpha}\) (Lacerda et al. 2018), as well as the theoretical prediction of shocked gas from photoionization model (Alatalo et al. 2016). We stress that such low-\(A_{V,\text{gas}}\) at small-[\text{N II}]/H\alpha end dose not arise from the relatively larger uncertainties of DIG-dominated spaxels since the SNR of both H\alpha and H\beta for the small-[\text{N II}]/H\alpha spaxels are slightly higher than those of the large-[\text{N II}]/H\alpha spaxels if we simply separate the sample by \(\log([\text{N II}] \lambda 6584/H\alpha) = -0.75\). Therefore,
the low-\(A_{V,\text{gas}}\) and high-\(A_{V,\text{star}}/A_{V,\text{gas}}\) sequences cannot be explained by DIG alone. We will show later that these sequences result from the combination of the DIG-dominated spaxels and the metal-poor spaxels in which the latter ones lead to the low-[N\(\text{II}\)]/H\(\alpha\) values on the [N\(\text{II}\)]-[O\(\text{III}\)] diagram.

Moreover, the theoretical grids of both [N\(\text{II}\)]-[O\(\text{III}\)] and [S\(\text{II}\)]-[O\(\text{III}\)] diagrams are able to cover most of the spaxels in our sample, whereas the grid on the [O\(\text{I}\)]-[O\(\text{III}\)] diagram only occupies about one half of the observed regime. As elucidated in Dopita et al. (2013), their calculations of the [O\(\text{I}\)] line are much less reliable than those of the [N\(\text{II}\)] and [S\(\text{II}\)] lines due to the fact that the [O\(\text{I}\)] emission comes out from a very narrow zone near the ionization front in which shocks may be an important heating source (Dopita 1997). Thus, the [O\(\text{I}\)]-

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**Figure 6.** Median maps of \(A_{V,\text{star}}/A_{V,\text{gas}}\) (top), \(A_{V,\text{gas}}\) (middle), and \(A_{V,\text{star}}\) (bottom) on the BPT diagrams for all selected spaxels. On the [N\(\text{II}\)]/H\(\alpha\) vs. [O\(\text{III}\)]/H\(\beta\) diagnostic diagrams, the dashed curves indicate the extreme starburst classification line of Kewley et al. (2001), while the solid curves are the division between pure star-forming and the AGN-H\(\text{II}\) composite regions from Kauffmann et al. (2003). On the [S\(\text{II}\)]/H\(\alpha\) vs. [O\(\text{II}\)]/H\(\beta\) and [O\(\text{I}\)]/H\(\alpha\) vs. [O\(\text{III}\)]/H\(\beta\) diagnostic diagrams, the dashed-dotted curves are demarcations between star-forming regions, LINERs, and Seyfert galaxies from Kewley et al. (2006). The grid consisted of green solid lines (constant \(Z/Z_\odot\)) and black dashed lines (constant log \(q\)) denotes the predicted line ratios of theoretical photoionization model of a spherical H\(\text{II}\) region with \(\kappa = \infty\) from Dopita et al. (2013). The colors of these lines become faint as the value increase (see the directions of arrows in Figure 4). The values of \(Z\) and log \(q\) plotted in this digram are also given in the middle row. The contours over-plotting in the bottom row encompass 68%, 95%, and 99% of the spaxels on each diagram. The typical uncertainties are shown at the lower left corner of the top row.
[O\textsc{iii}] grid should be treated with caution. As can be seen in Figure 6, the low-$A_{V,\text{gas}}$ and high-$A_{V,\text{star}}/A_{V,\text{gas}}$ sequences on these diagrams are all overlaid by the low-$Z$ ends of the corresponding grids. In Section 3.3, we already show that metal-poor spaxels tend to have smaller $A_{V,\text{gas}}$ and higher $A_{V,\text{star}}/A_{V,\text{gas}}$ ratios, irrespective of the populations we defined. Accordingly, metallicity may be another main factor to explain the location of the low-$A_{V,\text{gas}}$ and high-$A_{V,\text{star}}/A_{V,\text{gas}}$ sequences in the BPT diagrams.

To further separate the effects of DIG and metallicity, we plot similar median maps for the H\textsc{ii}-dominated subsample in Figure 7. The most significant difference between Figure 6 and Figure 7 is the truncation of the low-$A_{V,\text{gas}}$ and high-$A_{V,\text{star}}/A_{V,\text{gas}}$ sequences on the $[\text{S}\text{ii}]-[\text{O}\text{iii}]$ and $[\text{O}\text{i}]-[\text{O}\text{iii}]$ diagrams. The removal of DIG contamination leads to the disappearance of the sequence at the low $[\text{O}\text{iii}]/\text{H}\beta$, high $[\text{S}\text{ii}]/\text{H}\alpha ([\text{O}\text{i}]/\text{H}\alpha)$ regime on the $[\text{S}\text{ii}]-[\text{O}\text{iii}]/([\text{O}\text{i}]-[\text{O}\text{iii}])$ diagram, indicating the low ionization state of DIG (e.g., Hoopes & Walterbos 2003; Haffner et al. 2009; Kaplan et al. 2016; Zhang et al. 2017). The remaining blue sequences in the H\textsc{ii}-dominated population can be well described by the low-$Z$ end of the theoretical grids, even on the “unreliable” $[\text{O}\text{i}]-[\text{O}\text{iii}]$ diagram. Interestingly, the extended region of the H\textsc{ii}-dominated subsample is now well constrained by the Kewley et al. (2006) boundary on the $[\text{S}\text{ii}]-[\text{O}\text{iii}]$ diagram.

In short, DIG contamination alone cannot explain the low-$A_{V,\text{gas}}$ and high-$A_{V,\text{star}}/A_{V,\text{gas}}$ sequences found

**Figure 7.** Median maps of $A_{V,\text{star}}/A_{V,\text{gas}}$ (top), $A_{V,\text{gas}}$ (middle), and $A_{V,\text{star}}$ (bottom) on the BPT diagrams for H\textsc{ii}-dominated spaxels. The symbols are the same as Figure 6.
on the [S ii]–[O iii] and [O i]–[O iii] diagrams, metal-poor spaxels seem to be the origin of the remaining half of the sequences after removing DIG-dominated regions. This result reinforces the conclusions drawn from the analysis on the metallicity and ionization parameter in Section 3.3.

3.5. \( N2S2/A_{V,\text{star}}/A_{V,gas} \) Correlation

In Section 3.2, we find that the N2S2 index has the strongest correlation with the \( A_{V,\text{star}}/A_{V,gas} \) ratio among local properties we explored. We use the predictions of theoretical model of \( \text{HII} \) regions from Dopita et al. (2013) to examine how the N2S2 index varies with metallicity and ionization parameter, and find that this index increases toward high-\( Z \) (high-\( q \)) end when \( q (Z) \) is fixed within the adopted parameter ranges (i.e., \( Z = 0.1Z_\odot - 5Z_\odot \) and \( \log q = 6.5 - 8.5 \)). Observations of ionized gas also revealed that DIG tends to have smaller N2S2 ratio relative to the average value of traditional \( \text{HII} \) regions excited by massive OB stars due to their softer ionized field (Madsen et al. 2006; Haffner et al. 2009). Namely, the N2S2 ratio is sensitive to both metallicity and ionization parameter, we thus use the N2S2–O32 diagrams to separate effect of ionization parameter. In Figure 8 we present the median maps of \( A_{V,\text{star}}/A_{V,gas} \) and \( A_{V,gas} \) on the N2S2–O32 diagram for all and the \( \text{HII} \)-dominated spaxels. Theoretical predictions of ionization model of \( \text{HII} \) regions from Dopita et al. (2013) are also plotting. The median map of \( A_{V,\text{star}} \) is not shown here due to the fact that, similar to the maps in other emission line ratio diagrams (e.g., Figure 5 and Figure 6), it exhibits a uniform distribution across the diagram and does not reveal any more useful information.

The observed trends of \( A_{V,\text{star}}/A_{V,gas} \) are dominated by those of \( A_{V,gas} \). With the help of the O32 index, the role of ionization parameter is well separated. We find that the N2S2 index decreases toward the low-metallicity end at fixed log \( q \), leading to a larger \( A_{V,\text{star}}/A_{V,gas} \) (smaller \( A_{V,gas} \)). Although DIG tends to have smaller N2S2 values, the removal of the DIG-dominated population cannot totally flatten the trend between the N2S2 index and \( A_{V,\text{star}}/A_{V,gas} \), while the correlation between the N2S2 index and \( A_{V,gas} \) is still significant (\( \rho = 0.57 \)) for the \( \text{HII} \)-dominated population. Therefore, we ascribe the emergence of the N2S2–\( A_{V,\text{star}}/A_{V,gas} \) correlation to the combination of DIG contamination (i.e., geometry effect) and the small N2S2 values of metal-poor spaxels.

3.6. Effect of Spatial Resolution

The two-component dust model, which we use to describe the role of geometry in determining the expected relation between \( A_{V,\text{star}} \) and \( A_{V,gas} \), presumes that all line emission arises from \( \text{HII} \) regions (Charlot & Fall 2000). However, this presumption might not be true for all our spaxels. Although the physical sizes of our spaxels have a median of 0.20 kpc, the reconstructed PSF of the MaNGA datacubes has a FWHM of \( \sim 2'5 \) (Law et al. 2016), corresponding to a physical size of \( \sim 1.5 \) kpc at the mean redshift of the MaNGA targets (\( \langle z \rangle = 0.03 \); Bundy et al. 2015). This scale is significantly larger than the typical size of \( \text{HII} \) regions (Hunt & Hirashita 2009; Lawton et al. 2010), arising a problem that how the low spatial resolution of the MaNGA datacubes impacts the measured dust attenuations.

Based on a multi-scale study of M33, Boquien et al. (2015) found that both nebular attenuation (\( A_{H\alpha} \)) and stellar attenuation (\( A_{FUV} \)) are scale-dependent. As the resolution downgrades (from 33 pc to 2048 pc), the dynamic ranges of both attenuations and the \( A_{FUV}/A_{H\alpha} \) ratio become smaller, indicating a smooth effect at coarser resolutions where intense \( \text{HII} \) regions and quiescent regions merge.

For our \( \text{HII} \)-dominated spaxels, since \( A_{V,\text{star}} \) is derived from the overall shape of the underlying stellar continuum and is not closely linked to the young stellar populations compared to \( A_{FUV} \) computed in Boquien et al. (2015), the smooth effect on our stellar attenuation should be weaker than the one reported by these authors. However, the surrounding more diffuse, less attenuated regions might have a non-negligible contribution to the emission line measurements of the spaxels, possibly leading to a smaller \( A_{V,gas} \) on average and thus a slightly larger \( A_{V,\text{star}}/A_{V,gas} \). Given that the systematic differences between \( A_{V,\text{star}} \) and \( A_{V,gas} \) are still observed for the \( \text{HII} \)-dominated population, we conclude that the smooth effect stemmed from the coarse spatial resolution is too weak to eliminate the geometry effect of the two-component dust model. Therefore, the large PSF size of the MaNGA datacubes has little impact on the comparison with the dust model, as well as most of the conclusions drawn from this section.

3.7. The Smooth \( A_{V,\text{star}} \) Maps

Since the derivation of \( A_{V,\text{star}} \) is independent of emission lines, the relatively uniform distribution of \( A_{V,\text{star}} \) on the (gas-phase) metallicity-ionization parameter space (Figure 5) and the BPT diagrams might be an effect of the methodology. However, it is noteworthy that the overall trends of \( A_{V,gas} \) observed in Figure 5 still exist in the maps of \( A_{V,\text{star}} \) but are much weaker. Particularly, the median of \( A_{V,\text{star}} \) at the low-\( Z \), low-\( q \) regime is slightly higher for the \( \text{HII} \)-dominated population, which is similar to the case of \( A_{V,gas} \).
Another effect that might contribute to the uniformity of $A_{V,\text{star}}$ is the smooth arisen from large physical scale. Multi-scale study of M33 suggested that either stellar or nebular attenuation suffers a smooth effect at some level (Boquien et al. 2015). As discussed in Section 3.6, the ranges of both attenuations become narrower as the resolution becomes coarser. However, the median maps of $A_{V,\text{gas}}$ on either the N2O2 vs. O32 diagram or the BPT diagrams (Figure 6) are not as smooth as those of $A_{V,\text{star}}$, implying that the coarse resolution should not be the main reason for the uniform $A_{V,\text{star}}$ distribution. Thus, we argue that the observed uniform distribution of $A_{V,\text{star}}$ indeed has physical origin, indicating that the stellar attenuation is less relevant to the physical conditions of the ionized gas. In fact, as implied by the two-component dust model (Charlot & Fall 2000; Wild et al. 2011), $A_{V,\text{star}}$ might reflect the local environment of the diffuse ISM along the line of sight rather than the birth clouds. Studies of young star clusters (YSCs) confirmed that YSCs with ages of $\sim 10$ Myr are no longer embedded in their birth clouds (Whitmore et al. 2014; Hollyhead et al. 2015; Grasha et al. 2019). In other words, stellar population older than this time scale might only suffer dust attenuation from the diffuse ISM.

Due to the lack of a second method to compute $A_{V,\text{star}}$ at present, we still cannot rule out the possibility that the derivation method has any contribution in flattening the trends in the $A_{V,\text{star}}$ maps.

Figure 8. Median maps of $A_{V,\text{star}}/A_{V,\text{gas}}$ (top) and $A_{V,\text{gas}}$ (bottom) on the N2S2–O32 diagram for all (left) and the Hii-dominated (right) spaxels. In each panel, the brown contours encompass 68%, 95%, and 99% of the spaxels, respectively, while the grid denotes the predicted line ratios of theoretical photoionization model of a spherical H ii region with $\kappa = \infty$ from Dopita et al. (2013). The typical uncertainties are shown at the lower right corners.
4. RELATION BETWEEN $A_{V,\text{star}}/A_{V,\text{gas}}$ AND GLOBAL PROPERTIES

4.1. Determining the Global $A_{V,\text{star}}/A_{V,\text{gas}}$

As shown in Kreckel et al. (2013), the $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio tend to converge to a constant at high Hα flux end within individual galaxy. After visual inspection of the $A_{V,\text{star}}/A_{V,\text{gas}}$ vs. $\Sigma_{H\alpha}$ plot of each galaxy, we find not only the similar trend presented in Kreckel et al. (2013) but also a galaxy-to-galaxy variation of the convergent value, i.e., the global $A_{V,\text{star}}/A_{V,\text{gas}}$ may vary between galaxies. To demonstrate this feature, we plot the density contours of all spaxels in the $A_{V,\text{star}}/A_{V,\text{gas}}$-$\Sigma_{H\alpha}$ plane in the upper panel of Figure 9. Since the convergent value may be a variable between galaxies, we calculate a representative value of $A_{V,\text{star}}/A_{V,\text{gas}}$ via a sigma-clipped statistics. The median of the 3-σ clipping after three iterations is taken as the global value of $A_{V,\text{star}}/A_{V,\text{gas}}$ for each galaxy. Inspection of the histogram of $A_{V,\text{star}}/A_{V,\text{gas}}$ within individual galaxy confirms that this parameter can be a good estimate of the peak of the distribution. Then the global $A_{V,\text{star}}/A_{V,\text{gas}}$ is subtracted from the individual ones within corresponding galaxy to obtain $\Delta(A_{V,\text{star}}/A_{V,\text{gas}})$. The density distribution of spaxels in the $\Delta(A_{V,\text{star}}/A_{V,\text{gas}})$-$\Sigma_{H\alpha}$ plane is given in the bottom panel of Figure 9.

Both $A_{V,\text{star}}/A_{V,\text{gas}}$ and $\Delta(A_{V,\text{star}}/A_{V,\text{gas}})$ exhibit great reductions in scatters toward high $\Sigma_{H\alpha}$, indicating a common geometry of dust/star and local physical conditions for high-$\Sigma_{H\alpha}$ spaxels. The convergent $A_{V,\text{star}}/A_{V,\text{gas}}$ of 0.425, resulting from a peak detection utilizing the PeakUtils package\(^7\) based on the histogram of $A_{V,\text{star}}/A_{V,\text{gas}}$, is slightly smaller than the one of Calzetti (1997). Comparison between the two sets of contours in Figure 9 reveals that the scatter of $\Delta(A_{V,\text{star}}/A_{V,\text{gas}})$ is further reduced after normalization by the global $A_{V,\text{star}}/A_{V,\text{gas}}$ of each galaxy. This result implies that the global values of $A_{V,\text{star}}/A_{V,\text{gas}}$ indeed vary between galaxies, which is already suggested by many previous works on either local (e.g., Wild et al. 2011; Koyama et al. 2015; Zahid et al. 2017; Koyama et al. 2019) or high-redshift (e.g., Price et al. 2014; Puglisi et al. 2016) galaxies.

4.2. Observational Evidences of Correlations between $A_{V,\text{star}}/A_{V,\text{gas}}$ and Other Properties

Naturally, one would wonder whether the global $A_{V,\text{star}}/A_{V,\text{gas}}$ correlates with other physical properties of galaxies if it is thought of as a variable. Previous works had demonstrated that this ratio may correlate

\(^7\) https://peakutils.readthedocs.io/en/latest/index.html

![Figure 9. Density contours of all spaxels in the $A_{V,\text{star}}/A_{V,\text{gas}}$-$\Sigma_{H\alpha}$ (upper panel) and $\Delta(A_{V,\text{star}}/A_{V,\text{gas}})$-$\Sigma_{H\alpha}$ (bottom panel) planes. The contours contain 20%, 40%, 60%, and 80% of the spaxels, respectively. The underlying maps are color-coded by the median value of log([NII]/Hα)/[SII]/Hα. The red solid line is the canonical value of $A_{V,\text{star}}/A_{V,\text{gas}}$ = 0.44 from Calzetti (1997), while the orange dashed-dotted line indicates $\Delta(A_{V,\text{star}}/A_{V,\text{gas}}) = 0$. The vertical green dashed lines show the criterion of [NII]-dominated spaxels from Zhang et al. (2017), i.e., $\Sigma_{H\alpha} > 10^{39}$ erg s$^{-1}$ kpc$^{-2}$. The typical uncertainties are shown at the upper right corner of the top panel. Only statistical uncertainties are plotted.](https://www.sdss.org/dr15/manga/manga-target-selection/nsa/)

with $M_*$ (e.g., Koyama et al. 2015; Puglisi et al. 2016; Zahid et al. 2017; Koyama et al. 2019), SFR (e.g., Reddy et al. 2015), sSFR (e.g., Wild et al. 2011; Price et al. 2014; Koyama et al. 2019), inclination (Wild et al. 2011), and so on. Making use of the Pipe3D VAC and the NASA-Sloan Atlas (NSA) catalog used by the MaNGA survey\(^8\), we calculate the Pearson correlation coefficients $r$ and the Spearman’s rank correlation coefficients $\rho$ between the global $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio and several physical properties and list them in Table 1. Taking the medians of $A_{V,\text{star}}$ and $A_{V,\text{gas}}$ of spaxels

\(^8\) https://www.sdss.org/dr15/manga/manga-target-selection/nsa/
within individual galaxy as the corresponding global values, the correlation coefficients between these global attenuations and other physical properties are also given in Table 1. Note that these “global” dust attenuations (also the “global” $A_{V,\text{star}}/A_{V,\text{gas}}$ defined in Section 4.1) are the typical values of local H\textsc{ii} regions within galaxies, which should might be different from those derived from the integrated light. The global SFR is obtained by summing up the H\textalpha luminosities over the field of view (FOV) and applying the Kennicutt (1998b) conversion. The metallicities are taken from the Pipe3D VAC, while $M_\star$ and axis ratio $b/a$ are from the NSA catalog after correcting for the differences in the adopted cosmology and IMF. Although the Pipe3D VAC provides a global stellar mass of galaxies, it is found to be slightly smaller at high-mass end due to the limited FOV of MaNGA. sSFR is calculated by SFR/$M_\star$ using the adopted parameters. Here, $12+\log(O/H)$ are measured at the effective radius $R_e$ to represent the global oxygen abundance. Studies based on CALIFA survey suggested that this parameter has a pretty good one-to-one relation with the average oxygen abundance over the entire FOV but with a smaller uncertainty, regardless of metallicity calibrations (Sánchez et al. 2013, 2017). To ensure a robust estimate of the global $A_{V,\text{star}}/A_{V,\text{gas}}$, we only include galaxies with more than 50 selected spaxels in the following analysis. In total, 1949 galaxies remain after this selection. We stress that changing this critical number of spaxels can not significantly alter the following results.

From Table 1, it is clear that $M_\star$ presents the strongest correlation with the global $A_{V,\text{star}}/A_{V,\text{gas}}$ in either $r$ or $\rho$, implying smaller $A_{V,\text{star}}/A_{V,\text{gas}}$ values for more massive galaxies. We show the global $A_{V,\text{star}}/A_{V,\text{gas}}$ as a function of $M_\star$ for the selected galaxies in Figure 10, together with the best-fit result for all galaxies using a linear function in the form of

$$A_{V,\text{star}}/A_{V,\text{gas}} = a_0 + a_1 x,$$

in which $x = \log(M_\star/M_\odot)$. The typical uncertainty of $A_{V,\text{star}}/A_{V,\text{gas}}$ shown in the figure is the median of the standard deviation of $A_{V,\text{star}}/A_{V,\text{gas}}$ within each galaxy. Since the NSA catalog dose not contain a formal uncertainty for $M_\star$, we give a rough estimation based on the comparison of $M_\star$ from Kauffmann et al. (2003) and the kcorrect code from which the NSA $M_\star$ was calculated (Blanton & Roweis 2007).

![Figure 10](https://example.com/figure10.png)

**Figure 10.** Global $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio as a function of global stellar mass ($M_\star$) of galaxies. The black solid line shows the best-fit result with a linear function for all galaxies. The upper panel show the $A_{V,\text{star}}/A_{V,\text{gas}}$ vs. $M_\star$ distribution for individual galaxy, while the bottom panel shows the residuals between the observed and the predicted $A_{V,\text{star}}/A_{V,\text{gas}}$ from the best-fit line. The blue diamonds with error bars indicate the medians and the corresponding 1-σ scatters (i.e., 16%-84% range) of the binned distributions for all galaxies. These bins are adjusted to equalize the number of galaxies in each bin for each set of bins. The typical uncertainties are denoted at the upper left corner.
Table 1. Correlation coefficients between global dust attenuation (ratio) and some physical properties

| Parameters   | log($M_\star$) | log(SFR) | log(sSFR) | 12 + log(O/H)$^c$ | 12 + log(O/H)$^c$ | b/a$^d$ |
|--------------|----------------|----------|-----------|-------------------|-------------------|--------|
| $A_{V,\text{star}}/A_{V,\text{gas}}$ | $[M_\odot]$ | $[M_\odot \text{ yr}^{-1}]$ | $[\text{yr}^{-1}]$ | $[\text{O3N2}]$ | $[\text{N2}]$ |       |
| $A_{V,\text{star}}$ | $-0.66$ | $-0.59$ | $0.18$ | $-0.59$ | $-0.62$ | $-0.27$ |
| $A_{V,\text{star}}$ | $-0.72$ | $-0.62$ | $0.24$ | $-0.60$ | $-0.63$ | $-0.32$ |
| $A_{V,\text{gas}}$ | $-0.12$ | $-0.08$ | $0.06$ | $0.11$ | $0.14$ | $-0.54$ |
| $A_{V,\text{gas}}$ | $-0.13$ | $-0.09$ | $0.07$ | $0.05$ | $0.05$ | $-0.55$ |
| $0.49$ | $0.46$ | $-0.10$ | $0.59$ | $0.62$ | $-0.23$ |
| $0.54$ | $0.50$ | $-0.15$ | $0.62$ | $0.65$ | $-0.21$ |

$^a$For each parameter, the first row lists the Pearson correlation coefficients $r$, while the second row presents the Spearman's rank correlation coefficients $\rho$.

$^b$Stellar mass from K-correction fit for Sérsic fluxes, taken from the NSA catalog.

$^c$Oxygen abundance $12 + \log(O/H)$ at the effective radius derived based on the O3N2 and N2 calibrations of Marino et al. (2013).

$^d$Axis ratio $b/a$ from two-dimensional, single-component Sérsic fit in r-band, taken from the NSA catalog.

Figure 11. Global $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio as a function of oxygen abundances derived from N2 indicators based on the Marino et al. (2013) calibrations. The symbols are the same as Figure 10. The typical uncertainties are shown at the upper left corner.

$A_{V,\text{star}}/A_{V,\text{gas}}$. These correlations are shown in Figure 12, together with a median curve and the corresponding scatters around the medians of the binned distributions for each case. The $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio decreases with increasing SFR, while the scatters become smaller toward high-SFR end. Although the median curves of $A_{V,\text{star}}/A_{V,\text{gas}}$ in sSFR and inclination are fairly flat, slight elevations can be identified when log(sSFR[yr$^{-1}$]) $>-10.5$ and toward smaller $b/a$ (i.e., larger inclination). The global $A_{V,\text{star}}$ has moderate anti-correlation with $b/a$, while the global $A_{V,\text{gas}}$ shows very weak anti-correlation with $b/a$. Similar result was reported by Yip et al. (2010) in which the stellar attenuation is found to increase with inclination, while the Hα/Hβ ratio remains nearly unchanged with $b/a$. Such behaviors are consistent with the picture of two-component dust model (e.g., Charlot & Fall 2000; Wild et al. 2011). In this model, $A_{V,\text{star}}$ arises from the diffuse ISM that distributes more homogeneous in stellar disk (e.g., Mosenkov et al. 2019), so that galaxies with larger inclination would have larger $A_{V,\text{star}}$ due to the increasing dust column density. $A_{V,\text{gas}}$ describe the combination of dust effect from the dense birth clouds, which are more likely spherical, and the diffuse ISM but is dominated by the former (e.g., Wild et al. 2011). Therefore, the inclination only has small effect on $A_{V,\text{gas}}$, and the global $A_{V,\text{star}}/A_{V,\text{gas}}$ would show weak correlation with the inclination.

Koyama et al. (2019) presented a detailed study on the relation between the global $A_{V,\text{star}}/A_{V,\text{gas}}$ and $M_\star$, $9$ Koyama et al. (2019) used $E(B-V)_{\text{star}}/E(B-V)_{\text{gas}}$ to indicate the ratio between stellar and nebular attenuation. In
SFR, sSFR using local SFGs samples. They found that the $A_{V,\text{star}}/A_{V,\text{gas}}$ decreases with increasing $M_*$ decreases at $-1 \lesssim \log(\text{SFR}[M_\odot \text{ yr}^{-1}]) \lesssim 0.5$ and then increases at $0.5 \lesssim \log(\text{SFR}[M_\odot \text{ yr}^{-1}]) \lesssim 1.5$, and increases toward high-sSFR end for their SDSS-GALEX-WISE sample. Within the parameter ranges explored by our sample, the overall trends of these three correlations are in good agreement with ours. By stacking SDSS spectra of local SFGs, Zahid et al. (2017) reported that the trend between the global $A_{V,\text{star}}/A_{V,\text{gas}}$ and $M_*$ increase first at $M_* \lesssim 10^{9.5} \ M_\odot$ and then decrease toward high-$M_*$ end with an increasingly slope, whereas the same relation from both this work and Koyama et al. (2019) can be well described by a monotonic decreasing function with a gradual flattening at high-$M_*$ end. However, due to the different data treatment between our work (or Koyama et al. 2019) and Zahid et al. (2017) (i.e., individual calculation vs. stacking), it is difficult to find out the reasons for these conflicts at present. Such different observations need to be understood in future studies.

As for the global dust attenuations, Table 1 shows that $A_{V,\text{star}}$ only correlates with $b/a$, while $A_{V,\text{gas}}$ moderately correlates with $M_*$, SFR, and gas-phase metallicity, weakly correlates with $b/a$, and does not correlate with sSFR. Similar to the local case, the correlations between $A_{V,\text{star}}/A_{V,\text{gas}}$ and other physical properties discussed above are mainly driven by the correlations between $A_{V,\text{gas}}$ and these properties. However, we also note that, compared to $A_{V,\text{gas}}$, $A_{V,\text{star}}/A_{V,\text{gas}}$ has slightly stronger correlations (in term of either $r$ or $p$) with $M_*$, SFR, and $b/a$, and comparable correlation with gas-phase metallicity, indicating the non-negligible role of $A_{V,\text{star}}$ in these correlations.

### 4.3. Correlations along Scaling Relations

All the physical properties discussed above can be linked to $M_*$ except the inclination (i.e., $b/a$) via two well-studied scaling relations of SFGs. On the one hand, the star-forming main sequence (SFMS, e.g., Speagle et al. 2014) connects SFR and sSFR to $M_*$. One the other hand, the metal enrichment in ISM is closely related with the growth of galaxies and can be characterized by the well known mass-metallicity relation (MZR, e.g., Lequeux et al. 1979; Tremonti et al. 2004).

We present the SFMS and MZR of our sample in Figure 13, color-coding by their global $A_{V,\text{star}}/A_{V,\text{gas}}$ ratios and dust attenuations. Both plots exhibit a gradual trend of decreasing $A_{V,\text{star}}/A_{V,\text{gas}}$ along the sequence toward high-$M_*$ ends. The trend of $A_{V,\text{star}}/A_{V,\text{gas}}$ in our SFMS resembles the one using $H_\alpha$-based SFR (SFR$_{H\alpha}$) in Koyama et al. (2019), however, their fiducial total SFR is derived from a combination of UV and IR observations (SFR$_{UV+IR}$) for which the global $A_{V,\text{star}}/A_{V,\text{gas}}$ presents an evident trend across the SFMS. Their WISE-SDSS-GALEX sample suggests that galaxies with higher SFR tend to have a larger $A_{V,\text{star}}/A_{V,\text{gas}}$ value at fixed $M_*$. By Comparing the SFR$_{H\alpha}$ and SFR$_{UV+IR}$, they

![Figure 12. Global $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio as a function of SFR (left), sSFR (middle), and $b/a$ (right). The blue diamonds with error bars indicate the medians and the corresponding 1-$\sigma$ scatters (i.e., 16%-84% range) of the binned distributions for all galaxies. These bins are adjusted to equalize the number of galaxies in each bin for each set of bins. The typical uncertainties are given at the upper left corner except for the $b/a$ subplot.](image-url)
Variations in Dust Attenuation Ratio

Figure 13. Star-forming main sequence (top row) and mass-metallicity relation (bottom row) of our selected galaxies, color-coded by their global $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio (left), $A_{V,\text{star}}$ (middle), and $A_{V,\text{gas}}$ (right). The typical uncertainties are shown at the upper left corner of the left panels.

Further found that galaxies with SFR$\text{H} \alpha < $ SFR$_{\text{UV+IR}}$ tend to have substantially larger $A_{V,\text{star}}/A_{V,\text{gas}}$. However, such trend is inevitable because both the stellar and nebular attenuation are directly linked to the corresponding SFR in their calculation. The $E(B-V)_{\text{star}}$ in Koyama et al. (2019) is derived from the SFR$_{\text{UV+IR}}$ in the form of

\[
E(B-V)_{\text{star}} \propto \log(\text{SFR}_{\text{UV+IR}}/\text{SFR}_{\text{UV}}) = \log(1 + \text{SFR}_{\text{IR}}/\text{SFR}_{\text{UV}}),
\]

in which SFR$_{\text{IR}}$ and SFR$_{\text{UV}}$ are SFR obtained from IR and UV data, respectively. While the $E(B-V)_{\text{gas}}$ can be connected to SFR$\text{H} \alpha$ via

\[
A_{\text{H} \alpha} \propto E(B-V)_{\text{gas}} \propto \log(1 + \text{SFR}_{\text{H} \alpha,\text{atten}}/\text{SFR}_{\text{H} \alpha,\text{obs}}),
\]

in which SFR$_{\text{H} \alpha,\text{atten}}$ and SFR$_{\text{H} \alpha,\text{obs}}$ are SFR calculated from attenuated and observed H$ \alpha$ fluxes, respectively. Then we can obtain

\[
\frac{A_{V,\text{star}}}{A_{V,\text{gas}}} \propto \frac{\log(1 + \text{SFR}_{\text{IR}}/\text{SFR}_{\text{UV}})}{\log(1 + \text{SFR}_{\text{H} \alpha,\text{atten}}/\text{SFR}_{\text{H} \alpha,\text{obs}})}.
\]

Although Koyama et al. (2019) claimed that the physical reason for the difference between SFR$_{\text{H} \alpha}$ and SFR$_{\text{UV+IR}}$ is unclear, we can expect that either the overestimation of SFR$_{\text{IR}}$, e.g., due to the large PSF of WISE W4 band (Wright et al. 2010) and contaminations from their neighbors, or the underestimation of SFR$_{\text{H} \alpha,\text{atten}}$, e.g., due to saturation in emission line attenuation (Calabrò et al. 2018), would lead to an elevation on $A_{V,\text{star}}/A_{V,\text{gas}}$ if the unattenuated parts are thought to be more reliable. Therefore, we suggest that a SFR-independent $E(B-V)_{\text{star}}$ (in calculation) and an IR-clear sample are required to solve this puzzle.

As suggested in Section 4.2, $A_{V,\text{star}}$ exhibits a relatively uniform distribution in either SFMS or MZR, while $A_{V,\text{gas}}$ dominates the observed trends along the tow scaling relations for $A_{V,\text{star}}/A_{V,\text{gas}}$. These results imply that the properties of dust in the diffuse ISM do not significantly alter as galaxies grow, while the dust in H$ \text{II}$ regions and/or the surrounding dense clouds is more sensitive to the galaxy evolution.
Since \( A_{V,\text{gas}} \) can be connected to dust mass surface density and also gas mass surface density \((\text{e.g., Boquien et al. 2013; Brinchmann et al. 2013; Kreckel et al. 2013, 2016})\), one would speculate that the observed \( A_{V,\text{star}}/A_{V,\text{gas}} \)-SFR relation might stem from the more basic Kennicutt-Schmidt star formation law \((\text{Schmidt 1959; Kennicutt 1998a})\), and leads to the \( A_{V,\text{star}}/A_{V,\text{gas}} - M_* \) and \( A_{V,\text{star}}/A_{V,\text{gas}} - 12 + \log(O/H) \) relations via the SFMS and MZR, respectively. We believe that the Kennicutt-Schmidt law can partly account for the \( A_{V,\text{star}}/A_{V,\text{gas}} \)-SFR relation, however, it cannot fully explain the the observed trends along the two scaling relations due to the following reasons. First, Table 1 shows that both \( M_* \) and gas-phase metallicity more strongly correlate with \( A_{V,\text{gas}} \) compared to SFR. If the \( A_{V,\text{gas}} \)-SFR relation is more fundamental and connects \( A_{V,\text{gas}} \) with \( M_* \) and gas-phase metallicity via the SFMS and MZR, respectively, we would expect a stronger correlation with SFR compared to \( M_* \) and gas-phase metallicity. Second, comparing with \( A_{V,\text{gas}} \), \( A_{V,\text{star}}/A_{V,\text{gas}} \) displays stronger correlations with \( M_* \) and SFR, and comparable correlation with gas-phase metallicity, implying that although \( A_{V,\text{star}} \) exhibits very weak correlations with these physical properties, its role is still non-negligible. Third, our partial correlation analysis discuss below suggests that when SFR is controlled, \( M_* \) still moderately correlates with \( A_{V,\text{star}}/A_{V,\text{gas}} \), and these three parameters seem to play comparable roles in the correlation.

Koyama et al. (2019) speculated that the decrease of \( A_{V,\text{star}}/A_{V,\text{gas}} \) with increasing SFR at their low-SFR side originates from the relation between \( M_* \) and \( A_{V,\text{star}}/A_{V,\text{gas}} \) because of the SFMS. Similarly, the correlation between \( A_{V,\text{star}}/A_{V,\text{gas}} \) and gas-phase metallicity revealed by Figure 11 also might result from the tight MZR. To test these conjectures, a partial correlation analysis is performed utilizing the R ppcor package\(^{10}\) (Kim 2015). We calculate the Pearson correlation coefficients \( r \) and Spearman’s rank correlation coefficients \( \rho \) to see how \( A_{V,\text{star}}/A_{V,\text{gas}} \) correlates with \( M_* \), SFR, and \( 12 + \log(O/H)[N_2] \), respectively, when the other one or two physical properties are controlled.

Results are presented in Table 2 in which the first four columns show the cases of controlling only one parameter and the last three columns are the cases of controlling two parameters simultaneously. When only one parameter is controlled, \( M_* \) gives the strongest correlation with \( A_{V,\text{star}}/A_{V,\text{gas}} \), regardless of the controlled parameters and the calculation methods. Comparing with the coefficients listed in Table 1, it is evident that all the three parameters can partly explain the corresponding correlations, while \( M_* \) seems to have a dominate effect. In the cases of controlling two physical properties at the same time, the effect of \( M_* \) becomes much smaller compared to SFR and metallicity when consider linear correlation. However, if non-linear correlation \((\text{i.e., } \rho)\) is also taken into account, the three parameters have comparable roles in the correlations with \( A_{V,\text{star}}/A_{V,\text{gas}} \). Given the bridge role of \( M_* \) in connecting SFR and metallicity, we argue that the apparent dominate effect of \( M_* \) when only control SFR (metallicity) is a combination of contributions from \( M_* \) itself and metallicity \((\text{SFR})\) via the MZR \((\text{SFMS})\). Therefore, we conclude that \( M_* \), SFR, and gas-phase metallicity play comparable role in the correlations with these physical properties, and either of them can fully account for the trends unveiled by Figure 13.

4.4. A Possible Picture based on Dust Growth

Both Table 1 and Figure 13 suggest that the correlations between \( A_{V,\text{star}}/A_{V,\text{gas}} \) and other galactic properties \((\text{i.e., } M_* \text{, SFR, and gas-phase metallicity})\) as well as the trends along the scaling relations are mainly driven by the global \( A_{V,\text{gas}} \). Integrating along the line of sight of Equation (2) results in \((\text{e.g., Galliano 2018})\)

\[
A_V = 1.086 \times \Sigma_{\text{dust}} = 1.086 \times \Sigma_{\text{gas}} \cdot D/G, \tag{7}
\]

where \( \Sigma_{\text{dust}} \) and \( \Sigma_{\text{gas}} \) are mass surface densities of dust and gas, respectively. Obviously, an increasing \( A_{V,\text{gas}} \) with \( M_* \) implies more dust in more massive galaxies, which is equivalent to more gas or/and a larger D/G ratio. The increasing dust mass and total gas mass with \( M_* \) in SFGs were reported by many previous works \((\text{e.g., De Vis et al. 2017a; Casasola et al. 2019})\). Considering the factor related to dust, here we only focus on the possible role of the D/G ratio in the observed correlations, attempting to provide an alternative origin of these correlations in the view of dust evolution.

In the analysis of the local \( A_{V,\text{star}}/A_{V,\text{gas}} \), we suggest that in addition to the geometry of star/dust, the local physical conditions of ionized gas also play an important role in determining the \( A_{V,\text{star}}/A_{V,\text{gas}} \) value. The D/G ratio is used to connect the local gas-phase metallicity and ionization parameter to dust attenuation. On galactic scale, the behaviors of the global D/G ratio are found to be controlled by some dust processes accompanied with galaxy growth \((\text{Asano et al. 2013; De Vis et al. 2017b; Aoyama et al. 2018; Galliano et al. 2018; De Vis et al. 2019})\).

As we mentioned in Section 3.3.3, metallicity is the main physical property that drives the D/G ratio (En-

\(^{10}\) https://cran.r-project.org/web/packages/ppcor/
mediate mass galaxies ($10^8 \, M_\odot$). As displayed in Aoyama et al. (2018), for inter-
by metallicity again, but with a larger dust-to-metal ra-
becomes efficient and the D/G increases steeply; when inter-
metallicities, metal accretion onto dust grains continues by stellar ejecta and the D/G is proportional to
their simulation), dust growth by accretion becomes ac-
tive and the D/G–Z relation becomes steeper. A large
scatter of the relation in this region emerges, suggest-
ing that the D/G is strongly impacted by local inter-
stellar processes and SFHs, as displayed in Aoyama et al. (2018). Because the global
D/G ratio in more massive SFGs leads to the increase of the overall $A_{V,\text{gas}}$, and thus a smaller
$A_{V,\text{star}}/A_{V,\text{gas}}$.
Furthermore, the $M_*$-dependent scatter shown in Figure 10 can be explained as the scatter of D/G which is found to be large for $10^{8.5} \, M_\odot \lesssim M_* \lesssim 10^{10} \, M_\odot$ and much smaller for $M_* \gtrsim 10^{10} \, M_\odot$ in simulation of Aoyama et al. (2018). Recent IFU study also sug-
gests that the global stellar mass have a non-negligible
role in regulating the local metallicity (Gao et al. 2018),
especially for low-mass galaxies, probably due to their
shallower gravitational potential wells for which is easier
to lose their metal by galactic outflows (Chisholm et al. 2018). Because the global
$A_{V,\text{star}}/A_{V,\text{gas}}$ used in this work is derived from the mode of the local ones, the
$M_*$ effect on local metallicity should also impacts the global
$A_{V,\text{star}}/A_{V,\text{gas}}$. Hence, besides the local internal processes and SFHs, $M_*$ itself may be another
factor that drives the $M_*$-dependent scatter in the $M_* \cdot A_{V,\text{star}}/A_{V,\text{gas}}$ relation.
Therefore, the evolution of dust growth in birth clouds
accompanied with galaxy growth might be one plau-
sible origin for our observed behaviors of the global
$A_{V,\text{star}}/A_{V,\text{gas}}$.

5. SUMMARY
In this work, we construct a sample of H II regions
using the IFU data of MaNGA survey released from the
SDSS DR15 and investigate how the $A_{V,\text{star}}/A_{V,\text{gas}}$ ratio varies with other physical properties on subgalactic and
galactic scales.

On subgalactic scale, we find that the $A_{V,\text{gas}}$ in-
deed correlates with the $A_{V,\text{star}}$, while the correlation

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**Table 2. Partial Correlations between $A_{V,\text{star}}/A_{V,\text{gas}}$ and some physical properties**

| Variables$^a$ | $M_*$ | $M_*$ | SFR | 12 + log(O/H) | $M_*$ | SFR | 12 + log(O/H) |
|---------------|------|------|-----|--------------|------|-----|--------------|
| Controlled$^b$ | SFR | 12 + log(O/H) | $M_*$ | $M_*$ | SFR & 12 + log(O/H) | $M_*$ & 12 + log(O/H) | $M_*$ & SFR |
| $r$ | −0.42 | −0.43 | −0.25 | −0.30 | −0.16 | −0.31 | −0.35 |
| $\rho$ | −0.50 | −0.52 | −0.24 | −0.23 | −0.26 | −0.29 | −0.29 |

$^a$ For each column, partial correlations coefficients are calculated between physical property in this row and $A_{V,\text{star}}/A_{V,\text{gas}}$ while the physical properties shown in the second row are controlled. $M_*$ and SFR are in log scale, 12 + log(O/H) is the N2-based one. Pearson correlation coefficients $r$ and Spearman’s rank correlation coefficients $\rho$ are derived.

$^b$ Physics properties that are controlled in partial correlation analysis.

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11 We note that the range of our N2-based 12 + log(O/H) is already in the most metal-rich (ISM growth) regime of the Galliano (2018) picture. However, the absolute value of gas-phase metallicity derived from different calibrations vary up to 0.7 dex (Kewley & Ellison 2008). On the other hand, both our $M_*$ and 12 + log(O/H) ranges cover the predicted regimes in which dust growth by accretion is from being efficient to being saturated in hydrodynamic simulation of Aoyama et al. (2018). Therefore, here we focus on the picture evolved with relative value of metallicity rather than the absolute value.
become much stronger for spaxels with higher \( \Sigma_{H\alpha} \). The local \( A_{V,\text{star}}/A_{V,\text{gas}} \) is found to have moderate correlations with DIG indicators (i.e., the N2S2 and S2 indices, \( \Sigma_{H\alpha} \)) and tracers of gas-phase metallicity and ionization parameter. Among these parameters, the N2S2 index shows the strongest correlation with the local \( A_{V,\text{star}}/A_{V,\text{gas}} \) ratio. The \( A_{V,\text{star}}/A_{V,\text{gas}} \) ratio of DIG-dominated spaxels tends to be systematically larger than that of classic H\( \text{II} \)-dominated spaxels. Local physical conditions of ionized gas show significant effects on the dust attenuation. Metal-poor spaxels with high ionization parameters tend to suffer less nebular attenuation (i.e., smaller \( A_{V,\text{gas}} \)) and thus larger \( A_{V,\text{star}}/A_{V,\text{gas}} \) values for either H\( \text{II} \)-dominated or DIG-dominated subsample. We argue that the systematic difference in \( A_{V,\text{star}}/A_{V,\text{gas}} \) between DIG-dominated and H\( \text{II} \)-dominated spaxels can be explained by the star/dust geometry based on the two-component dust model (Charlot & Fall 2000), while the dependences on metallicity and ionization parameters can be attributed to the change of dust properties in different local environments. We further suggest that the metallicity-dependent and ionization parameter-dependent dust-to-gas mass ratio could be one possible parameter to connect the physical conditions with dust attenuation. The median maps of dust attenuations (and the ratio) on the BPT diagrams form a low-\( A_{V,\text{gas}} \) and high-\( A_{V,\text{star}}/A_{V,\text{gas}} \) sequence that can be resolved into DIG-dominated and metal-poor spaxels. The local analyses reveal that both geometry between stars and gas/dust and physical conditions are important in determining the local \( A_{V,\text{star}}/A_{V,\text{gas}} \) values.

The local \( A_{V,\text{star}}/A_{V,\text{gas}} \) within each galaxy converge to one constant at high-\( \Sigma_{H\alpha} \) end, which is also the mode of the distribution of \( A_{V,\text{star}}/A_{V,\text{gas}} \) and is taken as the global \( A_{V,\text{star}}/A_{V,\text{gas}} \).

On galactic scale, this global \( A_{V,\text{star}}/A_{V,\text{gas}} \) ratio indeed varies from galaxy to galaxy, and correlates with physical properties such as stellar mass, SFR, and metallicity. It is found to show strong correlation with stellar mass, moderate correlations with SFR and metallicity, and weak correlations with \( b/a \) and sSFR. SFGs with larger \( M_* \), higher SFR, and more metal-rich tend to have smaller \( A_{V,\text{star}}/A_{V,\text{gas}} \) ratios. The global \( A_{V,\text{star}}/A_{V,\text{gas}} \) of AGNs follow the same relations as SFGs. A gradual trend of decreasing \( A_{V,\text{star}}/A_{V,\text{gas}} \) toward high-\( M_* \) end along the SFMS and MZR is found. Partial correlation analysis demonstrates that \( M_* \), SFR, and gas-phase metallicity have comparable effect in the observed correlations, and no single property can fully account for these correlations. We suggest that the metallicity-dependent dust-to-gas ratio together with the dust growth process accompanied with galaxy growth might partly explain these observations, although we cannot rule out any contribution from the geometry effect.

Overall, our results highlight the importance of local physical conditions in dust processes as well as the level of dust attenuation. High spatial resolution infrared observation is required to give quantitative conclusion. In addition, the most uncertain parameter in this study is the local \( A_{V,\text{star}} \) for which more constraint from infrared observation is required. Fortunately, the Mid-Infrared Instrument of the James Webb Space Telescope is able to provide mid-infrared (MIR) image of nearby galaxies from 5 to 28.5 \( \mu \)m with unprecedented spatial resolution (Rieke et al. 2015). Such high quality MIR observations, in combination with the optical IFU data and the well-calibrated monochromatic estimators of total infrared luminosity (e.g., Boquien et al. 2010; Elbaz et al. 2010; Lin et al. 2016), will allow us to put more constraints on the derivation of \( A_{V,\text{star}} \), and thus help us to better understand the relation between \( A_{V,\text{star}}/A_{V,\text{gas}} \) and other parameters on sub-kpc scale.

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As mentioned in Section 2.3, we require our sample to have a SNR of Balmer line (Hα and Hβ; SNRBal) greater than 5, a SNR of other main emission lines ([OIII]λ5007, [NII]λ6584, and [SII]λ6717; SNReml) greater than 3 to ensure reliable estimates of $A_{V,\text{gas}}$ and emission line indices. Here we examine that whether these SNR criteria affect our results.

![Figure 14](image)

**Figure 14.** Median maps of $\Sigma_{H\alpha}$ on the N2O2 vs. O32 diagram for spaxels with SNRBal > 5 & SNReml > 3 (left), SNRBal > 3 & SNReml > 3 (middle), and SNRBal > 1 & SNReml > 1 (right). The symbols are the same as Figure 4.

In Figure 14 we compare the $\Sigma_{H\alpha}$ maps on the N2O2 vs. O32 diagram for spaxels selected from three SNR cuts: SNRBal > 5 & SNReml > 3, SNRBal > 3 & SNReml > 3, and SNRBal > 1 & SNReml > 1, while the first one is the fiducial cut adopted by this work. Clearly, the selected sample is nearly unaffected by relaxing the SNRBal limit from 5 to 3 when SNReml cut is fixed to 3. However, setting both SNRBal and SNReml limits to 1 introduces a low-$\Sigma_{H\alpha}$ regime within which spaxels should be classified as DIG-dominated regions. This additional regime also cannot be covered by the model grid of HII region from Dopita et al. (2013). To understand these low-$\Sigma_{H\alpha}$ spaxels, we further select spaxels included by SNRBal > 1 & SNReml > 1 but excluded by SNRBal > 3 & SNReml > 3, and plot their $\Sigma_{H\alpha}$ map in Figure 15.

Intriguingly, the selected subsample exhibit a significant trend of increasing $\Sigma_{H\alpha}$ from high-[OIII]λ5007 & low-[NII]λ6584 corner to low-[OIII]λ5007 & high-[NII]λ6584 corner. The bimodal 68% contour indicates that this subsample might be a combination of two populations with different average $\Sigma_{H\alpha}$, and even different excitation mechanisms. We visually define a demarcation expressed as

$$\log \left( \frac{[\text{OIII}]\lambda5007}{[\text{OII}]\lambda3727} \right) = \log \left( \frac{[\text{NII}]\lambda6584}{[\text{OII}]\lambda3727} \right) - 0.1$$

(A1)

to cross two saddle points of the 68% contour and separate the subsample into low-$\Sigma_{H\alpha}$ (upper) and high-$\Sigma_{H\alpha}$ (lower) branches. The median $\Sigma_{H\alpha}$ and the corresponding 1-$\sigma$ ranges are $37.78^{+0.42}_{-0.92}$ and $38.71^{+0.41}_{-0.56}$ for the upper and lower branches, respectively.
To reveal the possible origins of the upper and lower branches, we present their histograms of \( D4000 \) and \( EW_{H\alpha} \) in Figure 16, and the \( \Sigma_{H\alpha} \) maps on the BPT diagrams in Figure 17. The two branches have distinct distributions for both \( D4000 \) and \( EW_{H\alpha} \). The medians and 68\% ranges of \( D4000 \) are \( 1.68 \pm 0.16 \) and \( 1.44 \pm 0.14 \) for the upper and lower branches, respectively, while the same parameters are \( -1.05 \pm 2.28 \) and \( -7.16 \pm 3.33 \) for \( EW_{H\alpha} \). Obviously, the upper branch is dominated by old stellar population for which star formation is almost quenched, whereas the lower one suggests a relatively young population with moderate level of star formation. For the BPT diagrams, nearly all the spaxels at the upper branch locate in the LINER regime on the [O i]-[O iii] diagram, and half of them lie beyond the H ii regime on the [S ii]-[O iii] diagram. For the lower branch, nearly all spaxels are within the H ii regime in the [S ii]-[O iii] plane, and only small fraction of spaxels with lower-\( \Sigma_{H\alpha} \) move toward to the LINER regime of [O i]-[O iii] plane.

The distinct distributions of the above properties of stellar population and ionized gas indicate different physical origins of the two branches. The upper branch is comprised of old stellar population with emission lines arising from
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Figure 17. Median maps of $\Sigma_{H\alpha}$ on the BPT diagrams for spaxels at the upper (top) and lower (bottom) branches defined in Figure 15. Boundaries from Kauffmann et al. (2003), Kewley et al. (2001), and Kewley et al. (2006) are denoted by solid, dashed and dashed-dotted black curves, respectively. The contours encompass 68%, 95%, and 99% of the spaxels on each diagram. The typical uncertainties are shown at the lower left corner.

LI(N)ER-like regions or the so-called hDIG in Lacerda et al. (2018) which is heated by hot, low-mass, evolved stars. Spaxels at the lower branch are more likely faint H\textsc{ii} regions. Comparison between Figure 14 and Figure 15 shows that our adopted SNR criteria indeed reduce the covered N2O2–O32 parameter space of non-star-forming origins, while the star-forming regime (i.e., the lower branch of Figure 15 or the main star-forming cloud revealed in Figure 4) is almost unaffected. Given the aim of studying the dust attenuation ratio for classical H\textsc{ii} regions, we concluded that the fiducial SNR cuts (i.e., SNR$_{Bal} > 5$ & SNR$_{eml} > 3$) are suitable, and relaxing the criteria to smaller SNR values cannot change our results.

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