

Mapping Dust Attenuation at Kiloparsec Scales. II. Attenuation Curves from Near-ultraviolet to Near-infrared (Postprint)

Authors: Ruonan Guo, Cheng Li, Shuang Zhou, Niu Li, Tao Jing and Zhuo Cheng

Date: 2025-06-13T16:50:50+00:00

Abstract

This is the second paper in a series that utilizes integral field spectroscopy from MaNGA, NUV imaging from Swift/UVOT, and NIR imaging from 2MASS to investigate dust attenuation properties on kpc scales in nearby galaxies. We apply the method developed in our previous work to the updated SwiM_{v4}.2 catalog, and measure the optical attenuation curve and the attenuation in three NUV bands for 2487 spaxels selected from 91 galaxies with $S/N > 20$ and $AV > 0.25$. We classify all spaxels into two subsets: star-forming (SF) regions and non-SF regions. We explore the correlations of optical opacity (AV) and the optical and NUV slopes of the attenuation curves (AB/AV and Aw2/Aw1) with a broad range of stellar population and emission-line properties, including specific surface brightness of H α emission ($\Sigma H\alpha/\Sigma$), *stellar age, stellar and gas-phase metallicity, and diagnostics of recent star formation history*. Overall, when comparing SF and non-SF regions, we find that AV and AB/AV exhibit similar correlations with all the stellar population and emission-line properties considered, while the NUV slopes in SF regions tend to be flatter than those in non-SF regions. The NUV slope Aw2/Aw1 exhibits an anti-correlation with $\Sigma H\alpha/\Sigma$, a trend that is primarily driven by the positive correlation between Aw2/Aw1 and Σ^* . The NUV slope flattens in SF regions that contain young stellar populations and have experienced recent star formation, but it shows no obvious dependence on stellar or gas-phase metallicity. The spatially resolved dust attenuation properties exhibit no clear correlations with the inclination of host galaxies or the galactocentric distance of the regions. This finding reinforces the conclusion from Paper I that dust attenuation is primarily regulated by local processes on kpc scales or smaller, rather than by global processes at galactic scales.

Full Text

Preamble

Research in Astronomy and Astrophysics, 25:065017 (15pp), 2025 June © 2025 National Astronomical Observatories, CAS and IOP Publishing Ltd. All rights, including for text and data mining, AI training, and similar technologies, are reserved. Printed in China. <https://doi.org/10.1088/1674-4527/add673> CSTR: 32081.14.RAA.add673

Mapping Dust Attenuation at Kiloparsec Scales. II. Attenuation Curves from Near-ultraviolet to Near-infrared

Ruonan Guo¹, Cheng Li¹, Shuang Zhou², Niu Li^{1,3}, Tao Jing¹, and Zhuo Cheng^{1,4}

¹ Department of Astronomy, Tsinghua University, Beijing 100084, China; grn19@mails.tsinghua.edu.cn, cli2015@tsinghua.edu.cn

⁴ Department of Physics, The Chinese University of Hong Kong, Sha Tin, NT, Hong Kong, China

Received 2025 March 20; revised 2025 April 29; accepted 2025 May 6; published 2025 June 3

Abstract

This is the second paper in a series that utilizes integral field spectroscopy from MaNGA, NUV imaging from Swift/UVOT, and NIR imaging from 2MASS to investigate dust attenuation properties on kpc scales in nearby galaxies. We apply the method developed in our previous work to the updated SwiM_{v4}.2 catalog, and measure the optical attenuation curve and the attenuation in three NUV bands for 2487 spaxels selected from 91 galaxies with $S/N > 20$ and $AV > 0.25$. We classify all spaxels into two subsets: star-forming (SF) regions and non-SF regions. We explore the correlations of optical opacity (AV) and the optical and NUV slopes of the attenuation curves (AB/AV and A) with a broad range of stellar population and emission-line properties, including specific surface brightness of H α emission ($\Sigma H\alpha/\Sigma$), stellar age, stellar and gas-phase metallicity, and diagnostics of recent star formation history. Overall, when comparing SF and non-SF regions, we find that AV and AB/AV exhibit similar correlations with all the stellar population and emission-line properties considered, while the NUV slopes in SF regions tend to be flatter than those in non-SF regions. The NUV slope A exhibits an anti-correlation with $\Sigma H\alpha/\Sigma$, a trend that is primarily driven by the positive correlation between A and Σ^* . The NUV slope flattens in SF regions that contain young stellar populations and have experienced recent star formation, but it shows no obvious dependence on stellar or gas-phase metallicity. The spatially resolved dust attenuation properties exhibit no clear correlations with the inclination of host galaxies or the galactocentric distance of the regions. This finding reinforces the conclusion from Paper I that dust

attenuation is primarily regulated by local processes on kpc scales or smaller, rather than by global processes at galactic scales.

Key words: (ISM:) dust, extinction – (ISM:) HII regions – galaxies: evolution – galaxies: ISM

1. Introduction

Dust is ubiquitously distributed throughout the interstellar medium, absorbing and scattering stellar and nebular radiation at wavelengths shorter than the near-infrared (NIR) while re-emitting it in the mid-infrared and far-infrared (e.g., da Cunha et al. 2008; Galliano et al. 2018). Consequently, despite constituting only a small fraction of the baryonic mass (Rémy-Ruyer et al. 2014; Driver et al. 2018), interstellar dust plays a crucial role in shaping a galaxy’s observed spectral energy distribution (SED). The wavelength-dependent extinction of starlight along different sightlines—referred to as dust extinction curves—is determined by dust absorption and scattering and depends on the chemical composition and size distribution of dust grains (Weingartner & Draine 2001).

Extinction curves can be directly measured only for the Milky Way and a few nearby galaxies (e.g., Prevot et al. 1984; Clayton & Martin 1985; Fitzpatrick & Massa 1986; Cardelli et al. 1989; Gordon & Clayton 1998; Fitzpatrick 1999; Gordon et al. 2003; Clayton et al. 2015). For more distant galaxies, the observed wavelength-dependent dimming of light—described as dust attenuation curves—accounts not only for absorption and scattering but also for additional effects such as light scattered into the line of sight, as well as the complex spatial distribution of dust relative to the stars (Calzetti 2001). A fundamental task in extragalactic astrophysics is to measure dust attenuation curves and understand the underlying mechanisms that shape them. This is essential for accurately recovering the intrinsic SED and correctly measuring key physical properties of galaxies (Conroy 2013; Salim & Narayanan 2020).

For a galaxy or a local region within a galaxy, the dust attenuation curve is obtained by comparing the observed spectrum or SED with its intrinsic, dust-free counterpart. Broadly, the intrinsic spectrum or SED can be obtained using two categories of methods, either through empirical comparison with selected reference galaxies that are less attenuated (e.g., Calzetti et al. 1994, 1997, 2000; Kinney et al. 1994; Johnson et al. 2007; Wild et al. 2011; Battisti et al. 2016, 2017a, 2017b), or by fitting the observed spectrum/SED with stellar population models (e.g., Spinrad & Taylor 1971; Faber 1972; Sawicki & Yee 1998; Papovich et al. 2001; Kauffmann et al. 2003; Salim et al. 2005, 2007; Noll et al. 2009; Conroy 2013; Leja et al. 2017; Boquien et al. 2019, 2022; Johnson et al. 2019; Zhou et al. 2019; Jones et al. 2022; Nagaraj et al. 2022; Belles et al. 2023; Zhou et al. 2023; Humire et al. 2025). Over the past three decades, numerous observational studies have employed both categories of methods to measure attenuation curves and investigate their correlations with galactic properties on global scales, spanning both the local Universe and high redshifts (see Salim & Narayanan 2020 for a comprehensive review).

These studies have consistently shown that dust attenuation curves vary in three key aspects: the overall slope from the optical to the ultraviolet (UV), which is typically approximated by a power law; the excess attenuation around 2175 Å, commonly referred to as the 2175 Å bump; and their relationship with nebular attenuation, often quantified using the Balmer decrement of emission lines.

Early studies found that the attenuation curves of local starburst galaxies tend to have shallow slopes, a weak or absent 2175 Å bump, and an average stellar-to-nebular color excess ratio of $E(B - V)_{\text{star}}/E(B - V)_{\text{gas}} = 0.44$ (Calzetti et al. 1994, 2000). In contrast, relatively quiescent galaxies, such as the Milky Way, typically exhibit steeper attenuation slopes and a prominent 2175 Å bump (e.g., Cardelli et al. 1989; Fitzpatrick 1999). It is now well established that attenuation curves span a broad range in both UV-through-optical slopes and the strength of the 2175 Å bump, encompassing curves with no 2175 Å bump and slopes shallower than the Calzetti curve, as well as those with strong 2175 Å bumps and slopes steeper than the Milky Way-type curves. The ratio of $E(B - V)_{\text{star}}/E(B - V)_{\text{gas}}$ is also found to span a wide range from 0.44 to 1, depending on the mass, star formation rate (SFR), and axis ratio of galaxies (e.g., Wild et al. 2011; Wuyts et al. 2011; Zahid et al. 2017). In addition, the slopes of attenuation curves are found to be strongly correlated with the optical opacity, with shallower slopes in galaxies of lower visual attenuation. As summarized in Salim & Narayanan (2020), both the correlations between the slope and optical opacity and the variation of the 2175 Å bump may be explained as consequences of geometric and radiative transfer effects based on theoretical studies.

Therefore, spatially resolved observations down to the scale of star-forming regions and covering both the optical and UV bands are essential for disentangling the effects of local and galaxy-wide processes on variations in dust attenuation curves.

Over the past decade, integral field spectroscopy observations have facilitated numerous studies investigating spatially resolved dust attenuation in nearby galaxies at kiloparsec scales or smaller (e.g., Kreckel et al. 2013; Jimmy et al. 2016; Bassett et al. 2017; Li et al. 2019, 2020, 2021; Greener et al. 2020; Lin & Kong 2020; Teklu et al. 2020; Rupke et al. 2021; Ji et al. 2023; Li & Li 2024; Lin & Yan 2024). For instance, in a series of studies on optical dust attenuation using data from the Mapping Nearby Galaxies at Apache Point Observatory (MaNGA; Bundy et al. 2015) survey, Li et al. (2020) developed a novel method to derive model-independent attenuation curves from optical spectra. This method was subsequently applied in Li et al. (2021) to conduct a comprehensive analysis of the correlations between stellar and nebular attenuation and a broad range of stellar population and emission-line properties, and in Li & Li (2024) to further examine the radial variations of these correlations. The measurements of optical dust attenuation properties, as well as stellar population and emission-line properties for the final sample of MaNGA, are publicly released in Li & Li (2023). Their findings revealed that $E(B - V)_{\text{star}}/E(B - V)_{\text{gas}}$ at kiloparsec

scales spans an even larger range than previously observed at galactic scales. More importantly, their results suggest that stellar age is the primary driver of variations in $E(B - V)_{\text{star}}/E(B - V)_{\text{gas}}$, implying that both young and old stellar populations may play significant roles in shaping the properties of dust attenuation. Recently, a spatially resolved study of the multiband SED of the nearby galaxy NGC 253 further reinforced this finding, revealing a clear correlation between the difference in stellar and nebular attenuation and stellar age (Humire et al. 2025).

In recent years, UV photometry has been incorporated alongside optical integral field spectroscopy (IFS) data, enabling the inclusion of the UV slope in studies of spatially resolved dust attenuation. Such studies have been conducted in individual nearby galaxies, including M81 and Holmberg IX (Hoversten et al. 2011), M82 (Hutton et al. 2014, 2015), the Small Magellanic Cloud (Hagen et al. 2017), NGC 628 (Decleir et al. 2019), the Milky Way (Ferreras et al. 2021), and NGC 253 (Humire et al. 2025). Additionally, such analyses have been extended to samples of galaxies across the local Universe (e.g., Molina et al. 2020a; Belles et al. 2023; Duffy et al. 2023; Zhou et al. 2023; Battisti et al. 2025). For instance, utilizing NUV photometry from Swift/UVOT and optical IFS data from MaNGA, as provided by the SwiM_{v3}.1 catalog (Molina et al. 2020b), in addition to NIR imaging from 2MASS, Zhou et al. (2023, hereafter Paper I) applied the technique of Li et al. (2020) and the Bayesian spectral fitting code BIGS developed in Zhou et al. (2019) to measure the 2175 Å bump and optical attenuation curve for a sample of kpc-sized regions in nearby galaxies. They found that previously established correlations—namely, the anti-correlation between the attenuation curve slope and optical opacity, as well as the decrease in 2175 Å bump strength with increasing star formation rate—persist at kpc scales. This finding strongly suggests that dust attenuation is primarily regulated by local processes on kpc scales or smaller, rather than by global processes at galactic scales.

Following Paper I, this is the second paper in a series studying dust attenuation at kiloparsec scales in nearby galaxies, utilizing NUV photometry from Swift/UVOT, optical IFS data from MaNGA, and NIR photometry from 2MASS. This paper extends the work of Paper I by employing the latest version of the SwiM catalog, SwiM_{v4}.2 (Molina et al. 2023), which is nearly four times larger than the SwiM_{v3}.1 catalog used in Paper I. Additionally, we classify all kpc-sized regions in the catalog into two subsamples: star-forming (SF) regions and non-SF regions. This classification allows us to investigate dust attenuation properties separately for regions dominated by young stellar populations and star formation-related processes, and for regions dominated by older populations and diffuse ionized gas. Furthermore, while Paper I primarily examined the specific SFR, this work incorporates a broader range of stellar population and emission-line properties into the analysis, including stellar age, stellar and gas-phase metallicity, and diagnostics of recent star formation history. In this paper, we focus on optical opacity, characterized by the V-band attenuation (AV), and the slopes of the attenuation curve in the optical and

NUV. In the next paper (Paper III, R.N. Guo et al. 2025, in preparation), we will investigate the 2175 Å bump and its correlations with stellar population and emission-line properties. In the fourth paper (Paper IV, Guo et al. 2025, in preparation), we will use the attenuation curve measurements obtained in this study to constrain a two-component dust model, enabling us to derive the distributions of dust grain sizes and the fractional contributions of dust mass from silicate and graphite compositions.

This paper is organized as follows. In Section 2, we describe the data used in this work, along with the methods for measuring stellar population and emission-line properties. We present our results in Section 3, discuss our findings in Section 4, and summarize our conclusions in Section 5. Throughout this paper, we assume a standard Λ CDM cosmology with $\Omega_m = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}$.

2.1. SwiM_{v4}.2, MaNGA and 2MASS

We use the latest version of the Swift/UVOT+MaNGA (SwiM) Value-Added Catalog, SwiM_{v4}.2, which is publicly available from the SDSS website and described in detail in Molina et al. (2023). The SwiM_{v4}.2 catalog includes 559 galaxies, nearly four times more than the original SwiM_3.1 catalog (Molina et al. 2020b) used in Paper I. By construction, the SwiM galaxies have optical IFS from MaNGA (Bundy et al. 2015; Yan et al. 2016a), as well as NUV photometry from Swift/UVOT (Roming et al. 2005) in three bands: uvw2, uvm2, and uvw1, centered at 1928 Å, 2246 Å, and 2600 Å, respectively. The uvm2 filter is centered near 2175 Å, thus allowing the investigation of the UV bump feature in dust attenuation curves.

The galaxies in SwiM_{v4}.2 are selected by cross-matching the final sample of MaNGA with the UVOT data archive as of 2021 August. MaNGA is one of the three major experiments of the SDSS-IV project (Blanton et al. 2017), accomplished over a period of six years from 2014 July through 2020 August (Bundy et al. 2015). The full MaNGA sample consists of 10,010 unique galaxies selected from the NASA Sloan Atlas (NSA; Blanton et al. 2011), covering a redshift range of $0.01 < z < 0.15$ with a median redshift of $z = 0.03$ and a stellar mass range of $5 \times 10^8 M \leq M^* \leq 3 \times 10^{11} M$ (Wake et al. 2017). The galaxies were observed with a typical exposure time of 3 hr, using 17 pluggable hexagonal-formatted Integral Field Units (Drory et al. 2015) that are fed to the two dual-channel BOSS spectrographs on the Sloan 2.5 m telescope (Gunn et al. 2006; Smee et al. 2013) to obtain IFS data with a field of view ranging from 12 to 32, effective spatial resolution of FWHM = 2.5, and spectral resolution of $R = 2000$ in the wavelength range from 3622 to 10354 Å (Law et al. 2015). The observational data reach an r-band continuum signal-to-noise ratio (S/N) of 4–8 per Å per fiber at 1–2 effective radii (R_e) of galaxies. MaNGA raw data are reduced with the Data Reduction Pipeline (DRP; Law et al. 2016, 2021) to produce a data cube for each galaxy, with a spaxel size of 0.5×0.5 and absolute flux calibration better than 5% for more than 80% of the wavelength range (Yan et al. 2016a, 2016b). Additionally, the Data Analysis Pipeline (DAP) performs

full spectral fitting to the DRP data cubes, providing measurements of stellar kinematics, emission lines, and spectral indices (Belfiore et al. 2019; Westfall et al. 2019). The DRP and DAP data products of all the MaNGA galaxies are released as part of the final data release of SDSS-IV (DR17; Abdurro'uf et al. 2022).

All 559 galaxies in SwiM_{v4}.2 have UVOT observations in uvw1 and uvw2, while 490 also have observations in uvm2. In addition to a catalog that provides integrated photometry from Swift, SwiM_{v4}.2 also includes two-dimensional maps of numerous emission lines and spectral indices as measured by the MaNGA DAP, as well as Swift/UVOT images in uvw1 (also uvm2 when available) and SDSS images in ugriz. All maps and images are convolved and resampled to match the spatial resolution and sampling of the uvw2 band, which has a point-spread function (PSF) with a full width at half maximum (FWHM) of 2.92 and a pixel size of 1.

Figure 1 [Figure 1: see original paper] displays all the galaxies in SwiM_{v4}.2 as gray dots in the color-mass diagram ($g - r$ versus $\log_{10}M$; *left panel*) and the diagram of SFR and mass ($\log_{10}SFR$ versus $\log_{10}M$; *right panel*). Here, $g - r$ and M^* are taken from the NSA, and SFRs are from the GSWLC-X2 catalog (Salim et al. 2018). In the figure, the MaNGA DR17 sample is plotted as background contours for comparison. As can be seen, the SwiM_{v4}.2 catalog spans similarly wide ranges in these parameters. Plotted in red circles are the galaxies in the earlier SwiM_{v3}.1 catalog, which was described in detail in Molina et al. (2020b) and has been used in several works to study spatially resolved dust attenuation in nearby galaxies (Molina et al. 2020a; Duffy et al. 2023; Zhou et al. 2023).

For each of the 559 SwiM galaxies, we retrieved its Ks-band image from the 2MASS data archive (2.16 m) (Skrutskie et al. 2006). Compared to the SwiM images, the 2MASS images have the same sampling of 1 per pixel and a similar spatial resolution of FWHM 2.5–3.5. Following Paper I, we simply resample the 2MASS images to match the sampling of the SwiM images, without performing additional resolution matching, which would lead to flux differences of <1% due to the similar spatial resolutions.

2.2. Deriving and Characterizing Dust Attenuation Curves

For each spaxel of each galaxy in SwiM_{v4}.2, we apply the same methodology as described in Paper I to derive the attenuation curve across the full wavelength range from NUV to NIR. Readers are referred to Paper I for a detailed description of our method and tests. Here, we provide a brief overview of the process, which consists of three steps. First, we use the technique of Li et al. (2020) to derive a relative attenuation curve from the MaNGA optical spectrum and apply it to obtain an attenuation-corrected spectrum with an arbitrary flux unit. Next, we employ the Bayesian spectral fitting code BIGS (Zhou et al. 2019) to fit the attenuation-corrected spectrum, yielding the best-fit model spectrum that spans the full wavelength range from NUV to NIR. Finally, assuming that

dust attenuation in the NIR band is negligible, we use the Ks-band image to calibrate the absolute flux of the dust-free best-fit model spectrum. We then derive the absolute attenuation curve in the optical and determine the attenuation in the three NUV bands by comparing the observed spectrum and images with the model spectrum.

To characterize the dust attenuation curves, we measure the following parameters from each curve: (1) AV, the optical opacity, defined as the attenuation in the V-band; (2) AB/AV, the optical slope of the attenuation curve, given by the attenuation ratio between the B ($\lambda = 4400 \text{ \AA}$) and V ($\lambda = 5500 \text{ \AA}$) bands; and (3) A, the NUV slope, defined as the attenuation ratio between the uw2 and uw1 bands. In the literature, another commonly used parameter for the optical slope is the total-to-selective attenuation ratio in the V-band, defined as $RV = AV/E(B - V)$, where $E(B - V) = AB - AV$ is the color excess. By this definition, AB/AV is related to RV as $AB/AV = (RV + 1)/RV$. For example, the standard Calzetti curve with $RV = 4.05$ gives $AB/AV = 1.25$ (Calzetti et al. 1994, 2000), while the Milky Way-like curve with $RV = 3.1$ yields $AB/AV = 1.32$ (Cardelli et al. 1989). The NUV slope is $A = 1.19$ for the Calzetti curve and 1.24 for the Milky Way curve.

Tests on mock spectra, as conducted in Paper I, demonstrated that our method can reliably recover the average dust attenuation properties in individual spaxels of SwiM galaxies, provided that the spectral S/N is sufficiently high. We adopt the same selection criteria as in Paper I to identify spaxels for this study: $S/N > 20$ and $AV > 0.25$. Here, S/N refers to the S/N in the continuum, measured around 5500 \AA . Applying these criteria, we obtain a total of 2487 spaxels across 91 galaxies. These galaxies are represented as blue dots in Figure 1, where the size of each dot is proportional to the number of selected spaxels contributed by the galaxy. Both the number of spaxels and the number of host galaxies are increased by about three times compared with Paper I, which included 750 spaxels across 28 galaxies under the same selection criteria. Notably, the selected galaxies are predominantly blue and star-forming, and they tend to be more massive than those in the parent sample.

2.3. Measuring Stellar Populations and Emission Lines

Using the attenuation curves derived above, we correct the observed MaNGA spectrum in each spaxel for dust attenuation. We then perform full spectral fitting on the dust-corrected spectrum, extracting both stellar population parameters from the best-fit stellar spectrum and emission-line parameters from the starlight-subtracted spectrum. The methodology is described in detail in Li et al. (2021). In brief, we fit the dust-corrected spectra using a set of 150 simple stellar populations (SSPs) selected from the SSP library of Bruzual & Charlot (2003, BC03). This library provides model spectra for 1326 SSPs at a spectral resolution of 3 \AA , covering 221 ages from 0 to 20 Gyr and six metallicities ranging from $0.005Z$ to $2.5Z$. The models are computed using the initial mass function (IMF) of Chabrier (2003) and the Padova evolutionary tracks (Bertelli et al. 1994). Each spectrum is fitted with a linear combination of the SSPs,

with the effect of stellar velocity dispersion taken into account by convolving the spectra of the SSPs with a Gaussian. During the fitting, we have carefully masked out all the detected emission lines following the scheme described in Li et al. (2005).

Based on the best-fit stellar spectrum and the corresponding fractional contributions of the SSPs, we then measure the following stellar population parameters:

1. $\log_{10}\Sigma^*$ —logarithm of the stellar mass surface density in units of $M_{\odot}\text{ kpc}^{-2}$.
2. $\log_{10}tL$ and $\log_{10}tM$ —logarithm of the luminosity-weighted and mass-weighted stellar age in units of yr.
3. ZL and ZM —logarithm of the luminosity-weighted and mass-weighted stellar metallicity in units of solar metallicity Z_{\odot} , where $Z = 0.02$.
4. $Dn4000$ —the narrow-band version of the 4000 Å break (Balogh et al. 1999).
5. $EW(H\delta A)$ —the equivalent width of the $H\delta$ absorption line in units of Å.

We subtract the best-fit model spectrum from the observed spectrum to isolate the emission-line spectrum. Each emission line is then fitted with either a single Gaussian or a double Gaussian function, providing measurements of the flux, line width, central wavelength, and equivalent width (EW). To correct for the effects of gas attenuation, we calculate the Balmer decrement using the observed $H\alpha/H\beta$ flux ratio and assume case-B recombination. From $H\alpha/H\beta$, we estimate the gas attenuation, quantified by the color excess $E(B - V)_{\text{gas}}$, and use it to correct the flux of all emission lines. Based on these emission-line measurements, we derive the following parameters to characterize the gas-related properties of each spaxel:

1. $\log_{10}\Sigma H\alpha$ —logarithm of the surface brightness of the $H\alpha$ emission line in units of $\text{erg s}^{-1} \text{ kpc}^{-2}$.
2. $\log_{10}sSFR$ —logarithm of the specific star formation rate (sSFR) defined as the ratio of SFR to stellar mass in a given spaxel. We estimate the SFR for each spaxel from the $H\alpha$ luminosity using the estimator from Kennicutt (1998). It is worth noting that the SFR estimated in this way is reliable only for SF regions where $H\alpha$ emission is dominantly contributed by young massive stars.
3. $\log_{10}(\Sigma H\alpha/\Sigma)$ —logarithm of surface specific $H\alpha$ brightness, defined as $\Sigma H\alpha/\Sigma$. For SF regions, this parameter is equivalent to $\log_{10}sSFR$.
4. $\log_{10}EW(H\alpha)$ —logarithm of the equivalent width of the $H\alpha$ emission line in units of Å.
5. $12 + \log(O/H)_{\text{O3N2}}$ —the gas-phase metallicity estimated using the O3N2 indicator: $O3N2 = ([O\text{ III}] 5007/H) / ([N\text{ II}] 6583/H)$ (Marino et al. 2013).
6. $12 + \log(O/H)_{\text{R23}}$ —the gas-phase metallicity estimated using the R23 indicator: $R23 = ([O\text{ III}] 5007, 4959 + [O\text{ II}] 3727) / H$ (Nakajima et al. 2022).
7. $N2S2$ —logarithm of the flux ratio between emission lines $[N\text{ II}] 6583$ and $[S\text{ II}] 6717$, a parameter that is sensitive to both gas-phase metallicity and ionization

parameter.

2.4. Classification of SF and Non-SF Regions

We classify all spaxels in our sample into two categories: SF and non-SF regions, based on the diagnostic diagram developed by Ji & Yan (2020). This diagram is derived by projecting the traditional BPT diagrams (Baldwin et al. 1981) into a new parameter space, allowing for a clearer separation of different ionization models. The new parameters, P1 and P2, are linear combinations of $\log_{10}([\text{S II}] 6717/H)$ and $\log_{10}([\text{SII}] 6731/H)$. The left panel of Figure 2 [Figure 2: see original paper] shows the diagram of P1 versus P2 for the SF and non-SF spaxels in our sample, separated by the blue dashed line from Ji & Yan (2020) and plotted as blue and yellow dots, respectively. The right panel presents the SF and non-SF regions on the $\log_{10}(\Sigma H)$ versus $\log_{10}(\Sigma^*)$ plane. The dashed lines represent different constant values of $\Sigma \text{H}\alpha/\Sigma$, which, for SF regions, corresponds to $\log_{10} \text{sSFR}$. As expected, while the two types of regions exhibit some degree of separation in this diagram, they also show significant overlap. Compared to the parent MaNGA sample, our sample is dominated by relatively dense regions with $\Sigma \sim 10^{7.5} \text{ M kpc}^{-2}$.

3.1. Mutual Relation Between AV, AB/AV and Aw2

We begin by examining the interrelationships between optical opacity, characterized by AV, and the slopes of the attenuation curves in the optical (AB/AV) and NUV (A), as shown in Figure 3 [Figure 3: see original paper]. The results are presented separately for SF and non-SF regions. In both cases, the optical slope AB/AV exhibits an inverse correlation with AV. The NUV slope A shows a similar but weaker anti-correlation with AV in non-SF regions, while this correlation is nearly absent in SF regions. Additionally, the optical and NUV slopes display a slight positive correlation in non-SF regions but appear uncorrelated in SF regions. Overall, these findings are consistent with those reported in Paper I (see their Figure 7 [Figure 7: see original paper]), where similar trends were observed across all regions collectively. Beyond the results of Paper I, we also find that non-SF regions generally exhibit steeper NUV slopes than SF regions, even when AV and AB/AV are restricted to narrow ranges.

3.2. Dependence on sSFR and Recent Star Formation History

In the top panels of Figure 4 [Figure 4: see original paper], we examine the correlations between attenuation properties—characterized by optical opacity (AV) and the slopes of the attenuation curves in the optical (AB/AV) and NUV (A)—and the specific surface brightness of the H α emission line, $\Sigma \text{H}\alpha/\Sigma$. In SF regions, this parameter is essentially equivalent to the sSFR, as noted earlier. SF and non-SF regions are plotted in different colors. For clarity, we label the bottom x-axis with $\Sigma \text{H}\alpha/\Sigma$ and the top x-axis with sSFR to facilitate direct comparison between these parameters. Consistent with Paper I, we find that in both SF and non-SF regions, AV increases with $\Sigma \text{H}\alpha/\Sigma^*$, while the optical slope AB/AV shows no clear correlation with this parameter. However, unlike Paper I, which found the NUV slope A to be nearly independent of sSFR, we

identify a significant anti-correlation between these two properties in both SF and non-SF regions. This discrepancy is likely due to several factors in this study, including the larger (and potentially different) sample, the SF/non-SF classification, and the slightly wider sSFR range.

In the middle and bottom panels of Figure 4, we present the three attenuation curve parameters as functions of the $H\alpha$ surface brightness ($\Sigma H\alpha$) and the surface density of stellar mass (Σ). *For the optical slope AB/AV , we find no clear dependence on either $\Sigma H\alpha$ or Σ .* In contrast, the optical opacity AV shows a positive correlation with $\Sigma H\alpha$ but exhibits little to no correlation with Σ . *This suggests that the positive correlation between AV and $\Sigma H\alpha/\Sigma$ seen in the top-left panel is primarily driven by the relationship between AV and $\Sigma H\alpha$.* For the NUV slope A , we find no or weak dependence on $\Sigma H\alpha$ and a positive correlation with Σ . *Therefore, the anti-correlation between A and $\Sigma H\alpha/\Sigma$ as observed in the top-right panel is primarily driven by the correlation of A with Σ^* , rather than with $\Sigma H\alpha$.* This result indicates that the steeper NUV slopes in non-SF regions compared to SF regions, as seen in Figure 3, are primarily attributed to the relatively high surface stellar mass densities in non-SF regions.

One might question whether the observed anti-correlation between A and $\Sigma H\alpha/\Sigma^*$ is an independent relationship or merely a consequence of the correlations between A and AV (middle panel of Figure 3) and between AV and $\Sigma H\alpha/\Sigma^*$ (top-left panel of Figure 4). To investigate this possibility, we divide both SF and non-SF regions into subsamples based on AV and examine how A correlates with $\Sigma H\alpha/\Sigma$, $\Sigma H\alpha$, and Σ within these subsamples. The results, shown in Figure 5 [Figure 5: see original paper], reveal that all previously identified correlations in the full samples of SF and non-SF regions remain unchanged even when AV is restricted to narrow ranges. This finding confirms that the anti-correlation between A and $\Sigma H\alpha/\Sigma^*$ is intrinsic and not driven by the other two correlations.

In Figure 6 [Figure 6: see original paper], we further investigate the dependence of attenuation curve properties on recent star formation history (SFH), using three observational diagnostics: $EW(H\alpha)$, $Dn4000$, and $EW(H\delta A)$. The first diagnostic, $EW(H\alpha)$, represents the equivalent width of the $H\alpha$ emission line. This parameter is widely used as a proxy for the sSFR, effectively measuring the strength of ongoing star formation. As expected, $EW(H\alpha)$ exhibits correlations with dust attenuation properties similar to those observed in the top panels of Figure 4. The second parameter, $Dn4000$, quantifies the strength of the continuum break around 4000 Å. It is particularly sensitive to stellar populations formed within the past 1–2 Gyr. The third parameter, $EW(H\delta A)$, measures the equivalent width of the $H\delta$ absorption line, serving as an indicator of massive stars formed over the past few Myr. Together, these three diagnostic parameters provide a broad picture of the recent SFH in a given region, covering timescales from the present back to approximately 1–2 Gyr ago. As shown in the figure, both SF and non-SF regions exhibit similar correlations between AV and AB/AV and the recent SFH diagnostics. However, the NUV slope,

A , behaves differently between the two types of regions. In non-SF regions, it shows little to no dependence on $Dn4000$ and $EW(H\delta A)$, whereas in SF regions, a significant correlation is observed. Specifically, the NUV slope of attenuation curves becomes flatter as $Dn4000$ decreases or $EW(H\delta A)$ increases, both of which indicate the presence of recently formed young stellar populations.

3.3. Dependence on Age and Metallicity

In Figure 7, we explore how dust attenuation properties depend on the average stellar age, weighted either by luminosity (tL) or mass (tM). Results are shown separately for SF and non-SF regions. The optical slope AB/AV exhibits little to no dependence on either tL or tM , across both SF and non-SF regions. In contrast, we observe a negative correlation between AV and stellar age, as well as a positive correlation between A and stellar age. This aligns with the previously noted dependence of AV and A on $Dn4000$, which also serves as an indicator of the mean stellar age of the population.

In Figure 8 [Figure 8: see original paper], we present the attenuation parameters as functions of metallicity, both stellar and gas-phase. The first two rows of panels show the results for luminosity-weighted (ZL) and mass-weighted (ZM) stellar metallicity. Overall, the dependence on stellar metallicity is weak for all three dust attenuation parameters across both SF and non-SF regions, except for a slight increase in A with increasing metallicity in SF regions. In the next two rows of panels in Figure 8, we further explore the relationship between dust attenuation parameters and gas-phase metallicity, using the oxygen abundance as estimated by O3N2 and R23 indicators. While we display spaxels from both SF and non-SF regions, oxygen abundance estimates are meaningful only for SF regions. Therefore, we present the median and scatter only for SF regions in each panel. As shown, the dust attenuation parameters exhibit a rather weak dependence on oxygen abundance, consistent with the trends observed for stellar metallicity. However, a positive correlation between A and gas-phase metallicity is also noticeable in SF regions.

In the bottom panels of Figure 8, we examine the three attenuation parameters as functions of $N2S2$, defined as $\log_{10}([N\text{ II}]/[SII])$. This parameter is sensitive to both gas-phase metallicity and the ionization parameter. At a fixed ionization level, metal-poorer regions tend to have smaller $N2S2$ values (Lin & Kong 2020). Similar to the results for stellar metallicity and oxygen abundance, both the optical opacity and optical slope show little to no dependence on $N2S2$. However, the NUV slope exhibits a positive correlation with $N2S2$. Together, these results consistently suggest that while the optical properties of attenuation curves remain largely unaffected by metallicity, the NUV slope shows a weak but noticeable dependence on both stellar and gas-phase metallicities.

3.4. Dependence on Inclination and Galactocentric Radius

In this subsection, we examine the potential dependence of dust attenuation parameters on the inclination of host galaxies and the galactocentric distances

of the spaxels. Following Paper I, galaxy inclination is quantified by the minor-to-major axis ratio (b/a) measured from SDSS r-band images, while the galactocentric distance is given by the radius of the spaxels in the MaNGA data cube, scaled by the effective radius (Re).

Figure 9 [Figure 9: see original paper] presents the three dust attenuation parameters as functions of b/a , shown in panels from left to right. The upper and lower panels display results for SF and non-SF regions, respectively. In each panel, different colors represent subsamples divided by specific $H\alpha$ surface brightness ($\Sigma H\alpha/\Sigma$). *Overall, we find that, in both SF and non-SF regions, both the optical and NUV slopes of attenuation curves are largely independent of galaxy inclination when $\Sigma H\alpha/\Sigma$ is restricted to a narrow range.* However, at fixed $\Sigma H\alpha/\Sigma^*$, AV tends to decrease as b/a increases, which aligns with the expectation that more inclined galaxies experience stronger dust attenuation.

The dependence of the three attenuation parameters on the galactocentric distance, Rc/Re , is presented in Figure 10 [Figure 10: see original paper], using the same symbols and color coding as in the previous figure. Overall, we find that when $\Sigma H\alpha/\Sigma^*$ is restricted to a narrow range, none of the dust attenuation parameters exhibit a clear correlation with Rc/Re . This result is true for both SF and non-SF regions. Our results reinforce the conclusion from Paper I that dust attenuation is primarily governed by local processes on kpc scales or smaller, rather than by global processes at the scale of entire galaxies.

4. Discussion

This paper extends the findings of Paper I by utilizing the updated SwiM_{v4}.2 catalog, which is nearly four times larger than the earlier SwiM_{v3}.1 catalog used in Paper I. While Paper I primarily explored the correlations between dust attenuation properties and sSFR across all regions collectively, this study refines the analysis by categorizing regions into SF and non-SF subsets and incorporating a broader range of stellar population and emission-line properties. Given that sSFR is meaningful only for SF regions, we replace it with the specific surface brightness of $H\alpha$ emission, $\Sigma H\alpha/\Sigma$, *as a proxy for the strength of $H\alpha$ emission. Importantly, all key findings from Paper I are consistently reproduced in this work. However, we uncover a distinct anti-correlation between the NUV slope A and $\Sigma H\alpha/\Sigma$, a trend that was not evident in Paper I, likely due to the smaller sample size used in that study.*

When dividing all regions into SF and non-SF regions, we find that both types exhibit similar trends in optical attenuation properties (AV and AB/AV), which correlate in comparable ways with all the stellar population and emission-line properties examined. However, the NUV slope A behaves differently between the two, with SF regions generally displaying flatter slopes than non-SF regions. In addition to Paper I, the SwiM_{v3}.1 catalog has been used to investigate the relationship between NUV stellar attenuation (characterized by the NUV power-law index, β) and optical nebular attenuation (measured via the Balmer emission-line ratio) by Molina et al. (2020a), as well as the infrared excess-NUV

spectral index (IRX- β) relation by Duffy et al. (2023). Molina et al. (2020a) found that regions dominated by diffuse ionized gas (DIG) deviate from the relation observed in SF regions, suggesting that light from old stellar populations contributes to the scatter in this relation. Meanwhile, Duffy et al. (2023) reported that both β and IRX positively correlate with Dn4000 in SF regions, indicating a connection between dust attenuation in the NUV and stellar populations of different ages. These findings are consistent with our result that the NUV attenuation curve slope differs between SF and non-SF regions, reinforcing the notion that dust attenuation in the NUV is influenced by both young and old stellar populations in distinct ways.

The Swift/UVOT data have also been combined with far-infrared photometry from the SINGS/KINGFISH samples of nearby galaxies to investigate the impact of assumed star formation history (SFH) parameterizations on the derivation of attenuation laws from SED fitting (Belles et al. 2023). It was found that the NUV slope of attenuation curves varies depending on the assumed SFH form, a result that may be related to the correlation between the NUV slope and recent SFH diagnostics identified in this work. In a more recent study, Swift/UVOT photometry was combined with mid-infrared imaging from the PHANGS-JWST survey to investigate the connection between the 2175 Å bump and polycyclic aromatic hydrocarbons (PAHs; Battisti et al. 2025). Both the 2175 Å bump and PAH abundance were found to be negatively correlated with sSFR. This result is fully consistent with our previous findings from Paper I, which also measured the UV bump at 2175 Å and explored its correlations with sSFR. As pointed out in both Paper I and Battisti et al. (2025), the observed anti-correlation between the 2175 Å bump and sSFR suggests that the carrier of the UV bump is small dust grains that are susceptible to destruction by UV photons.

Theoretically, Narayanan et al. (2018) demonstrated that both the 2175 Å bump strength and the attenuation curve slope are primarily influenced by the fraction of unobscured young/massive stars, such that a higher fraction of these stars results in a flatter attenuation curve with a weaker 2175 Å bump. The positive correlations of A with stellar age and the negative correlations of A with specific H α surface brightness found in this work align well with the theoretical expectations from Narayanan et al. (2018). In fact, we have conducted the same analysis for the UV bump using the expanded SwiM_{v4}.2 catalog. The results of this investigation will be presented in the next paper of this series (Paper III, Guo et al. 2025, in preparation). In the fourth paper of this series (Paper IV, Guo et al. 2025, in preparation), we will use the attenuation curve measurements obtained in this study to constrain a two-component dust model. This model will allow us to derive the distributions of dust grain size and the fractional contributions of dust mass from silicate and graphite compositions. As we will show, the flattening of the NUV slope in SF regions with relatively high $\Sigma H\alpha/\Sigma^*$ and young stellar populations can be understood in terms of a lower fraction of small-sized dust grains in such regions. This aligns with the conclusion from Paper I that variations in NUV attenuation, including both the

attenuation curve slope and the 2175 Å bump, are driven by star formation-related processes, such as the destruction of small dust grains by UV radiation in SF regions. Moreover, this work extends that conclusion to non-SF regions, indicating that the UV radiation responsible for small dust grain destruction is not solely emitted by massive stars in SF regions but can also originate from other ionizing sources in non-SF regions.

Focusing solely on the optical regime, numerous studies have investigated spatially resolved dust attenuation in nearby galaxies at kiloparsec scales using integral field spectroscopy observations (e.g., Kreckel et al. 2013; Jimmy et al. 2016; Bassett et al. 2017; Li et al. 2019, 2020, 2021; Greener et al. 2020; Lin & Kong 2020; Teklu et al. 2020; Rupke et al. 2021; Ji et al. 2023; Li & Li 2024; Lin & Yan 2024). For instance, Teklu et al. (2020) estimated the optical attenuation curves for star-forming regions in MaNGA galaxies using the empirical method of Calzetti et al. (1994), finding that SF regions with relatively small values of Dn4000 ($1.1 < \text{Dn4000} < 1.2$) exhibit shallower average attenuation curves when they have lower surface stellar mass density, smaller SFR surface density, or are located in the outskirts of galaxies. In contrast, our analysis finds no significant correlations between the optical slope of attenuation curves and any of the regional or global properties considered. This discrepancy is likely due to differences in the methods used to derive attenuation curves. The empirical method adopted by Teklu et al. (2020) determines attenuation curves by comparing observed SEDs/spectra between dusty galaxies and those with little to no attenuation (e.g., Calzetti et al. 1994, 1997, 2000; Kinney et al. 1994; Johnson et al. 2007; Wild et al. 2011; Battisti et al. 2016, 2017a, 2017b). As noted by Wild et al. (2011), this approach can introduce bias, as the more attenuated galaxy in a pair will contribute more strongly to the final average curve if the attenuation curve slope depends on the dust attenuation itself, as observed in previous studies. Given the substantial variation in dust content across galaxies and the wide range of attenuation curve slopes, assuming a single attenuation form to rank and compare templates or paired galaxies is no longer appropriate (Salim & Narayanan 2020).

Our findings regarding the optical slope are in good agreement with those of Li et al. (2021), who also used IFS data from MaNGA but applied the new technique developed by Li et al. (2020) to derive attenuation curves. As demonstrated in these studies, our method allows attenuation curves to be obtained without assuming a predefined functional form, and it derives the attenuation curve before applying our spectral fitting code to derive stellar population properties, thereby significantly reducing the influence of degeneracies between model parameters. Although Li et al. (2021) did not explicitly examine the correlations between the optical curve slope and stellar population or emission-line properties, their results regarding the correlations of stellar and nebular reddening ($E(B - V)_{\text{star}}$ and $E(B - V)_{\text{gas}}$) with Dn4000 and stellar age are broadly consistent with our findings in this work.

Numerous previous studies have measured attenuation curves and investigated

their correlations with galactic properties at the scale of entire galaxies, covering both the local Universe and high redshifts. A recent review by Salim & Narayanan (2020) provides a comprehensive summary of these studies. In particular, the anti-correlation between the slope of attenuation curves and sSFR has been well established at galactic scales across a broad redshift range. Our findings from Paper I and the current work demonstrate that these global trends hold at kiloparsec scales in both SF and non-SF regions, regardless of the inclination of host galaxies or the galactocentric distance of regions. This further reinforces the idea that dust attenuation laws are primarily governed by local processes occurring on kpc scales or smaller, rather than by global mechanisms at the scale of entire galaxies.

5. Summary

This is the second paper in a series utilizing the SwiM catalog to investigate dust attenuation properties on kiloparsec scales in nearby galaxies. The SwiM catalog was constructed by cross-matching the Swift/UVOT data archive with the SDSS-IV/MaNGA sample, providing both integral field spectroscopy in the optical and NUV imaging in three bands (uvw1, uvm2 near 2175 Å, and uvw2; Molina et al. 2020b, 2023). This data set is particularly well-suited for studying dust attenuation in kpc-sized regions across optical and NUV wavelengths. In the first paper of this series (Zhou et al. 2023, Paper I), based on an earlier version of the SwiM catalog (SwiM_{v3}.1) supplemented with Ks-band imaging from 2MASS, we developed a novel method to measure dust attenuation curves. We explored the correlations of optical opacity (AV), the optical and NUV slopes of the attenuation curves (AB/AV and A), and the strength of the UV bump at 2175 Å with the specific sSFR of kiloparsec-sized regions.

In this study, we extend the work of Paper I by applying the same methodology to the latest version of the SwiM catalog, SwiM_{v4}.2, which is nearly four times larger than SwiM_{v3}.1. Additionally, we classify all regions into two subsets: SF and non-SF regions. Instead of sSFR, we use the specific surface density of H α emission ($\Sigma H\alpha / \Sigma^*$) to quantify the relative strength of H α emission, as sSFR is meaningful only for SF regions. Furthermore, we examine the correlations of AV, AB/AV and A with a broad range of stellar population and emission-line properties, including stellar age, stellar metallicity, gas-phase metallicity, and diagnostics of recent star formation history. Finally, we investigate the potential dependence of spatially resolved dust attenuation properties on the inclination of host galaxies and the galactocentric distance of the regions. To ensure reliable measurements of dust attenuation properties, and based on the tests of our method conducted in Paper I, we have restricted our analysis to regions with a continuum S/N greater than 20 and an optical opacity of AV > 0.25 . Our main conclusions can be summarized as follows:

1. Overall, when comparing SF and non-SF regions, we find that the optical attenuation properties, characterized by AV and AB/AV, exhibit similar correlations with all the stellar population and emission-line properties considered. In contrast, the NUV slopes in SF regions tend to be flatter

than those in non-SF regions, and this difference is mainly attributed to the relatively low surface densities of stellar mass in SF regions.

2. The optical slope of attenuation curves AB/AV shows little to no dependence on any of the stellar population or emission-line properties in both SF and non-SF regions. In contrast, the optical opacity AV exhibits a positive correlation with specific H α surface brightness (and related parameters), a negative correlation with stellar age (and related parameters), and no clear dependence on stellar or gas-phase metallicity. This is also true in both SF and non-SF regions.
3. The NUV slope of attenuation curves, A, exhibits an anti-correlation with specific H α surface brightness. This trend is primarily driven by the positive correlation between A and the stellar surface mass density, rather than by the correlation with H α surface brightness itself.
4. The NUV slope of attenuation curves flattens in SF regions that contain young stellar populations and have experienced recent star formation, but it shows no obvious dependence on stellar or gas-phase metallicity.
5. The spatially resolved dust attenuation properties exhibit no clear correlations with the inclination of host galaxies or the galactocentric distance of the regions. This finding reinforces the conclusion from Paper I that dust attenuation is primarily regulated by local processes on kpc scales or smaller, rather than by global processes at galactic scales.

Acknowledgments

This work is supported by the National Key R&D Program of China (grant No. 2022YFA1602902), the National Natural Science Foundation of China (grant Nos. 12433003, 11821303 and 11973030), and the China Manned Space Program through its Space Application System.

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

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

University, University of Notre Dame, Observatório Nacional/MCTI, The Ohio State University, Pennsylvania State University, Shanghai Astronomical Observatory, United Kingdom Participation Group, Universidad Nacional Autónoma de México, University of Arizona, University of Colorado Boulder, University of Oxford, University of Portsmouth, University of Utah, University of Virginia, University of Washington, University of Wisconsin, Vanderbilt University and Yale University.

We acknowledge the Tsinghua Astrophysics High-Performance Computing platform at Tsinghua University for providing computational and data storage resources that have contributed to the research results reported within this paper.

ORCID iDs

Ruonan Guo <https://orcid.org/0009-0008-4962-665X> Cheng Li <https://orcid.org/0000-0002-8711-8970> Shuang Zhou <https://orcid.org/0000-0002-8999-6814> Niu Li <https://orcid.org/0000-0002-0656-075X> Tao Jing <https://orcid.org/0009-0004-6271-4321> Zhuo Cheng <https://orcid.org/0009-0001-5437-410X>

References

Abdurro'uf, Accetta, K., Aerts, C., et al. 2022, ApJS, 259, 35 Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5 Balogh, M. L., Morris, S. L., Yee, H. K. C., Carlberg, R. G., & Ellingson, E. 1999, ApJ, 527, 54 Bassett, R., Glazebrook, K., Fisher, D. B., et al. 2017, MNRAS, 467, 239 Battisti, A. J., Calzetti, D., & Chary, R. R. 2016, ApJ, 818, 13 Battisti, A. J., Calzetti, D., & Chary, R. R. 2017a, ApJ, 851, 90 Battisti, A. J., Calzetti, D., & Chary, R. R. 2017b, ApJ, 840, 109 Battisti, A., Shvarei, I., Park, H. J., et al. 2025, PASA, 42, e022 Belfiore, F., Westfall, K. B., Schaefer, A., et al. 2019, AJ, 158, 160 Belles, A., Decleir, M., Bowman, W. P., et al. 2023, ApJ, 953, 54 Bertelli, G., Bressan, A., Chiosi, C., Fagotto, F., & Nasi, E. 1994, A&AS, 106, 275 Blanton, M. R., Bershady, M. A., Abolfathi, B., et al. 2017, AJ, 154, 28 Blanton, M. R., Kazin, E., Muna, D., Weaver, B. A., & Price-Whelan, A. 2011, AJ, 142, 31 Boquien, M., Buat, V., Burgarella, D., et al. 2022, A&A, 663, A50 Boquien, M., Burgarella, D., Roehlly, Y., et al. 2019, A&A, 622, A103 Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000 Bundy, K., Bershady, M. A., Law, D. R., et al. 2015, ApJ, 798, 7 Calzetti, D. 1997, AJ, 113, 162 Calzetti, D. 2001, PASP, 113, 1449 Calzetti, D., Armus, L., Bohlin, R. C., et al. 2000, ApJ, 533, 682 Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, ApJ, 429, 582 Cardelli, J. A., Clayton, G. C., & Mathis, J. S. 1989, ApJ, 345, 245 Chabrier, G. 2003, PASP, 115, 763 Clayton, G. C., Gordon, K. D., Bianchi, L. C., et al. 2015, ApJ, 815, 14 Clayton, G. C., & Martin, P. G. 1985, ApJ, 288, 558 Conroy, C. 2013, ARA&A, 51, 393 da Cunha, E., Charlot, S., & Elbaz, D. 2008, MNRAS, 388, 1595 Decleir, M., De Looze, I., Boquien, M., et al. 2019, MNRAS, 486, 743 Driver, S. P., Andrews, S. K., da Cunha, E., et al. 2018, MNRAS, 475, 2891 Drory, N., MacDonald, N., Bershady, M. A., et al. 2015, AJ, 149, 77 Duffy, L., Molina, M., Eracleous, M., et al. 2023, MNRAS, 526, 904 Faber, S. M. 1972, A&A, 20, 361 Ferreras, I., Tress, M., Bruzual, G., et al. 2021, MNRAS, 505, 283

Fitzpatrick, E. L. 1999, PASP, 111, 63 Fitzpatrick, E. L., & Massa, D. 1986, ApJ, 307, 286 Galliano, F., Galametz, M., & Jones, A. P. 2018, ARA&A, 56, 673 Gordon, K. D., & Clayton, G. C. 1998, ApJ, 500, 816 Gordon, K. D., Clayton, G. C., Misselt, K. A., Landolt, A. U., & Wolff, M. J. 2003, ApJ, 594, 279 Greener, M. J., Aragón-Salamanca, A., Merrifield, M. R., et al. 2020, MNRAS, 495, 2305 Gunn, J. E., Siegmund, W. A., Mannery, E. J., et al. 2006, AJ, 131, 2332 Hagen, L. M. Z., Siegel, M. H., Hoversten, E. A., et al. 2017, MNRAS, 466, 4540 Hoversten, E. A., Gronwall, C., Vanden Berk, D. E., et al. 2011, AJ, 141, 36 Humire, P. K., Dey, S., Ronconi, T., et al. 2025, arXiv:2501.15082 Hutton, S., Ferreras, I., Wu, K., et al. 2014, MNRAS, 440, 150 Hutton, S., Ferreras, I., & Yershov, V. 2015, MNRAS, 452, 1412 Ji, X., & Yan, R. 2020, MNRAS, 499, 5749 Ji, X., Yan, R., Bundy, K., et al. 2023, A&A, 670, A125 Jimmy, Tran, K.-V., Saintonge, A., et al. 2016, ApJ, 825, 34 Johnson, B. D., Leja, J. L., Conroy, C., & Speagle, J. S. 2019 Prospector: Stellar Population Inference from Spectra and SEDs, Astrophysics Source Code Library, ascl:1905.025 Johnson, B. D., Schiminovich, D., Seibert, M., et al. 2007, ApJS, 173, 392 Jones, G. T., Stanway, E. R., & Carnall, A. C. 2022, MNRAS, 514, 5706 Kauffmann, G., Heckman, T. M., White, S. D. M., et al. 2003, MNRAS, 341, 33 Kennicutt, R. C., Jr. 1998, ARA&A, 36, 189 Kinney, A. L., Calzetti, D., Bica, E., & Storchi-Bergmann, T. 1994, ApJ, 429, 172 Kreckel, K., Groves, B., Schinnerer, E., et al. 2013, ApJ, 771, 62 Law, D. R., Cherinka, B., Yan, R., et al. 2016, AJ, 152, 83 Law, D. R., Westfall, K. B., Bershady, M. A., et al. 2021, AJ, 161, 52 Law, D. R., Yan, R., Bershady, M. A., et al. 2015, AJ, 150, 19 Leja, J., Johnson, B. D., Conroy, C., van Dokkum, P. G., & Byler, N. 2017, ApJ, 837, 170 Li, C., Wang, T.-G., Zhou, H.-Y., Dong, X.-B., & Cheng, F.-Z. 2005, AJ, 129, 669 Li, H., Wuys, S., Lei, H., et al. 2019, ApJ, 872, 63 Li, N., & Li, C. 2023, ChPhB, 32, 039801 Li, N., & Li, C. 2024, ApJ, 975, 234 Li, N., Li, C., Mo, H., et al. 2020, ApJ, 896, 38 Li, N., Li, C., Mo, H., et al. 2021, ApJ, 917, 72 Lin, Z., & Kong, X. 2020, ApJ, 888, 88 Lin, Z., & Yan, R. 2024, A&A, 691, A201 Marino, R. A., Rosales-Ortega, F. F., Sánchez, S. F., et al. 2013, A&A, 559, A114 Molina, M., Ajgaonkar, N., Yan, R., et al. 2020a, MNRAS, 494, 4751 Molina, M., Ajgaonkar, N., Yan, R., et al. 2020b, ApJS, 251, 11 Molina, M., Duffy, L., Eracleous, M., et al. 2023, ApJS, 268, 63 Nagaraj, G., Forbes, J. C., Leja, J., Foreman-Mackey, D., & Hayward, C. C. 2022, ApJ, 932, 54 Nakajima, K., Ouchi, M., Xu, Y., et al. 2022, ApJS, 262, 3 Narayanan, D., Conroy, C., Davé, R., Johnson, B. D., & Popping, G. 2018, ApJ, 869, 70 Noll, S., Burgarella, D., Giovannoli, E., et al. 2009, A&A, 507, 1793 Papovich, C., Dickinson, M., & Ferguson, H. C. 2001, ApJ, 559, 620 Prevot, M. L., Lequeux, J., Maurice, E., Prevot, L., & Rocca-Volmerange, B. 1984, A&A, 132, 389 Rémy-Ruyer, A., Madden, S. C., Galliano, F., et al. 2014, A&A, 563, A31 Roming, P. W. A., Kennedy, T. E., Mason, K. O., et al. 2005, SSRv, 120, 95 Rupke, D. S. N., Thomas, A. D., & Dopita, M. A. 2021, MNRAS, 503, 4748 Salim, S., Boquien, M., & Lee, J. C. 2018, ApJ, 859, 11 Salim, S., Charlot, S., Rich, R. M., et al. 2005, ApJL, 619, L39 Salim, S., & Narayanan, D. 2020, ARA&A, 58, 529 Salim, S., Rich, R. M., Charlot, S., et al. 2007, ApJS, 173, 267 Sawicki, M., & Yee, H. K. C. 1998, AJ, 115, 1329 Skrutskie, M. F., Cutri, R. M., Stiening, R., et al. 2006, AJ, 131, 1163

Smee, S. A., Gunn, J. E., Uomoto, A., et al. 2013, AJ, 146, 32 Spinrad, H., & Taylor, B. J. 1971, ApJS, 22, 445 Teklu, B. B., Lin, Z., Kong, X., et al. 2020, ApJ, 893, 94 Wake, D. A., Bundy, K., Diamond-Stanic, A. M., et al. 2017, AJ, 154, 86 Weingartner, J. C., & Draine, B. T. 2001, ApJ, 548, 296 Westfall, K. B., Cappellari, M., Bershady, M. A., et al. 2019, AJ, 158, 231 Wild, V., Charlot, S., Brinchmann, J., et al. 2011, MNRAS, 417, 1760 Wuyts, S., Förster Schreiber, N. M., Lutz, D., et al. 2011, ApJ, 738, 106 Yan, R., Bundy, K., Law, D. R., et al. 2016a, AJ, 152, 197 Yan, R., Tremonti, C., Bershady, M. A., et al. 2016b, AJ, 151, 8 Zahid, H. J., Kudritzki, R.-P., Conroy, C., Andrews, B., & Ho, I. T. 2017, ApJ, 847, 18 Zhou, S., Li, C., Li, N., et al. 2023, ApJ, 957, 75 Zhou, S., Mo, H. J., Li, C., et al. 2019, MNRAS, 485, 5256

Note: Figure translations are in progress. See original paper for figures.

Source: ChinaXiv — Machine translation. Verify with original.