The Most Predictive Physical Properties for the Stellar Population Radial Profiles of Nearby Galaxies

Guangwen Chen1,2, Hong-Xin Zhang1,2,3, Xu Kong1,2,3, Zesen Lin1,2, Zhixiong Liang1,2, Xinkai Chen1,2, Zuyi Chen1,2, and Zhiyuan Song1,2

1 CAS Key Laboratory for Research in Galaxies and Cosmology, Department of Astronomy, University of Science and Technology of China, Hefei 230026, People’s Republic of China; guangwen@mail.ustc.edu.cn, hzhang18@ustc.edu.cn, sxkong@ustc.edu.cn
2 School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, People’s Republic of China

Abstract

We present a study on the radial profiles of the D4000, luminosity-weighted stellar ages \( \tau_L \), and luminosity-weighted stellar metallicities \( [Z/H]_L \) of 3654 nearby galaxies \((0.01 < z < 0.15)\) using the IPU spectroscopic data from the MaNGA survey available in the SDSS DR15, in an effort to explore the connection between median stellar population radial gradients (i.e., \( \nabla D4000 \), \( \nabla \tau_L \), \( \nabla [Z/H]_L \)) out to \(\sim 1.5 R_e \) and various galaxy properties, including stellar mass \( (M_*) \), specific star formation rate \((sSFR)\), morphologies, and local environment. We find that \(M_* \) is the single most predictive physical property for \( \nabla D4000 \) and \( \nabla [Z/H]_L \). The most predictive properties for \( \nabla \tau_L \) are sSFR and, to a lesser degree, \(M_* \). The environmental parameters, including local galaxy overdensities and central–satellite division, have virtually no correlation with stellar population radial profiles for the whole sample, but the \( \nabla D4000 \) of star-forming satellite galaxies with \( M_* \lesssim 10^{10} M_\odot \) exhibit a significant positive correlation with galaxy overdensities. Galaxies with lower sSFR have on average steeper negative stellar population gradients, and this sSFR dependence is stronger for more massive star-forming galaxies. The negative correlation between the median stellar population gradients and \(M_* \) are best described largely as segmented relationships, whereby median gradients of galaxies with \( log M_* \lesssim 10.0 \) (with the exact value depending on sSFR) have much weaker mass dependence than galaxies with higher \(M_* \). While the dependence of the radial gradients of ages and metallicities on T-Types and central stellar mass surface densities are generally not significant, galaxies with later T-Types or lower central mass densities tend to have significantly lower D4000, younger \( \tau_L \), and lower \( [Z/H]_L \) across the radial ranges probed in this study.

Unified Astronomy Thesaurus concepts: Galaxy evolution (594); Galaxies (573); Star formation (1569); Galaxy stellar content (621)

1. Introduction

The stellar population distribution within galaxies holds important clues to the assembly history of galaxies. In the classical dissipative collapse models of galaxy formation (e.g., Eggen et al. 1962; Larson 1974; Carlberg 1984; Pipino et al. 2010), the outer parts of galaxies have less efficient star formation and self-enrichment than the inner parts, due to lower gas densities and a shallower local potential well toward larger radii. In this framework, galaxies naturally develop significant negative abundance gradients and slightly positive stellar age gradients, with more massive galaxies having steeper gradient slopes than lower mass galaxies. In the modern \( \Lambda \) cold dark matter (\( \Lambda \)CDM) paradigm of hierarchical structure formation, present-day galaxies formed their central parts first, through either cold stream accretion or violent disk instabilities (e.g., Dekel et al. 2009) or galaxy merging, followed by a gradual buildup of galaxy disks from the inside out (e.g., Mo et al. 1998; Taylor & Kobayashi 2017), which gives rise to negative radial gradients of both metallicities and stellar ages. Galaxy mergers are expected to play an important role (especially) at early cosmic epochs in the \( \Lambda \)CDM framework. Gas-poor mergers of comparable-mass galaxies (i.e., major mergers) can flatten preexisting stellar population gradients (Kobayashi 2004; Di Matteo et al. 2009), while gas-rich major mergers may preserve or regenerate negative gradients (Bekki & Shioya 1999; Hopkins et al. 2009).

With the advent of large integral field unit (IFU) spectroscopic surveys in the past decade, such as the Calar Alto Large Integral Field Area (CALIFA; Sánchez et al. 2012), Sydney Australian Astronomical Observatory Multi-object Integral Field Spectrograph (SAMI; Bryant et al. 2015), and Mapping Nearby Galaxies at the Apache Point Observatory (MaNGA; Bundy et al. 2015), it has become possible to obtain the spatial distribution of luminosity-weighted stellar ages and chemical abundances of large samples of galaxies in the local universe, which enables a direct investigation of the connection between stellar population gradients and other galaxy properties and thus a relatively straightforward test of galaxy formation models in general.

On one hand, the stellar population gradients are expected to be affected by the internal properties of galaxies. Studies of the radial profiles or gradients of the stellar ages and metallicities for over a hundred CALIFA galaxies (e.g., Pérez et al. 2013; González Delgado et al. 2014) revealed that the assembly of stellar mass and the cessation of star formation proceed from the galactic centers to the outskirts for massive galaxies, in line with the so-called “inside-out” growing mode, and there seems to be a negative correlation between stellar population gradients and stellar mass, which may naturally connect to the “outside-in” mode found for many nearby dwarf galaxies (Zhang et al. 2012). These findings agree well with previous studies of the radial stellar gradients based on multiwavelength
broadband photometry (e.g., Tortora et al. 2010; Gonzalez-Perez et al. 2011; Pan et al. 2015, 2016). Recent studies found more complicated dependences of stellar population gradients on stellar mass or other properties based on larger samples from the CALIFA survey (e.g., García-Benito et al. 2017; González Delgado et al. 2017) and the MaNGA survey (e.g., Ibarra-Medel et al. 2016; Goddard et al. 2017a; Ellison et al. 2018; Wang et al. 2018b). In particular, the radial gradients of metallicities were found to depend on morphologies (e.g., Hubble type) rather than stellar mass in González Delgado et al. (2015). Woo & Ellison (2019) found that the radial gradients of stellar age, specific star formation rates (sSFR), and abundance (O/H) for isolated galaxies rely on the galaxy’s position on the diagram of stellar mass surface density within 1 kpc ($\Sigma_{1\text{kpc}}$) and stellar mass. Based on a study of 62 spiral galaxies, Sánchez-Blázquez et al. (2014) claimed that there is no dependence of stellar population radial gradients on stellar mass or morphological types when gradients are normalized to the effective radius of galaxy disks.

On the other hand, the environment of galaxies might also play a nonnegligible role in regulating the radial stellar population gradients. Schaefer et al. (2017) found that the SFR gradients are steeper in higher local galaxy density based on 201 SFGs from the SAMI survey. However, the radial gradients of stellar age and metallicity have also been found to be independent of environmental parameters (e.g., the large-scale structure type and the local density in Zheng et al. 2017; the tidal strength parameter and the central–satellite division in Goddard et al. 2017b).

Above all, it is not clear whether and how different galaxy properties (either internal or external) affect the radial distribution of the stellar population in nearby galaxies. In this work, taking advantage of IFU observations of a large sample of nearby galaxies from the most recent data release of SDSS-IV MaNGA survey, we attempt to explore the connection of stellar population radial gradients with other galaxy properties such as stellar mass, star formation, morphologies, and environments. Unlike most previous surveys that are either flux limited or volume limited, the MaNGA survey is designed to have a more or less uniform coverage in stellar mass. A series of recent studies have used the stellar population radial profiles of MaNGA galaxies to explore the general topic of galaxy quenching (e.g., Li et al. 2015; Goddard et al. 2017a; Belfiore et al. 2018; Wang et al. 2018b). The current paper focuses on a straightforward question: What physical properties are closely connected to the observed stellar population gradients of nearby galaxies?

The outline of this paper is as follows. In Section 2, we describe our sample selection, determination of the radial gradients of D4000 indices, luminosity-weighted stellar ages, and luminosity-weighted stellar metallicities, as well as various morphological and environmental properties to be explored in this work. The results are presented in Section 3, and the summary and discussion of our primary results follow in Section 4.

2. Data

2.1. Sample and Selection

As one of the three core programs in the fourth-generation Sloan Digital Sky Survey (SDSS-IV; Albareti et al. 2017; Blanton et al. 2017), MaNGA (Bundy et al. 2015; Yan et al. 2016a, 2016b) is an ongoing integral field spectroscopic (IFS) survey for obtaining twodimensional spectral mapping of $\sim$10,000 nearby galaxies (0.01 < z < 0.15). MaNGA covers the wavelength range between 3600 and 10300 Å with a spectral resolution of R $\sim$ 2000 (Drory et al. 2015). The sizes of the IFUs vary from 19 to 127 fibers, covering $12''$–$32''$ on the sky. The effective spatial resolution is 2''/5 (Law et al. 2015, 2016).

In this work, we use the reduced data from the MaNGA Pipe3D Value Added Catalog (VAC; Sánchez et al. 2018) available in SDSS DR15 (Aguado et al. 2019). SDSS DR15 includes 4656 MaNGA galaxies. Pipe3D provides spectroscopic redshift, star formation rate (SFR) derived from the H$\alpha$ luminosities, and stellar mass for each galaxy. Because the Pipe3D SFRs and stellar masses are consistently estimated based on the MaNGA data, we use their ratios to quantify the sSFR for our galaxies. In addition, the NASA Sloan Atlas catalog (NSA; Blanton et al. 2011) provides auxiliary galaxy properties, such as the galaxy effective radius ($R_e$), axis ratio ($b/a$), position angle, Sérsic index ($n$) measured in the $r$ band, and stellar masses for SDSS galaxies. The NSA stellar masses are determined based on the SDSS imaging data and are expected to be a better representation of the total stellar masses than those based on the MaNGA data. Throughout this paper, we use the NSA stellar masses $M_*$ except when exploring the mass–SFR relations (Figure 1(a)), where the Pipe3D stellar masses (and SFR) are used. Because the Pipe3D stellar parameters used in this work are based on the Salpeter (1955) initial mass function (IMF), we adjust the NSA stellar masses, which were originally based on the Chabrier (2003) IMF, to be consistent with the Salpeter (1955) IMF.

Following the quality control catalog included in the Pipe3D VAC, 84 of the 4656 galaxies have either wrong redshift, poor signal-to-noise ratio (S/N), or other warning issues and are thus excluded from our sample. In addition, 532 galaxies that were observed with the 19-fiber IFUs are also excluded from our final sample because the radial gradients estimated using the low spatial-resolution IFUs may be subject to relatively large biases (e.g., Ibarra-Medel et al. 2018). We also exclude 140 galaxies that have minor-to-major axis ratios ($b/a$) less than 0.3. We further restrict our analysis in this paper to galaxies with $0.01 < z < 0.15$, $10^6 M_\odot \lesssim M_* \lesssim 10^{12} M_\odot$, and $10^{-5} M_\odot yr^{-1} < SFR < 10^4 M_\odot yr^{-1}$ and abandon galaxies without calculations of radial stellar population gradients (Section 2.2), which leaves us with 3654 galaxies in total. Both the “Primary” and “Secondary” MaNGA samples are used in this work.

Figure 1(a) shows the stellar mass–SFR distribution of our sample galaxies. We divide our sample into galaxies above (MS+)–1132 galaxies and below (MS−)–1222 galaxies) the galaxy star formation main-sequence (SFMS) relation, and quiescent galaxies (QGs; 1300 galaxies) by using the lines of demarcation from Cano-Díaz et al. (2019).

2.2. Radial Stellar Population Gradients

Two-dimensional maps of the 4000 Å break (D4000) and stellar population parameters, including the surface density of stellar mass, linear values of the luminosity-weighted stellar age ($\tau_L$), and logarithmic values of the luminosity-weighted stellar metallicity ([Z/H]$_L$), are retrieved from Pipe3D pipeline. We choose to use the D4000 index as a representative age-sensitive observable, because this broad feature can be measured with relatively small uncertainties (<10%) compared
to other commonly used absorption features (e.g., Hβ line) at spectral S/Ns down to $\gtrsim 1/\AA$ (Cardiel et al. 1998). This practical advantage is particularly relevant for a comparative analysis of galaxies or regions with different luminosities or surface brightnesses, as is presented in this work.

The model-dependent stellar population parameters $\tau_e$ and $[Z/H]_L$ from Pipe3D are derived through stellar population synthesis modeling of the MaNGA spectra, as described in Sánchez et al. (2016a, 2016b). Pipe3D also produces mass-weighted stellar ages and metallicities. Generally speaking, stellar population parameters estimated from integrated spectra of unresolved (sub)galactic regions are biased toward younger stellar populations, and the constraints on older stellar populations are unavoidably subject to larger uncertainties. On the other hand, the stellar mass contribution of relatively old stellar populations in local galaxies usually dominates over that of young stellar populations. Therefore, the very poor constraints on star formation history (SFH) at ancient times means that the mass-weighted stellar parameters derived from integrated spectra are subject to substantially larger uncertainties than the luminosity-weighted ones, which may frustrate any attempt to obtain useful estimates of mass-weighted parameters for a comparative study as presented in this work. Throughout this paper, our discussion of stellar ages and metallicities is focused on the luminosity-weighted ones, but we also present the relevant results based on mass-weighted ones in the Appendix (Figures A1, A2, and A3).

We derive the radial gradient slopes of the D4000, $\tau_e$, and $[Z/H]_L$ of each galaxy by performing linear least-squares fitting to the median radial profiles. Specifically, we first calculate the deprojected galactocentric distance of each spaxel by using the observed axis ratio of its host galaxy. Then, we obtain radial profiles of D4000, $\tau_e$, and $[Z/H]_L$ by calculating the median D4000, $\tau_e$, and $[Z/H]_L$ of spaxels falling within the 2σ wide concentric elliptical annuli. The radial gradient slopes are derived via linear least-squares fitting to the median radial profiles, defined as

$$\nabla \text{D4000} = \frac{d\text{D4000}}{d(R/R_e)},$$

$$\nabla \tau_e = \frac{d\tau_e [\text{Gyr}]}{d(R/R_e)},$$

$$\nabla [Z/H]_L = \frac{d[Z/H]_L}{d(R/R_e)},$$

where $R/R_e$ is the radius in units of the effective radius. A negative $\nabla \text{D4000}$ represents a larger D4000 in the galactic center compared to its outskirts, corresponding to the inside-out scenario, while a positive $\nabla \text{D4000}$ is consistent with the outside-in scenario. We note that only spaxels with S/N $\geq 10/\AA$ are used for calculating the medians, and only radial bins containing $\geq 5$ data points with S/N $\geq 10/\AA$ are used in the gradient determination. Although the MaNGA “Secondary” sample observations extend to $\sim 2.5 R_e$, we only analyze their radial profiles out to $\sim 1.5 R_e$ in order to be consistent with the “Primary” sample.

It is worth noting that we choose to quantify the gradients of ages on linear scales instead of the logarithmic scales that were adopted in many previous studies. The same linear age gradient corresponds to flatter logarithmic age gradients at older ages than at younger ages, which may give one a misleading impression that stellar age gradients flatten over time. Indeed, we found that the logarithmic age gradients become significantly flatter for galaxies with lower sSFR (not shown here), but the linear age gradients barely show such a trend (Figure 3).

2.3. Morphological Properties

In order to quantify the morphological dependence of stellar population radial profiles of our galaxies, we consider four morphological parameters, i.e., T-Type, stellar mass surface density averaged within the central 1 kpc ($\Sigma_{1 \text{kpc}}$), central velocity dispersion ($\sigma_{\text{cen}}$), and Sérsic index $n$ (Sérsic 1968).
The T-Type values are retrieved from the MaNGA PyMorph Photometric and Deep Learning Morphological Catalogs (Fischer et al. 2019). \( \Sigma_{1\ kpc} \) is calculated by summing up the stellar mass map within the central 1 kpc of each galaxy. \( \sigma_{cen} \) is retrieved from the Pipe3D VAC (Sánchez et al. 2018), and the Sérsic index \( n \) is retrieved from the NSA catalog (Blanton et al. 2011).

The T-Type values of our sample galaxies are quantified as \( T = -4.6 \times P(\text{EII}) - 2.4 \times P(\text{SII}) + 2.5 \times P(\text{SAb}) + 6.1 \times P(\text{Sed}) \) (Meert et al. 2015), where \( P \) is the probability of the morphological class indicated in parentheses (Huertas-Company et al. 2011). This T-Type definition has been extensively used to quantify the visual morphologies of galaxies (e.g., Nair & Abraham 2010; Willett et al. 2013; Domínguez Sánchez et al. 2018). According to this definition, elliptical and S0 galaxies (ETG) have T-Types \( \leq 0 \), while late-type disk galaxies (LTG) have T-Types \( > 0 \).

\( \Sigma_{1\ kpc} \) has been widely used to quantify the central stellar mass surface densities (Fang et al. 2013; Wang et al. 2018a; Woo & Ellison 2019). There is a well-established correlation between \( \Sigma_{1\ kpc} \) and \( M_* \) (e.g., Figure 1(b)). We perform piecewise linear least-squares fitting to log \( \Sigma_{1\ kpc} \) as a function of log \( M_* \) for our galaxies. The best-fit broken linear relation is log \( \Sigma_{1\ kpc} = 0.93(\log M_* - 10.95) + 9.44 \) for \( \log M_* \leq 10.95 \), log \( \Sigma_{1\ kpc} = 0.13(\log M_* - 10.95) + 9.44 \) for \( \log M_* > 10.95 \). In what follows, we use the vertical offset of log \( \Sigma_{1\ kpc} \) (\( \Delta \log \Sigma_{1\ kpc} \)) with respect to this best-fit log \( \Sigma_{1\ kpc} \) to quantify the relative excess or deficit of the central stellar mass of each galaxy for its \( M_* \). We note that, at given stellar masses, the \( \Delta \log \Sigma_{1\ kpc} \) difference is more or less equivalent to the logarithmic difference of the bulge-to-total mass ratios \( (B/T) \).

2.4. Environmental Parameters

In order to explore the environmental dependence of stellar population radial profiles, we separate our sample into central and satellite galaxies by using the halo-based group catalog of SDSS galaxies derived by Lim et al. (2017), and then use the projected local galaxy overdensity within a projected distance to the fifth nearest neighbor to quantify the local environment of each galaxy. The Lim et al. (2017) group catalog improves upon that of Yang et al. (2005, 2007) and Lu et al. (2016), with a more uniform group halo assignment over a wider range of halo masses \( M_{\text{halo}} \). The local overdensities are quantified as log \( \langle 1 + \delta \rangle = \log (1 + (\rho_i - \rho_{\text{m}})/\rho_{\text{m}}) \) (Etherington & Thomas 2015), where \( \rho_i \) is the local galaxy number density and \( \rho_{\text{m}} \) is the mean galaxy number density. Among our sample galaxies, 2569 have log \( \langle 1 + \delta \rangle \) measurements available in the Galaxy Environment for MaNGA Value Added Catalog (GEMAGA-VAC; M. Argudo-Fernández et al. 2020, in preparation), and among these 2569 galaxies, 2543 have available central–satellite division (1699 centrals and 844 satellites).

3. Results

This section is devoted to an exploration of the connection of the radial profiles of D4000, \( \tau_\alpha \), and [Z/H]_L with the various galaxy properties introduced above. We first present an evaluation of the relative importance of different galaxy properties in predicting \( \Delta \log D4000, \Delta \tau_\alpha, \) and \( \Delta [Z/H]_L \), as well as the average D4000, \( \tau_\alpha \), and [Z/H]_L within 0.5 effective radius (i.e., D4000_{cen}, \( \tau_{\alpha\text{cen}} \), and [Z/H]_{L,cen}) and around one effective radius (i.e., D4000_{R_e}, \( \tau_{\alpha\text{R_e}} \), and [Z/H]_{L,R_e}). Of our sample galaxies using a Random Forests (RF; Breiman 2001) algorithm, and then present the dependence of stellar population profiles on the most relevant galaxy properties separately.

3.1. The Most Predictive Properties for Stellar Population Profiles

We adopt the RF estimator implemented in the Python package SCIKIT-LEARN (Pedregosa et al. 2011) to evaluate the relative importance of different galaxy properties in predicting \( \Delta \log D4000, \Delta \tau_\alpha, \) and \( \Delta [Z/H]_L \), as well as D4000_{cen}, \( \tau_{\alpha\text{cen}} \), [Z/H]_{L,cen}, D4000_{R_e}, \( \tau_{\alpha\text{R_e}} \), and [Z/H]_{L,R_e}. The RF algorithm is an ensemble method commonly used in astrophysics not only for classification (e.g., Dubath et al. 2011; Richards et al. 2011), but also in regression (e.g., Miller et al. 2015), where the prediction can be for a real-valued response variable. More details of the decision tree regression can be found in Hastie et al. (2009) and Kuhn & Johnson (2013). Basically, the RF estimator fits a number of decision tree classifiers on various subsamples randomly drawn with replacement from our galaxy sample and uses the averaging of individual decision trees to improve the predictive accuracy. Every decision tree in the ensemble is trained by using a random selection of features (i.e., the galaxy properties we are interested in) to split galaxy samples belonging to the tree. The more often a feature is used in splitting galaxies of a tree, the more important that feature is, and the final relative importance of the different galaxy properties in predicting our stellar population parameters of interest is simply the average of feature importances of individual trees in the ensemble.

Because a fraction of our galaxies do not have log \( (1 + \delta) \) measurements, we run the RF estimator separately on the full sample to evaluate the relative importance of \( M_* \), sSFR, T-Type, \( \Delta \log \Sigma_{1\ kpc} \), \( \sigma_{cen} \), and Sérsic index \( n \), and on the subsample of 2569 galaxies with log \( (1 + \delta) \) measurements for the relative importance of \( M_* \), sSFR, T-Type, \( \Delta \log \Sigma_{1\ kpc} \), \( \sigma_{cen} \), \( n \), and log \( (1 + \delta) \). The most important parameters for setting up the RF estimator are the number of decision trees (n_estimators) and the minimum number/fraction of samples for node splitting (min_samples_split). The minimum number/fraction of samples at a split leaf node (min_samples_leaf) is set to be min_samples_split/2. After extensive testing, we find that the final results do not change with n_estimators as long as n_estimators \( \geq 100 \). The exact values of the feature importance vary with min_samples_split, but we note that the overall ranking of the relative importances of the top features (or galaxy properties) do not change qualitatively for our galaxy sample, as long as a reasonably small or large min_samples_split is used (e.g., min_samples_split = 0.1%–10% of the number of our galaxies). Lastly, we mention that the two criteria for measuring the quality of tree splitting “MSE” and “MAE” supported in the RF estimator give nearly the same results for our samples, and we choose to use the “MSE” criterion for presenting our results.

Figure 2 presents the RF ranking results by using n_estimators = 1000 and min_samples_split = 1%. The left column shows the results for radial gradients, while the right column shows the results for average stellar population parameters at the galaxy center and near one effective radius, respectively. For the sake of clarity, only subsamples with local overdensity measurements are considered for the average stellar population parameters. The coefficient of determination \( R^2 \) for each RF run, which quantifies the fraction of variance of
the data that is “explained” by the model, is indicated in Figure 2. $R^2$ normally ranges from 0.0 to 1.0 (best), but may go negative when the model is arbitrarily worse. The relative feature importance for a given RF run is normalized such that the sum for all the explored properties is equal to one.

3.1.1. Ranking of Galaxy Properties for Radial Gradients

For radial gradients, it is obvious that $M_*$ is the most predictive property for $\nabla D4000$ (top-left panel of Figure 2), and the next two most predictive properties for $\nabla D4000$ are, in order of decreasing importance, sSFR and T-Type. The first three most predictive properties combined account for $\sim$80% of the total feature importances. It is noteworthy that local galaxy overdensities have a very weak correlation with $\nabla D4000$. We also explored the importance of being central or satellite galaxies (not shown here) and found that the central–satellite division has almost zero predictive power for $\nabla D4000$.

D4000 varies with both stellar ages and metallicities. The middle and bottom panels of the left column of Figure 2 show the RF ranking results for $\nabla \tau_L$ and $\nabla [Z/H]_L$, respectively. sSFR and, to a lesser degree, $M_*$ are the two most predictive properties for $\nabla \tau_L$, while $M_*$ is the single most predictive property for $\nabla [Z/H]_L$. Therefore, the apparent dependence of $\nabla D4000$ on $M_*$ is primarily a metallicity effect, while the apparent dependence of $\nabla D4000$ on sSFR is primarily an age effect.

3.1.2. Ranking of Galaxy Properties for Stellar Populations at Center and One Effective Radius

As is shown in the right column of Figure 2, the sSFR is the single most predictive property for D4000 and $\tau_L$ at both the...
As the second most predictive property for local $D4000$ and $\tau_L$, the central velocity dispersion $\sigma_{\text{cen}}$ has a significantly smaller predictive power than sSFR. For central $[\text{Z}/\text{H}]_L$, $M_*$ is the most predictive property. However, at one effective radius, sSFR is the single most predictive property for $[\text{Z}/\text{H}]_L$, similar to $D4000$ and $\tau_L$.

### 3.2. Dependence of Stellar Population Gradients on Stellar Mass and sSFR

The whole sample is split into three stellar mass bins: $9 \leq \log M_* [M_\odot] \leq 10$ (low-mass galaxies), $10 < \log M_* [M_\odot] \leq 11$ (intermediate-mass galaxies), and $11 < \log M_* [M_\odot] \leq 12$ (high-mass galaxies). Figure 3 shows the variation of $\nabla D4000$ (top row), $\nabla \tau_L$ (middle row), and $\nabla [\text{Z}/\text{H}]_L$ (bottom row) with integrated sSFR for galaxies in the three stellar mass bins (from the first to the third columns). In each panel, MS+, MS−, and QGs are plotted with blue, green, and red symbols, respectively. The median curves for the $25$–$75$% quantiles of the galaxy distribution are calculated by using the Comprehensive R Archive Network (CRAN) package Constrained B-Splines (COBS; Ng & Maechler 2007, 2020), which gives qualitatively constrained smoothing spline curves. To determine the uncertainties of the median curves, we randomly resample with replacement the original sample 1000 times. The two dashed horizontal lines divide the sample into MS+ (blue dots), MS− (green dots), and QG (red dots) subsamples. The number of galaxies in each stellar mass bin is given in parentheses at the top of the corresponding column.
more or less constant negative value as sSFR falls $\gtrsim 1$ dex below the SFMS, corresponding roughly to the regime occupied by QGs. In contrast to the higher mass bins, the median $\nabla D4000$ of the low-mass galaxies stays close to zero until sSFR falls $> 2$ dex below the SFMS. In addition, the median $\nabla D4000$ values at a given sSFR are smaller (i.e., more negative) for more massive galaxies. The median $\nabla \tau_L$ exhibits a similar variation with sSFR at given $M_*$, in line with the RF ranking results that the sSFR dependence of $\nabla D4000$ is primarily driven by stellar age effect (Section 3.1). The median $\nabla [Z/H]_L$ becomes more negative as sSFR decreases for intermediate-mass galaxies but stays more or less constant for the low- and high-mass galaxies.

Figure 4 further illustrates a continuous mass-dependent variation of the median $\nabla D4000$, $\nabla \tau_L$, and $\nabla [Z/H]_L$ for the MS+, MS−, and QG subsamples. Smoothing curves depicting the 25%−50%(median)−75% quantities of the galaxy distribution as well as the uncertainties of the medians for different subsamples are calculated in the same way as in Figure 3. The mass-dependent variations for star-forming galaxies generally follow much shallower slopes at log $M_* \lesssim 10.0$−10.5, above which the MS− subsample exhibits significantly steeper slopes than the MS+ subsample for $\nabla D4000$ and $\nabla \tau_L$. It is noteworthy that while the median $\nabla [Z/H]_L$ monotonically decreases with $M_*$ across the whole mass range, the median $\nabla \tau_L$ of MS− galaxies reaches the most negative values at log $M_* \sim 10.8$ and stays more or less constant at larger masses.

We further use the Spearman’s rank correlation coefficients $\rho$ to measure the correlation between stellar population gradients and stellar mass for each subsample. We also determine the standard deviation of $\rho$ based on random resampling of the original samples with replacement. As indicated in Figure 4, there exist significant correlations ($\rho > 0.2$) between the explored radial gradients and stellar masses, except for the $\nabla \tau_L$ of the QG subsample.

### 3.3. Dependence of Stellar Population Profiles on Galaxy Morphologies

We have shown that stellar mass and sSFR are the two parameters that have the strongest correlation with stellar population gradients in previous sections. Here we explore the secondary dependence of stellar population gradients on morphological properties, as quantified by T-Type and $\Delta \log \Sigma_{1\, \text{kpc}}$, by controlling the stellar mass and sSFR. The dependence of the median $\nabla D4000$, $\nabla \tau_L$, and $\nabla [Z/H]_L$ on T-Type and $\Delta \log \Sigma_{1\, \text{kpc}}$ for MS+, MS−, and QGs in the three stellar mass bins defined in Section 3.2 are presented in Figures 5 and 7. The smoothing curves of the 25%−50%(median)−75% quantities shown in Figures 5 and 7 are derived in the same way as in previous sections. Correlations with the Spearman’s rank correlation coefficient $\rho > 0.2$ are regarded significant. In Figures 5 and 7, median smoothing curves for subsamples with significant correlations are plotted as solid lines, whereas those with insignificant correlations are plotted as dashed lines.

To illustrate the radial profile variations of $D4000$, $\tau_L$, and $[Z/H]_L$ with T-Type and $\Delta \log \Sigma_{1\, \text{kpc}}$, we divide our samples into separate bins of T-Type ($< 0$ and $> 0$) and $\Delta \log \Sigma_{1\, \text{kpc}}$ ($> 0$ and $\leq 0$), and show their respective median radial profiles in Figures 6 and 8. In the following subsections, we present the dependence of the median radial profiles and gradients on T-Type and $\Delta \log \Sigma_{1\, \text{kpc}}$ separately.

#### 3.3.1. Dependence on T-Type

As shown in Figure 5, galaxies of higher stellar masses generally have more negative median $\nabla D4000$, $\nabla \tau_L$, and $\nabla [Z/H]_L$ at given T-Type and sSFR ranges. The median $\nabla D4000$ and $\nabla \tau_L$ are generally more negative at later T-Types for given mass and sSFR ranges. However, we point out that the overall negative correlation between $\nabla \tau_L$ and T-Types is not significant for all but the intermediate-mass MS+ and high-mass MS− subsamples. There is no significant correlation between T-Types and $\nabla [Z/H]_L$ for any subsamples. Nevertheless, the median $D4000$, $\tau_L$, and $[Z/H]_L$ of earlier-type (smaller T-Type) galaxies are generally larger than that of later-type (larger T-Type) galaxies across the probed radial ranges for any given mass and sSFR ranges (Figure 6).

The overall more significant negative correlation between $\nabla D4000$ and T-Types than that between $\nabla \tau_L$ and T-Types may be qualitatively explained by the fact that the derivative of $D4000$ with respect to age decreases with age for a passively evolving stellar population. The same stellar age radial gradient results in a shallower $D4000$ radial gradient for earlier T-Types, which tend to have overall older ages. We can conclude here
that morphological type is a property that is connected with galaxy stellar populations largely in a radius-independent way.

### 3.3.2. Dependence on $\Delta \log \Sigma_{1\text{kpc}}$

As with T-Types, galaxies of higher stellar masses generally have more negative median $\nabla D4000$, $\nabla \tau_L$, and $\nabla [Z/H]_L$ at given $\Delta \log \Sigma_{1\text{kpc}}$ and sSFR ranges. While the dependence of $\nabla D4000$ on $\Delta \log \Sigma_{1\text{kpc}}$ is generally not significant except for the low- and intermediate-mass MS+ subsamples, the median trend is generally in the opposite sense with that on T-Types (Figure 7), which probably reflects the expected negative correlation between T-Types and central mass concentrations in general. Particularly, the $\nabla D4000$ of the low- and intermediate-mass MS+ subsamples exhibit significant positive correlations with $\Delta \log \Sigma_{1\text{kpc}}$, and the median $\nabla D4000$ becomes positive at the high $\Delta \log \Sigma_{1\text{kpc}}$ end. Such positive dependence on $\Delta \log \Sigma_{1\text{kpc}}$ is also found for the median $\nabla \tau_L$. Therefore, the low- and intermediate-mass MS+ galaxies with higher $\Delta \log \Sigma_{1\text{kpc}}$ tend to have more centrally concentrated star formation activities. The correlation between $\nabla [Z/H]_L$ and $\Delta \log \Sigma_{1\text{kpc}}$ is generally very weak. Although the dependence of radial gradients on $\Delta \log \Sigma_{1\text{kpc}}$ is overall weak, galaxies with higher $\Delta \log \Sigma_{1\text{kpc}}$ have on average larger $D4000$, older $\tau_L$, and higher $[Z/H]_L$ than those with smaller $\Delta \log \Sigma_{1\text{kpc}}$ across the probed radial ranges for any given mass and sSFR ranges (Figure 8), which suggests that, similar to T-Types, central stellar mass concentration is a property that is connected with galaxy stellar populations largely in a radius-independent way.

### 3.4. Dependence of Stellar Population Profiles on Environments

As in Section 3.3, we also explored the dependence of the median $\nabla D4000$, $\nabla \tau_L$, and $\nabla [Z/H]_L$ on local galaxy overdensities $\log (1 + \delta)$ for both central and satellite subsamples, but did not find significant correlations for all but the low-mass star-forming satellite galaxies which exhibit positive correlations between $\nabla D4000$ and local overdensities ($\rho > 0.2$) and may indicate a suppression of star formation at larger radii by tidal disturbances of nearby galaxies. The corresponding plots are not shown here for clarity. The median coadded radial

![Figure 5. Dependence of stellar population gradients on T-Types. Results for $\nabla D4000$, $\nabla \tau_L$, and $\nabla [Z/H]_L$ are shown respectively in the top, middle, and bottom rows. Galaxies that fall in the low ($9 \leq \log M_* < 10$), intermediate ($10 \leq \log M_* < 11$) and high ($11 \leq \log M_* < 12$) stellar mass ranges are plotted, respectively, in the left, middle, and right columns. In each panel, MS+, MS–, and QGs are plotted in blue, green and red colors, respectively. The 25%–50%(median)–75% quantities of the subsample galaxies with $1\sigma$ uncertainties of the median smoothing curve and the Spearman correlation coefficients $\rho$ with uncertainties for the subsamples are calculated in the same way as Figure 4. Note that the existence of a correlation is only confirmed for $\rho > 0.2$ (solid line), and those with insignificant correlations are plotted as dashed lines.](image-url)
files for central and satellite galaxies with $\log(1 + \delta) > 0.5$ and $\leq 0.5$ are shown in Figure 9. For given stellar masses and sSFR, star-forming galaxies located in a higher $\log(1 + \delta)$ environment have slightly (albeit systemically) larger D4000, older $\tau_L$, and higher $[Z/H]_L$ than those located in lower $\log(1 + \delta)$ environment across the probed radial ranges. Therefore, the local environment has influence on galaxy stellar populations in a global sense for all star-forming galaxies, and also in a local sense for low-mass star-forming galaxies.

**4. Summary and Discussion**

**4.1. Summary of Major Results from This Work**

Based on IFU spectroscopic data of a large sample of 3654 nearby galaxies with $10^9 M_\odot \leq M_s \leq 10^{12} M_\odot$ from the MaNGA survey available in the SDSS DR15, we have explored the dependence of radial profiles of stellar populations, as quantified by the nearly extinction-free observable D4000, and the model-dependent luminosity-weighted stellar ages $\tau_L$, and luminosity-weighted stellar metallicities $[Z/H]_L$, on various galaxy properties. We find that $M_*$ is the most predictive global physical property for the D4000 radial gradients $\nabla D4000$, and the next most predictive properties for $\nabla D4000$, in order of decreasing importance, are sSFR, T-Type, and $\Delta \log \Sigma_1$ kpc. The strongest predictive power of $M_*$ on $\nabla D4000$ reflects the strongest predictive power of $M_*$ on the metallicity gradient $\nabla [Z/H]_L$. The first and second most predictive properties for the age gradient $\nabla \tau_L$ are sSFR and $M_*$, respectively. The local environment quantified by the galaxy overdensities $\log(1 + \delta)$ have overall very weak predictive power for radial gradients of the whole sample, but star-forming satellite galaxies with $M_* \lesssim 10^{10} M_\odot$ exhibit a positive correlation between $\nabla D4000$ and $\log(1 + \delta)$, which may imply a significant suppression of star formation activities of relatively low-mass galaxies at large radii by tidal disturbances of nearby galaxies.
Regarding local stellar population values, the sSFR and, to a much lesser degree, the central velocity dispersion are the most predictive global properties for D4000 and $\tau_L$ values at both the galaxy center and effective radius for our sample. For local $[Z/H]_L$, $M_*$ is the most predictive property at the galaxy center, while sSFR is the single most predictive property at one effective radius. The environmental properties, as quantified by $\log (1 + \delta)$ and the central–satellite division, have virtually no correlation with galaxy stellar populations for the whole sample, but star-forming galaxies located in a higher $\log (1 + \delta)$ environment have on average larger D4000, older $\tau_L$, and higher $[Z/H]_L$ across the probed radial ranges, without regard for being central or satellite.

The correlation of stellar population gradients with $M_*$ and sSFR is in the sense that galaxies with higher $M_*$ or lower sSFR tend to have steeper negative gradients. Moreover, the negative correlation of median stellar population gradients with $M_*$ at a given sSFR is best described by segmented relationships, whereby galaxies with $\log M_* \lesssim 10$–10.5 (the transition mass being larger for galaxies with larger sSFR) generally have much shallower slopes than those with higher $M_*$. Galaxies with a higher global sSFR or younger age generally also have higher sSFR or younger ages locally at given galactocentric distances. The morphological properties (e.g., T-Types, $\Sigma_{1\,\text{kpc}}$) are connected with galaxy stellar populations largely in a radius-independent way.

### 4.2. Comparison to Relevant Results in the Literature

Our finding that the sSFR and, to a much lesser degree, the central velocity dispersion are the most predictive properties for local stellar ages within galaxies is in line with a recent study by Bluck et al. (2019). In particular, Bluck et al. (2019) found that the offset from the galaxy SFMS and, to a lesser degree, the central velocity dispersion of host galaxies are the two most predictive parameters for whether or not a spatially resolved region is quenched. Here we further show that sSFR is also the single most predictive global property for $[Z/H]_L$ at one effective radius, but at the galaxy centers, stellar mass is the most important property for predicting $[Z/H]_L$.

The positive correlation between stellar age gradients and the sSFR of star-forming galaxies suggests that (1) quenching of star formation proceeds spatially from inside out on average, and this inside-out trend is more significant for more massive galaxies, and (2) the star formation boost with respect to the SFMS primarily happens in the inner parts of galaxies, resulting in flatter or even positive stellar population gradients at higher sSFR. To the best of our knowledge, previous spectroscopic studies of the radial gradients of nearby galaxies mostly focus on the dependence on morphological types and mass (e.g., Sánchez-Blázquez et al. 2014; González Delgado et al. 2015; Zheng et al. 2017), but rarely explore the dependence on the global star formation status of galaxies.

![Figure 7](https://example.com/figure7.png)

*Figure 7.* Same as Figure 5, but for the dependence of radial gradients of D4000, $\tau_L$, and $[Z/H]_L$ on $\Delta \log \Sigma_{1\,\text{kpc}}$. 

---

The Astrophysical Journal, 895:146 (15pp), 2020 June 1

Chen et al.
which turns out to be the most predictive property for stellar age gradients. González Delgado et al. (2015) claimed that it is the Hubble type, rather than stellar mass, that has the closest connection to stellar age gradients, based on 300 CALIFA galaxies. They also found that age/metallicity gradient slopes reach a minimum (i.e., the most negative value) in Sb-Sbc galaxies and increase toward either earlier or later Hubble types. With an order of magnitude larger sample, we have shown that the sSFR and, to a lesser degree, stellar masses, rather than Hubble types (here quantified by T-Types) are the most predictive properties for stellar age gradients. At a given sSFR and stellar masses, the radial gradient slopes appear to monotonically decrease with T-Types, without an upturn at any intermediate T-Type value. Moreover, even at the same Hubble types, stellar age gradients generally exhibit a positive dependence on sSFR for given stellar masses (Figure 5).

The close connection between stellar age gradients and sSFR reported here is also in line with Ellison et al. (2018), who studied the radial star formation profiles of galaxies available in the MaNGA DR13 and found that the relative excess or deficit of star formation as a function of radius is correlated with the vertical offset of galaxies with respect to the global SFMS. Our analysis suggests that this close connection still exists when dividing galaxies into different stellar masses. In addition, Pan et al. (2016) studied the radial variations of the broadband (NUV−r) color of ~6000 local star-forming galaxies and found that galaxies with log $M_\star < 10.2$ have smaller radial color variations and weaker mass dependence than galaxies with higher stellar masses. Our analysis based on IFU spectroscopy suggests that the stellar mass dependence of radial (NUV−r) variations should be primarily attributed to a metallicity effect, rather than an age effect. Wang et al. (2018b) used the mass-weighted fraction of quenched spaxels with $D_4(4000) > 1.6$ and EW(Hα) < 2.0 to classify the MaNGA DR14 galaxies into star-forming, partially quenched (PQ) and totally quenched (TQ) subsamples, and they found that star-forming and PQ galaxies have on average similarly negative radial gradients of $D_4(4000)$, $\tau_L$, and EW(Hα), whereas the TQ galaxies have much weaker average gradients than star-forming and PQ galaxies over the whole stellar mass ranges. This is inconsistent with our finding that stellar population gradients generally become more negative as sSFR decreases, except at log $M_\star \gtrsim 10.5$, where QGs have radial gradients of $D_4000$ and $\tau_L$ that are shallower than those of MS− galaxies.

![Figure 8](image_url)

The Astrophysical Journal, 895:146 (15pp), 2020 June 1 Chen et al.
...but steeper than those of MS+ galaxies. The difference may be primarily attributed to a difference in the star formation status classification schemes adopted in our work and Wang et al. (2018b). The classification of the global star formation status of a galaxy should be based on the globally integrated sSFR, regardless of the relative spatial distributions of young and old stellar populations. D4000 and EW(Hα) maps reflect the proportional, instead of absolute, contribution of younger or metal-poorer stellar populations in any spaxels, which means that spaxels with the same amount of young stellar populations may be classified by Wang et al. (2018b) as being star-forming if located in the outer low stellar density regions (or galaxies with lower stellar masses and thus generally lower surface mass densities) or quenched if located in the inner high stellar density regions (or galaxies with higher stellar masses and thus higher surface mass densities). It is thus conceivable that there is some mass-dependent overlap in global sSFRs between the star-forming and PQ subsamples as well as between the PQ and TQ subsamples in Wang et al. (2018b), which tends to smear out the sSFR or mass dependence of stellar population radial gradients.

By using local stellar mass densities, galactocentric distances (in kiloparsecs), and host galaxy stellar masses as control parameters, Woo & Ellison (2019) obtained average radial profiles of the relative enhancement (or offset) of sSFR (or ages) for relatively isolated galaxies with either compact (Δlog Σ1 kpc > 0) or diffuse cores (Δlog Σ1 kpc < 0), and they found that, toward smaller galactocentric distances, star-forming galaxies with compact cores are characterized by substantially enhanced median sSFR and depressed chemical abundances, while those with diffuse cores by substantially suppressed median sSFR and enhanced chemical abundances. This led Woo & Ellison (2019) to conclude that galaxies with Δlog Σ1 kpc > 0 follow a compaction-like core-building growth mode whereas galaxies with Δlog Σ1 kpc < 0 follow a secular inside-out growth mode. However, by making a straightforward R_e-normalized (rather than using physical units of kiloparsecs) radial profile stacking separately for galaxies with different stellar masses and sSFR, we do not observe substantially larger Δlog Σ1 kpc-dependent differences between the median D4000/ages at smaller galactocentric distances than at larger galactocentric distances, regardless of the current sSFRs (Figure 8). Moreover, star-forming galaxies with compact cores tend to have similar or higher central stellar metallicities than those with relatively diffuse cores.

Our finding of a lack of significant correlation between stellar population gradients and local galaxy overdensities is largely in line with previous studies based on MaNGA data (Goddard et al. 2017b; Zheng et al. 2017; Spindler et al. 2018). Nevertheless, we additionally show that this lack of correlation applies to both star-forming and quiescent galaxies, which implies that local overdensities do not significantly affect the stellar population distribution in galaxies over either short or long timescales.

4.3. Implications for a Negative Dependence of Stellar Population Gradients on Stellar Mass

The classical monolithic dissipative collapse models of galaxy formation (e.g., Larson 1974; Carlberg 1984; Pipino et al. 2010) are qualitatively consistent with our finding of a monolithic negative dependence of stellar metallicity gradients on stellar mass, but are inconsistent with the overall negative stellar age gradients. In the ΛCDM hierarchical structure formation models, galaxy mergers are expected to be common especially in the early universe (e.g., Duncan et al. 2019). The early gas-dominated merging events (along with accretion-
driven violent disk instabilities; e.g., Dekel & Burkert (2014) might have formed the central parts of the present-day galaxies first, and later, the fallback of relatively high angular momentum cold gas ejected during the merging process might have rebuilt extended disks from inside out (e.g., Barnes 2002), giving rise to negative radial gradients of stellar ages and metallicities. Some numerical simulations (e.g., Bekki & Shioya 1999; Hopkins et al. 2009) suggest that gas-rich major mergers involving more massive progenitors give rise to steeper metallicity gradients due to a stronger central starburst sustained by tidally induced gas inflow.

Nevertheless, more recent simulations by Taylor & Kobayashi (2017) suggest that gas-rich major mergers do not significantly steepen metallicity gradients when active galactic nucleus (AGN) feedback is invoked to suppress the central SF activities. Instead, the redistribution of high-metallicity stars from the center to outskirts caused by merging tends to flatten preexisting metallicity gradients, resulting in a reversal of the mass dependence of metallicity gradients from being negative at log $M_*$ $\lesssim$ 10.5 to positive or flat at higher stellar masses. A similar reversal of metallicity gradients was also found by Tissera et al. (2016) in their simulation of disk galaxies, even though AGN feedback was not included. Moreover, Tissera et al. (2016) did not find a clear correlation between age gradients and stellar mass. These recent simulation results are in conflict with our observational finding of a monolithic mass dependence of the average age and particularly metallicity gradients. Nevertheless, we emphasize that the analysis presented in this work is limited to the central $\sim 1.5 R_e$ of nearby galaxies. Studies extending to larger galactocentric distances indeed found that age and metallicity gradients of nearby galaxies may flatten beyond $2 R_e$ (e.g., González Delgado et al. 2015), indicating that either satellite accretion or radial stellar migration might play an important role in the outer disks.

This work is supported by the National Key R&D Program of China (2017YFA0402600, 2017YFA0402702), the B-type Strategic Priority Program of the Chinese Academy of Sciences (XDB41000000), and NSFC grant Nos. 11973038, 11973039, and 11421303. H.X.Z. is also grateful for support from the CAS Pioneer Hundred Talents Program.

This work makes use of the MaNGA Pipe3D data products. We thank the IA-UNAM MaNGA team for creating this catalog and the Conacyt Project CB-285080 for supporting them. Funding for the Sloan Digital Sky Survey IV has been provided by the Alfred P. Sloan Foundation, the U.S. Department of Energy Office of Science, and the Participating Institutions. SDSS-IV acknowledges support and resources from the Center for High-Performance Computing at the University of Utah. The SDSS website is www.sdss.org.

Appendix

Results for Mass-weighted Stellar Ages and Metallicities

While we have restricted our discussion of model-dependent stellar parameters to the luminosity-weighted ages and metallicities in the main text of this paper, here we show the relevant results for mass-weighted ages and metallicities for the sake of completeness (Figures A1–A3). A brief discussion about the problem with mass-weighted stellar parameters derived based on integrated spectra is given in Section 2.2.
Figure A2. Same as Figure 3, but for global sSFR plotted against mass-weighted stellar population gradients ($\nabla \tau_M$ and $\nabla [Z/H]_M$) for galaxies in different log $M_*$ bins.

Figure A3. Same as Figure 4, but for mass-weighted stellar age and metallicity gradients (from left to right: $\nabla \tau_M$ and $\nabla [Z/H]_M$) as a function of stellar masses for MS+ (blue), MS− (green), and QG (red).

ORCID iDs
Guangwen Chen © https://orcid.org/0000-0002-4742-8800
Hong-Xin Zhang © https://orcid.org/0000-0003-1632-2541
Xu Kong © https://orcid.org/0000-0002-7660-2273
Zesen Lin © https://orcid.org/0000-0001-8078-3428
Zhixiong Liang © https://orcid.org/0000-0002-2384-3436
Xinkai Chen © https://orcid.org/0000-0002-5016-6901

Zuyi Chen © https://orcid.org/0000-0002-2178-5471
Zhiyuan Song © https://orcid.org/0000-0003-3041-3589

References
Aguado, D. S., Ahumada, R., Almeida, A., et al. 2019, ApJS, 240, 23
Albareti, F. D., Allende Prieto, C., Almeida, A., et al. 2017, ApJS, 233, 25
Barnes, J. E. 2002, MNRAS, 333, 481
