The Mass Assembly History for Galaxies with MaNGA Postprint

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Date: 2024-03-29T00:00:00+00:00

Abstract

How galaxies assemble masses through their own star formation or interaction with the external environment is still an important topic in the field of galaxy formation and evolution. We use Value Added Catalogs with galaxy features that are spatially and temporally resolved from Sloan Digital Sky Survey Data Release 17 to investigate the mass growth histories of early-type galaxies (ETGs) and late-type galaxies (LTGs). We find that the mass growth of ETGs is earlier than that of LTGs for massive galaxies (M* > 1010M), while low-mass (M* ≤ 1010M) ETGs have statistically similar mass assembly histories as low-mass LTGs. The stellar metallicity of all massive galaxies shows a negative gradient and basically does not change with time. However, in low-mass galaxies, the stellar metallicity gradient of elliptical galaxies is negative, and the stellar metallicity gradient of lenticular and spiral galaxies evolves from positive to negative. ETGs are not all in a high-density environment, but exhibit mass dependence. As the tidal strength increases, the star formation rate of low-mass ETGs rapidly decreases. These results support a picture where massive galaxies exhibit inside-out quenching mode, while low-mass galaxies show outside-in quenching mode. Environmental effects play an important role in regulating the mass assembly histories of low-mass ETGs.

Full Text

Preamble

Research in Astronomy and Astrophysics, 24:035006 (12pp), 2024 March

https://doi.org/10.1088/1674-4527/ad1c77

The Mass Assembly History for Galaxies with MaNGA

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Received 2023 June 14; revised 2023 December 28; accepted 2024 January 7; published 2024 February 21

Abstract

How galaxies assemble mass through their own star formation or interaction with the external environment remains a central question in galaxy formation and evolution. Using Value Added Catalogs with spatially and temporally resolved galaxy properties from Sloan Digital Sky Survey Data Release 17, we investigate the mass growth histories of early-type galaxies (ETGs) and late-type galaxies (LTGs). We find that for massive galaxies ($M_* > 10^{10} M_\odot$), ETGs assembled their mass earlier than LTGs, while low-mass ($M_* \leq 10^{10} M_\odot$) ETGs show statistically similar mass assembly histories as low-mass LTGs. The stellar metallicity of all massive galaxies exhibits a negative gradient and remains essentially constant over time. However, in low-mass galaxies, ellipticals show negative stellar metallicity gradients, while the gradients of lenticular and spiral galaxies evolve from positive to negative. ETGs are not exclusively found in high-density environments; rather, their distribution shows mass dependence. As tidal strength increases, the star formation rate of low-mass ETGs declines rapidly. These results support a scenario where massive galaxies undergo inside-out quenching, while low-mass galaxies exhibit outside-in quenching. Environmental effects play a crucial role in regulating the mass assembly histories of low-mass ETGs.

Key words: Galaxy: evolution – galaxies: star formation – Galaxy: formation

1. Introduction

Understanding how galaxies assemble their stellar mass spatially is fundamental to unraveling their formation and evolution. A prominent approach to this problem is the fossil record method applied to integral field spectroscopy (IFS) observations.

In the nearby universe, a large fraction of galaxies display negative age gradients, indicating that star formation preferentially occurs in their interiors rather than their exteriors \cite{Li_{2015}, Dale_{2016}}. These results suggest that inside-out stellar mass assembly is prevalent. Morphological type may also be a key factor influencing mass assembly. For early-type galaxies (ETGs), \cite{Sanchez_{{{Blazquez}}_{{2007}}}} found that neither pure inside-out nor outside-in scenarios can adequately explain their mass growth histories.

In summary, the radial assembly of stellar mass and the quenching of star formation in galaxies remain poorly understood.

Previous studies have demonstrated that galaxy mass assembly histories are closely linked to stellar mass \cite{Peng_{2010}, Fang_{2013}, Ceverino_{2015}}. \cite{Perez_{2013}} reported results from the Calar Alto Legacy Integral Field Area (CALIFA) survey showing that massive galaxies exhibit downsizing signatures, with both inner and outer regions growing faster, while galaxies with stellar masses below $\sim 10^{10} M_{\odot}$ show a transition to outside-in growth. Additionally, studies of dwarf galaxies have found positive age gradients \cite{Gallart_{2008}, Zhang_{2012}}. An observational fact shows that elliptical galaxies are typically more massive than spiral galaxies. Massive galaxies first experienced compaction processes at high redshift, such as major mergers and disk instability, leading to increased stellar mass. This evolutionary path is usually accompanied by the formation of compact bulges \cite{Driver_{2006}, Schiminovich_{2007}, Bell_{2012}, Barro_{2017}, Lee_{2018}, Ge_{2020}}. In contrast, low-mass galaxies, lacking sufficient cold gas, are more likely to form their mass through secular evolution and/or minor mergers.

Therefore, different star formation histories may be mass-dependent. Observational evidence has also shown that galaxy mass growth histories relate to their environment. First, most galaxies fainter than the characteristic luminosity tend to reside in sparse environments, while brighter galaxies prefer dense environments. This reflects the change in the optical luminosity function from sparse regions to galaxy groups and clusters \cite{Blanton_{2005}, Hoyle_{2005}, Popesso_{2005}}. Second, when examining the relationship between galaxy age and environment, older galaxies are found in denser environments \cite{Kauffmann_{2004}}. In the local universe, low-mass galaxies are more vulnerable to environmental impacts such as galaxy strangulation \cite{Larson_{1980}}, ram pressure stripping \cite{Gunn_{{{Gott}}*{{1972}}}}, and galaxy harassment \cite{Farouki*{{Shapiro}}*{{1981}}}, Moore*{1998}}. In galaxy groups and clusters, \cite{Geha_{2012}} found that the fraction of quiescent low-mass galaxies ($M_* \leq 10^9 M_{\odot}$) increases rapidly with decreasing distance from massive galaxies. However, field galaxies of the same mass continue forming stars. \cite{Peng_{2010}} studied the relationship between the fraction of quiescent galaxies and environmental density. At fixed stellar mass, the number of red galaxies increases with environmental density, a trend more significant for low-mass galaxies.

Although the standard cold dark matter universe model (ΛCDM) can properly explain the currently observed universe, reproducing the mass assembly histories of massive galaxies requires the cosmological model to incorporate mechanisms that can suppress or "quench" star formation. The literature discusses two meanings of star formation reduction. The first is that galaxies experience physical processes that rapidly consume gas to halt star formation. The other is that despite a supply of fresh cold gas, galaxies remain quiescent. One popular theory, hierarchical two-phase accumulation, is commonly used to explain star formation histories \cite{Oser_{2010}}. The first phase is the main mechanism for stellar growth via gas collapse at high redshift, while the second stage is size growth through the accretion of satellite systems at low redshift. This theory supports the picture proposed by \cite{Faber_{2007}}, where star-forming galaxies trigger new star formation mainly through mergers with gas-rich systems, leading to rapid stellar mass growth. Due to gas consumption and active galactic nucleus feedback, star-forming galaxies shut down star formation and become quiescent. These gas-poor quiescent galaxies then experience a series of dry mergers with gas-poor systems, accumulating stellar mass and shaping galaxy morphologies.

ETGs and late-type galaxies (LTGs) represent two basic classifications on the Hubble tuning fork diagram \cite{Hubble_{1936}}. These galaxy types show differences in stellar populations \cite{Gonzalez_{{{Delgado}}*{{2016}}}, Taylor*{{{Kobayashi}}*{{2017}}}, Lacerna*{2020}}, gas content \cite{Lagos_{2015}, Bolatto_{2017}}, kinematics \cite{Cappellari_{2016}, Aquino_{{{Ortiz}}*{{2018}}}, Graham*{2018}}, and environment \cite{Blanton_{{{Moustakas}}*{{2009}}}, Wilman*{{{Erwin}}*{{2012}}}}. \cite{Schawinski*{2014}} found that ETGs are mainly composed of quiescent, bulge-dominated galaxies, while LTGs primarily contain active, disk-dominated galaxies. These results suggest that the morphologies we observe today may be related to the mass assembly processes galaxies experienced.

\cite{Ibarra_{{{Medel}}_{{2016}}}} used the fossil record method with Mapping Nearby Galaxies at Apache Point Observatory (MaNGA) data from SDSS Data Release 13 to study radial stellar mass growth histories. They found that mass growth histories depend on stellar mass and that morphological types also affect these histories. Although previous work has used IFS to explore galaxy physical properties over time and space, the samples were relatively small and morphological classifications were not considered in detail (e.g., elliptical and S0 galaxies were not separated).

In this work, we use MaNGA surveys from Sloan Digital Sky Survey Data Release 17 (SDSS DR17) to study the mass assembly histories of ETGs and LTGs. MaNGA provides nearly 10,000 galaxies within $0.01 < z < 0.18$ \cite{Bundy_{2015}}, representing the largest IFS survey to date. The paper is organized as follows. Section 2 presents our sample and data. Sections 3 and 4 present our results and discussion. Finally, Section 5 provides a summary. Throughout this paper, we assume a cosmology with $\Omega_M = 0.3$, $\Omega_\Lambda = 0.7$, and $H_0 = 70$ km s^{-1} Mpc^{-1}, and adopt a \cite{Salpeter_{1955}} IMF.

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2. Sample and Data

We utilize four catalogs to analyze galaxy mass growth histories: the MaNGA Pipe3D Value Added Catalog (MAP3D-VAC), MaNGA Morphology Deep Learning DR17 Catalog (MADL-VAC), MaNGA PyMorph DR17 Photometric Catalog (MAPM-VAC), and MaNGA Value Added Catalog Galaxy Environment (GEMA-VAC). We briefly introduce these catalogs below.

The MAP3D-VAC for MaNGA DR17 is produced via Pipe3D, a spectroscopic analysis pipeline developed to characterize stellar populations and ionized gas properties in spatially resolved data from optical IFU surveys (such as MaNGA, CALIFA, and SAMI). Pipe3D adopts MILES simple stellar population templates \cite{Vazdekis_{2010}} assuming a \cite{Salpeter_{1955}} IMF and \cite{Calzetti_{2000}} dust extinction law. The template library comprises 156 templates covering 39 population ages (from 0.001 to 13 Gyr) and four metallicities (log[M/H] = −0.71, −0.4, 0.0, 0.17). MAP3D-VAC includes a table of integrated characteristics at the effective radius and gradients of various quantities, plus data cubes containing spatially resolved properties needed to recover star formation histories.

The MADL-VAC is a morphological catalog of MaNGA galaxies obtained with deep learning models trained and tested on SDSS-DR7 images with excellent performance. This catalog contains Galaxy Zoo-like attributes (edge-on, barred, projected pairs, bulge prominence, and roundness), along with T-Type values and finer separation between pure elliptical and S0 galaxies. All T-Type values in this catalog have been visually inspected and modified when necessary.

The MAPM-VAC provides photometric parameters from Sérsic and Sérsic+Exponential fits to the 2D surface brightness profiles of the final MaNGA DR17 galaxy sample (e.g., total fluxes, half-light radii, bulge-to-disk fractions, ellipticities, position angles). All galaxies were fitted using the PyMorph algorithm, extensively tested by \cite{Meert_{2013}} and \cite{Fischer_{2017}}.

Galaxy environment plays a crucial role in formation and evolution. Galaxies undergo intrinsic and secular evolution processes while also experiencing influences from local and large-scale structures. To investigate environmental effects, we use GEMA-VAC, which contains several environmental quantifications for MaNGA galaxies based on methods described in \cite{Argudo_{{{Fernandez}}*{{2015}}}}. We refer readers to \cite{Argudo*{{{Fernandez}}*{{2015}}}, Sanchez*{2018}, Fischer_{2019}, Dominguez_{{{Sanchez}}_{{2022}}}} for further details.

Our analysis proceeds as follows. First, we cross-match the four catalogs to obtain the necessary parameters. Second, we select three galaxy types (elliptical, S0, and spiral) following \cite{Dominguez_{{{Sanchez}}_{{2022}}}}, who recommend the following clean and restrictive selection criteria:

- **Elliptical galaxies**: (PLTG < 0.5) and (T-Type < 0) and (PS0 < 0.5) and (VC $= 1$) and (VF $= 0$)
- **S0 galaxies**: (PLTG < 0.5) and (T-Type < 0) and (PS0 > 0.5) and (VC $= 2$) and (VF $= 0$)
- **Spiral galaxies**: (PLTG > 0.5) and (T-Type > 0) and (VC $= 3$) and (VF $= 0$)

Here, PLTG and PS0 represent the probabilities of being LTG and S0 galaxy, T-Type indicates the separation between pure elliptical and S0 galaxies, VC is the visual classification parameter (VC $= 1$ for ellipticals, VC $= 2$ for S0s, VC $= 3$ for LTGs), and VF is the visual classification flag (VF $= 0$ for certain classification, VF $= 1$ for uncertain classification). Based on these criteria, we obtain 2441 elliptical, 889 S0, and 5103 spiral galaxies. Figure 1 shows examples of elliptical, S0, and spiral galaxies from our final sample. Figure 2 displays the relationships between stellar mass and star formation rate (SFR), and stellar mass and r-band effective radius for our sample. Our sample represents over 80% of the total MaNGA sample, excluding galaxies lacking parameter measurements or with undetermined morphology, making it representative within MaNGA.

Although a larger low-mass galaxy sample would be more statistically significant, our current sample is sufficient to explore their star formation histories. In addition to morphology classification parameters, we also obtain other parameters including stellar mass formation ratio, stellar metallicity gradient, angular momentum, Sérsic index, effective radius, and environmental parameters.

3. Results

3.1. Time-resolved Physical Properties of Galaxies

Thanks to Pipe3D \cite{Sanchez_{2016}}, an analysis pipeline based on the FIT3D fitting tool, we can explore stellar population and ionized gas properties from integral field spectroscopy (IFS) data. Pipe3D adopts single stellar population (SSP) templates comprising 156 SSPs with 39 ages and four metallicities.

Figure 3 shows the relationship between the stellar mass fraction formed at a given lookback time and the lookback time itself. To examine this in detail, we divide the sample into three stellar mass intervals. For massive galaxies ($M_* > 10^{10} M_\odot$), the stellar mass fraction of ellipticals is always higher than that of spirals, with S0 galaxies intermediate and more similar to ellipticals. However, this pattern does not hold for low-mass galaxies ($M_* \leq 10^{10} M_\odot$). Before reaching 60-70% of their final mass, LTGs assemble mass faster, while beyond that point ETGs assemble faster. Considering the data uncertainties (the red points and curve fall almost entirely within the confidence range of the blue curve), we conservatively conclude that low-mass ETGs have similar mass assembly histories to low-mass LTGs.

Additionally, we find that more massive galaxies evolve earlier, a trend more pronounced in ETGs ($ $2 Gyr earlier) than in LTGs. Our results agree with \cite{Garcia_{{{Benito}}_{{2017}}}}, who presented mass assembly times for CALIFA galaxies and found that downsizing is preserved as a function of stellar mass. We count 73 elliptical and 97 S0 galaxies in the low-mass ETG sample. This relatively small number may affect statistical significance and requires future exploration with larger samples.

Figure 4 shows that massive ETGs and LTGs exhibit similar metallicity gradient evolution, with gradients showing no significant changes over lookback time. This implies that massive galaxies have relatively uniform star formation histories. The formation of larger stellar masses may result from dry mergers at later times. Additionally, massive galaxies show negative metallicity gradients (higher central metallicity), suggesting an inside-out evolutionary model.

For low-mass galaxies, ETGs show evolution similar to high-mass ETGs but with slightly higher metallicity gradients, implying slower evolution than massive galaxies. However, the metallicity gradients of low-mass LTGs change significantly over time, transitioning from positive to negative, suggesting an outside-in evolutionary model. Such gradient changes indicate extended star formation histories in low-mass galaxies, where recently formed stars increase central metallicity (via gas inflow) or decrease outer metallicity (via metal-poor gas accretion).

The metallicity gradients of nearly all galaxies tend to flatten or even rise slightly in their later evolutionary stages. Since most stellar mass (80%) has already formed by this time, new star formation is unlikely to cause this change. Instead, external environmental effects may increase metal abundance in galaxy outskirts, flattening the metallicity gradient.

3.2. Integrated Physical Properties of Galaxies

To explore relationships between physical properties and stellar mass growth, we must understand star formation and quenching processes.

Figure 5 displays SFR distributions for different morphological types. ETGs have significantly lower SFRs than LTGs, while LTG SFRs increase with stellar mass. However, ETG SFRs also increase with mass, suggesting these galaxies experienced similar processes that systematically suppressed star formation. The reason ETGs with different masses formed is that they experienced different mass growth processes after star formation ceased. We also find a bimodal SFR distribution in low-mass ETGs, which we attribute to environmental effects (see Section 3.3).

Figures 6 and 7 show structural parameter distributions. For the Sérsic index (a concentration parameter), ellipticals, S0s, and spirals show clear differences. Across all mass ranges, ellipticals have the largest Sérsic index, followed by S0s, then spirals. Furthermore, the Sérsic index increases with stellar mass for all types, with differences between ellipticals and S0s becoming more significant. Increasing Sérsic index leads to bulge growth, which may be necessary for morphological transition \cite{Bremer_{2018}}. For effective radius, ellipticals and S0s have similar sizes across all mass bins, but LTGs are always larger than ETGs. Additionally, more massive galaxies generally have larger effective radii, implying that stellar mass growth accompanies size growth.

Galaxy kinematics contain information about mass growth histories. To explore kinematic characteristics, we use specific angular momentum (l_{R_e}) for the stellar population within one effective radius to quantify whether galaxies are rotation- or dispersion-dominated. Large l_{R_e} indicates rotation dominance, while small values indicate bulge dominance. Figure 8 shows that in low-mass galaxies, ETGs and LTGs have similar l_{R_e}, while in massive galaxies, different morphologies show significant differences. Elliptical l_{R_e} decreases from 0.73 to 0.46 to 0.34 with increasing stellar mass, while S0 (\$ 0.61)*andspiral*(\$0.83) values remain essentially constant with mass. Generally, ellipticals are bulge-dominated (larger velocity dispersion), spirals are disk-dominated (larger rotational velocity), and S0s are intermediate. This implies that massive galaxy mass growth is closely related to internal interactions that can alter galaxy kinematics.

3.3. Environment of Galaxies

To explore the role of environment in galaxy mass growth, we derive the environmental parameter Q_{LSS} (tidal strength of large-scale structures) from GEMA-VAC (see Figure 9). The tidal strength parameter Q_{LSS} is calculated following methods described in \cite{Argudo_{{{Fernandez}}*{{2015}}}} and \cite{Etherington*{{{Thomas}}_{{2015}}}}, defined as:

$$Q_{\text{LSS}} = \log\left(\sum_{i=1}^{N} \frac{M_i}{M_0}\left(\frac{D_P}{d_i}\right)^3\right)$$

where M_i is the stellar mass of the ith neighbor galaxy, M_0 is the stellar mass of the primary galaxy, d_i is the projected physical distance to the ith neighbor, and $D_P = 2\alpha r_{90}$ is the estimated diameter of the primary galaxy. Here r_{90}, the Petrosian radius containing 90% of the total r-band flux, is scaled by $\alpha = 1.43$ to recover D_{25} (the 25 mag arcsec^{-2} isophotal diameter).

We test environmental parameter differences using K-S tests. For $M_* \leq 10^{10} M_\odot$, results show only slight differences ($P = 0.005$) between ellipticals and spirals, with no differences among other types. For $10^{10} M_\odot < M_* \leq 10^{11} M_\odot$, no differences exist between ETGs, but slight differences appear between ETGs and LTGs. For the most massive galaxies, we find no differences between S0s and spirals, but significant differences ($P = 0.001$) between ellipticals and spirals. Some studies suggest environmental dependence is absent in shaping massive ETG morphologies \cite{Guo_{2009}, Weinmann_{2009}, Huertas_{{{Company}}_{{2013}}}}. Our K-S test results partially contradict this work, possibly due to small ETG sample sizes.

We find a bimodal environmental distribution in low-mass ETGs, consistent with \cite{Chen_{2022}}, who found elliptical galaxies exist in two environments: near cluster/group centers and far from them. This implies both environmental effects and secular evolution shape morphology. Based on tidal strength, we extract the lowest 25%, middle 50%, and highest 25% of galaxies to compare star formation activity across different masses and morphologies (see Figure 10). We find LTG SFR is independent of environment, as is massive ETG SFR. However, for low-mass ETGs, increasing tidal strength rapidly decreases SFR. Low-mass ETGs in the strongest tidal environments have SFRs 2-3 times lower than those in the weakest tidal environments, explaining the bimodal SFR distribution in Figure 5. These results indicate environmental effects play a crucial role in regulating the star formation histories of low-mass ETGs.

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4. Discussion

4.1. The Mass Assembly Histories

Our results provide insights into galaxy mass assembly histories. Galaxies assemble mass through star formation triggered by compaction events (e.g., wet mergers or disk instability) in the early universe when cold gas content was high. As found by \cite{Chowdhury_{2022}}, atomic gas accounts for about 70% of baryonic mass at $z \approx 1.3$. With cold gas consumption and declining star formation, galaxies expand their stellar populations through dry mergers, eventually forming massive ETGs. However, some galaxies may not have experienced extensive merging, retaining spiral signatures.

Many studies have revealed that mass and environment relate to mass assembly histories. \cite{Schawinski_{2014}} used SDSS+GALEX+Galaxy Zoo data to study local galaxy quenching, concluding that LTG quenching may result from slow cosmic gas exhaustion driven by secular and/or environmental processes, while ETG quenching involves violent processes accompanied by disk-to-spheroid morphological transformation. \cite{Sybilska_{2017}} studied ETG stellar population dependence on mass and environment, finding massive ETGs are not more environment-sensitive than less massive ones, likely because they are central galaxies in infalling groups. However, environmental effects are crucial for suppressing star formation in low-mass galaxies. The closer a satellite galaxy is to a cluster center, the more vulnerable it is to environmental influences. Across all morphologies, galaxies in denser environments show outside-in quenching, supporting the view that environment can shut down specific SFR through ram pressure stripping and/or galaxy interactions \cite{Medling_{2018}}.

\cite{Gonzalez_{{{Delgado}}*{{2016}}}} used CALIFA data to explore star formation characteristics along the Hubble sequence, finding ETG nuclear regions have lower SFR than outskirts (inside-out quenching). \cite{Belfiore*{2017}} found similar results in MaNGA. Our stellar metallicity gradient results support these conclusions. \cite{Scott_{2017}} analyzed integral stellar populations from the SAMI Galaxy Survey, finding that at fixed mass and size, ETGs are older and more compact than LTGs. Age and metallicity also correlate with environment, with galaxies appearing older and more metal-rich in dense environments. \cite{Medling_{2018}} presented spatially resolved star formation properties from SAMI, finding ETGs exhibit two behaviors: some on the star-forming main sequence show LTG-like SFRs, while others deviate significantly. Given their similar stellar masses and central mass surface densities, mass quenching is not the primary factor for deviation from the main sequence. The combination of stellar mass and environment may constitute a complex quenching process.

As shown in Figure 7, most massive LTGs are larger than ETGs, though some studies reach opposite conclusions \cite{Shen_{2003}, Lange_{2015}}. This may stem from different morphology definitions. Our classification uses deep learning with artificial intelligence, while others use Sérsic index \cite{Shen_{2003}} or may not classify S0s as ETGs \cite{Lange_{2015}}. Massive LTGs having larger sizes has been observed elsewhere. \cite{Fang_{2013}} used SDSS to explore the relationship between star formation and galaxy structure, finding LTGs have lower central density than ETGs, suggesting LTGs likely have larger R_e. Furthermore, \cite{Ge_{2020}} found that massive quiescent galaxies have smaller average R_e than star-forming galaxies of the same mass and redshift, while low-mass quiescent galaxies show no such trend. The average R_e difference is \$ \$0.4 dex for massive galaxies versus only 0.18 dex for low-mass galaxies, consistent with \cite{Lange_{2015}} and \cite{Roy_{2018}}. Methodological, data source, and classification differences can lead to divergent findings.

4.2. The Specific Stellar Angular Momentum and Merger

ETGs divide into slow rotators (low specific stellar angular momentum l_{R_e}) and fast rotators (high l_{R_e}). Slow rotation indicates complex stellar velocity fields, while fast rotation means regular velocity fields. \cite{Emsellem_{2011}} provided a census of apparent stellar angular momentum within one effective radius for a volume-limited sample of 260 nearby ETGs from the ATLAS$^{\rm 3D}$ project, finding the vast majority are fast rotators with regular stellar velocity fields. \cite{Veale_{2017}} analyzed environmental properties of 370 local ETGs from MASSIVE and ATLAS$^{\rm 3D}$, finding a strong inverse correlation between l_{R_e} and stellar mass, where l_{R_e} increases with decreasing mass. In this work, low-mass ($M_* \leq 10^{10} M_\odot$) ellipticals have similar l_{R_e} to LTGs, explained by the fact that at lower masses, gas accretion and mergers tend to preserve galaxy rotation. As \cite{Kormendy_{2009}} showed, elliptical galaxies, especially low-mass ones, retain rotation components. A widely accepted explanation is that high-mass ellipticals undergo numerous relatively gas-free mergers that effectively remove rotation characteristics, while low-mass galaxies experience gas accretion and mergers that preserve rotation \cite{Naab_{2014}, Choi_{{{Yi}}*{{2017}}}, Penoyre*{2017}}.

Mergers are key to mass growth and morphological diversity. Hierarchical models predict that up to 80% of the final stellar mass in massive bulge-dominated galaxies assembles through sequences of major and minor mergers \cite{Fontanot_{2011}, Wilman_{2013}}. Minor mergers, in particular, may drive size expansion of the most massive ETGs from compact red nuggets to large local ellipticals \cite{van_{{{Dokkum}}*{{2010}}}}. Cosmological hydrodynamic simulations show major merger incidence declines with cosmic time \cite{Maller*{2006}}, and the average merger rate of massive galaxies is $ $3 times that of low-mass galaxies at $z \sim 0.3$. Major mergers may quickly build dense cores (as seen in Figure 6) and destroy spiral structure. Minor mergers are expected to increase SFR in low-mass galaxies \cite{Saintonge_{2012}, Kaviraj_{2014}}, though less violently than major mergers. In the local universe, minor mergers are more common than major mergers.

4.3. The Metallicity Gradients

\cite{Camps_{{{Farina}}*{{2022}}}} presented chemical enrichment evolution in galaxies, finding average metallicity gradients are negative for all mass ranges, but reversed at some point in the past for low-mass galaxies, which previously had positive gradients. Our work also finds massive galaxies have negative metallicity gradients, while low-mass galaxies, especially LTGs, have positive gradients before some past epoch and negative afterward. \cite{Sharda*{2021}} explored ionized gas kinematics effects on gas-phase metallicity gradients, finding rotation-dominated galaxies (LTGs) show steep negative gradients, while dispersion-dominated galaxies (ETGs) show flat gradients. These results are explained by their analytical model: for galaxies with high or low velocity dispersion, strong inward gas advection or cosmic metal-poor gas accretion can dilute central regions, resulting in flatter gradients. For intermediate velocity dispersion galaxies, both processes are weak compared to metal production, yielding the steepest gradients. Similar findings emerge from galaxy formation simulations \cite{Ma_{2017}, Hemler_{2021}}. In this work, ETG stellar metallicity gradients are relatively flat, possibly because later-formed stars exist in high gas-phase metallicity environments caused by high velocity dispersions. The metallicity profile distribution is complex, with outflows \cite{Fu_{2013}} and AGN feedback \cite{Nelson_{2019}, Pillepich_{2019}} also playing important roles in setting metallicity gradients.

5. Summary

In this work, we divide MaNGA galaxies into ETGs and LTGs and explore how mass growth histories of different morphological types depend on stellar mass and environment by combining multiple catalogs. Our main results are:

1. **For massive galaxies**, ETGs assemble mass faster than LTGs of the same stellar mass. However, when $M_* < 10^{10} M_\odot$, ETGs have statistically similar mass assembly histories as LTGs. This change in growth rate may result from slowed ETG growth or accelerated LTG growth. Additionally, massive galaxies always show negative metallicity gradients that hardly change with time. For less massive galaxies, ETGs and LTGs exhibit opposite metallicity gradients. We also find galaxy metallicity gradients flatten at 3 Gyr lookback time, suggesting minor mergers may play an important role in shaping mass assembly histories.
2. **ETGs have denser central regions**, smaller sizes, and larger velocity dispersions than LTGs. These differences become more significant with increasing stellar mass, implying massive ETGs experienced violent physical processes in the early universe that led to rapid central mass growth (high Sérsic index). Subsequently, minor mergers dominated mass growth, primarily altering galaxy structure and/or extending sizes to produce elliptical or S0 morphologies.
3. **ETGs experience slightly stronger tidal forces** than LTGs. The environmental distribution of low-mass ETGs shows bimodal characteristics consistent with their SFR distribution. Low-SFR ETGs reside in high tidal force environments, while high-SFR ETGs are in low tidal force environments. We suggest environmental effects play a leading role in regulating the mass growth histories of low-mass ETGs.

Understanding which physical processes shape galaxy morphologies is fundamental to galaxy evolution. In the current framework, galaxies form stars at rates placing them on the star-forming main sequence \cite{Speagle_{2014}, Renzini_{{{Peng}}_{{2015}}}}. Internal and external processes can prevent star formation, causing galaxies to transition off the main sequence and undergo morphological changes. Morphologies are generally thought to arise from mixed formation mechanisms. More observational data are needed to investigate mass assembly histories across the entire Hubble sequence.

Acknowledgments

We thank the anonymous referee for critical comments and constructive suggestions that significantly strengthened this work. This work is supported by the Natural Science Research Programs of Jiangsu Province University (23KJB160001 and 23KJB140004) and the Scientific Research Fund of Jiangsu Second Normal University (927801/032). H.T.W. is supported by the Hebei

Natural Science Foundation (grant No. A2022408002) and the Fundamental Research Funds for Universities in Hebei Province (grant No. JYQ202003).

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