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Age-density relation of Main galaxies at fixed parameters or for different galaxy families

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Abstract: Using two volume-limited Main galaxy samples of the Sloan Digital Sky Survey Data Release 10 (SDSS DR10), we examine the environmental dependence of galaxy age at fixed parameters or for different galaxy families. Statistical results show that the environmental dependence of galaxy age is stronger for late type galaxies, but can be still observed for the early types: the age of galaxies in the densest regime is preferentially older than that in the lowest density regime with the same morphological type. We also find that the environmental dependence of galaxy age for red galaxies and Low Stellar Mass (LSM) galaxies is stronger, while the one for blue galaxies and High Stellar Mass (HSM) galaxies is very weak.

Keywords: physics literature and publications; publications in electronic media; bibliographies

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1 Introduction

Some studies demonstrated that galaxy age significantly depends on local environments: young galaxies tend to reside in the low-density environments, while old galaxies tend to reside in high-density environments (e.g., [1–14]). For example, [5] and [6] reported that the member galaxies of compact groups are generally older than field galaxies. [15] investigated the environmental dependence of galaxy age in two volume-limited Main galaxy [16] samples of the Sloan Digital Sky Survey Data Release 10 (SDSS DR10) [17], and found that old galaxies exist preferentially in the densest regions of the universe, while young galaxies are located preferentially in low density regions. Such an age-

density relation is consistent with the current hierarchical assembly paradigm (e.g., [18, 19]).

Considering tight correlations between galaxy properties (e.g., [20–30]), one must take care that the strong environmental dependence of a galaxy property is likely due to the environmental dependence of other galaxy properties and tight correlations between galaxy properties when exploring the environmental dependence of galaxy properties. In this condition, it would be of great interest to examine the environmental dependence of galaxy properties at fixed parameters or for different galaxy families (e.g., [25, 31–45]). [34] demonstrated that color, color-gradient, concentration, size, velocity dispersion, and star formation rate of galaxies are nearly independent of the local density at fixed luminosity and morphology. [32] found that at fixed luminosity and color, surface brightness or Sérsic index of galaxies is not closely related to density, and argued that galaxy color is the galaxy property most predictive of the local environment. [45] studied the environmental dependence of u-band luminosity at fixed parameters or for different galaxy families. In this work, we further examine the environmental dependence of galaxy age at fixed parameters or for different galaxy families.

A key step of this work is how to characterize the local galaxy environment. The measure of nearest neighbor densities is an popular method. However, there is no prior knowledge of the best choice of the number of neighbors, which is still a subject of debate. Values from $n = 3$ [46] up to $n = 10$ [47] is a reasonable region. [48] demonstrated that the choice of the number of neighbor does not change the resulting densities significantly. Here, we use the density estimator within the distance to the 5th nearest neighbor, like many authors did (e.g., [25, 49–51]). Most authors chose to measure the projected local density Σ_5 which is computed from the distance to the 5th nearest neighbor within a redshift slice $\pm 1000 \text{ km s}^{-1}$ of each galaxy (e.g., [25, 49]). But the projected local density only is a projected quantity, which is influenced by projection effects. Maybe, each method has its drawbacks. In this study, we intend to measure the local three-dimensional galaxy density within the distance to the 5th nearest neighbor.

The morphological type, color, and stellar mass are important parameters of galaxies, which strongly depend on the local environment (e.g., [31, 32, 47, 49, 52–58]).

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Much of other parameters-density relation is likely attributable to the relations between these galaxy parameters and density. The limiting, or fixing, of these parameters exerts substantial influence on the environmental dependence of galaxy age. Thus, we examine the environmental dependence of galaxy age at fixed morphology, for blue and red galaxies and for High Stellar Mass (HSM) and Low Stellar Mass (LSM) galaxies, like [45] and [59] did. We intend to use volume-limited Main galaxy samples. The chief advantage of this approach is to avoid the complication of modeling the radial selection function in the flux-limited survey.

The outline of this paper is as follows. Section 2 describes the data used. In Section 3, we discuss the environmental dependence of galaxy age at fixed parameters or for different galaxy families. Our main results and conclusions are summarized in Section 4.

In calculating the co-moving distance, we used a cosmological model with a matter density of $\Omega_0 = 0.3$, a cosmological constant of $\Omega_\Lambda = 0.7$, and a Hubble constant of $H_0 = 70 \text{ km} \cdot \text{s}^{-1} \cdot \text{Mpc}^{-1}$.

2 Data

[15] downloaded the data of the Main galaxy sample from the Catalog Archive Server of SDSS Data Release 10 [17] by the SDSS SQL Search (<http://www.sdss3.org/dr10/>), extracted 633172 Main galaxies with the redshift $0.02 \leq z \leq 0.2$ [the Main galaxy sample corresponds to LEGACY_TARGET1 & (64 | 128 | 256) > 0], and constructed two volume-limited Main galaxy samples from such an apparent-magnitude limited Main galaxy sample. The luminous volume-limited Main galaxy sample contains 129515 galaxies at $0.05 \leq z \leq 0.102$ with $-22.5 \leq M_r \leq -20.5$, while the faint volume-limited sample includes 34573 galaxies at $0.02 \leq z \leq 0.0436$ with $-20.5 \leq M_r \leq -18.5$. The absolute magnitude M_r is calculated from the r-band apparent Petrosian magnitude, using a polynomial fit formula [60] for the mean K-correction within $0 < z < 0.3$: $K(z) = 2.3537 \times (z - 0.1)^2 + 1.04423 \times (z - 0.1) - 2.5 \times \log(1 + 0.1)$.

In this work, we used two volume-limited Main galaxy samples constructed by [15]. [15] downloaded the data set of age and stellar mass measurements from the Stellar-MassStarFormingPort table obtained with the star-forming template and the Kroupa IMF [61]. [15] considered the mass lost via stellar evolution and used best-fit age of galaxy [in Gyr] and best-fit stellar mass [in $\log M_{\text{sun}}$].

3 Environmental dependence of galaxy age at fixed parameters or for different galaxy families

Following previous works (e.g., [44, 56, 57]), we measured the local three-dimensional galaxy density (Galaxies Mpc^{-3}) which is defined as the number of galaxies ($N=5$) within the three-dimensional distance to the 5th nearest galaxy to the volume of the sphere with the radius of this distance. Like [56] did, for each sample, we arrange galaxies in a density order from the smallest to the largest, selects approximately 5% of the galaxies, construct two sub-samples at both extremes of density according to the density, and compare distribution of age in the lowest density regime with that in the densest regime.

3.1 Environmental dependence of galaxy age at fixed morphology

When performing morphological classification of galaxy samples with large numbers of galaxies, one often used a galaxy parameter or combination of some parameters that exhibit a strong correlation with morphological type, as the morphology classification tool (e.g., [21, 31, 62–69]). The concentration index is closely related to the morphological type ([62, 64, 65, 70–72]). Some authors demonstrated that the concentration index is a relatively good and straightforward parameter to use for classifying the morphology of galaxies (e.g., [62, 64, 65, 73]). Following previous works (e.g., [10, 37, 44, 45, 62]), in this study, we also use the r-band concentration index $ci = R_{90}/R_{50}$ to separate early-type ($ci \geq 2.86$) galaxies from late-type ($ci < 2.86$) galaxies [62, 64]. R_{50} and R_{90} are the radii enclosing 50% and 90% of the Petrosian flux, respectively. We divide each volume-limited Main galaxy sample into two distinct populations: the early-type and the late-type. The luminous volume-limited Main galaxy sample contains 50130 early-type galaxies and 79385 late-type galaxies, the faint volume-limited Main galaxy sample includes 6468 early-type galaxies and 28105 late-type galaxies.

Between early types and late types, the environmental dependence of galaxy properties is likely to be fairly different. [34] reported that the environmental dependence of r-band luminosity is stronger for early type galaxies, and is weaker but can be still observed for the late types. [37] also observed stronger local density dependence of r-band luminosity for the early type galaxies. However, some studies showed the environmental dependence of

many other properties is stronger for late type galaxies (e.g., [34, 37, 44, 45, 51]). [51] found that for the red/early-type population color of galaxies does not change significantly with density; for the blue/late-type population, the color of galaxies becomes redder with increasing density. [34] showed that when the local density varies from $\rho/\bar{\rho} \approx 15$ to ≈ 0.37 , the color of galaxies changes only by 0.03 for early types and by 0.11 for late types. [37] argued that the correlation between color and the environment in the late-type sample is much stronger than the one in the early-type sample. [44] demonstrated that the environmental dependence of the star formation rate (SFR) and the specific star formation rate (SSFR) for late-type galaxies is stronger than the one for early-type galaxies. [45] also observed that the abnormal environmental dependence of u-band luminosity for late-type galaxies is fairly strong in the redshift range $0.03 \leq z \leq 0.09$, while the one for early-type galaxies is very weak in nearly all redshift bins. Figure 1 and Figure 2 present the age distribution at both extremes of density for early-types and late-types in the luminous and faint volume-limited Main galaxy samples. Overall, our results indicate that the age of galaxies in the densest regime is preferentially older than that in the lowest density regime with the same morphological type. The Kolmogorov-Smirnov (KS) test checks if two independent distributions in each figure are similar or different, by calculating a probability value. Table 1 lists statistical results of the Kolmogorov-Smirnov (KS) test. As shown by Figures 1–2 and Table 1, in two volume-limited Main galaxy samples, we can get the same conclusions: the environmental dependence of galaxy age is stronger for late type galaxies, similar to the behavior of many other properties.

[57] found that r-band luminosity of galaxies strongly depend on local environments in the luminous volume-limited Main galaxy sample, but this dependence is very weak in the faint volume-limited Main galaxy sample. However, some works demonstrated other properties of galaxies still strongly depends on local environments in the faint volume-limited sample, like the one in the luminous volume-limited sample does (e.g., [40, 41, 44, 57, 74, 75]). Here, we again note the abnormal behavior of r-band luminosity, compared with other galaxy properties. This question merits further investigation.

3.2 Environmental dependence of galaxy age for blue and red galaxies

Galactic extinction correction is applied to our galaxy samples. Above and below the divider (the observed u-

r color=2.22) developed by [21], we classify galaxies in the two volume-limited Main galaxy samples as 'red' and 'blue', respectively. The luminous volume-limited Main galaxy sample contains 77635 red galaxies and 51880 blue galaxies, the faint volume-limited Main galaxy sample includes 10574 red galaxies and 23999 blue galaxies.

As indicated as above-mentioned, previous works showed that except r-band luminosity, the environmental dependence of galaxy properties for late-type galaxies is much stronger than that for early-type galaxies (e.g., [34, 37, 44, 45, 51]). In this work, we again demonstrate that the environmental dependence of galaxy age is stronger for late type galaxies, similar to the behavior of many other properties. In the past, it is widely accepted that the majority of the red population corresponds to objects with early-types, and that the majority of the blue population corresponds to late-types [21]. Therefore, one can expect that the environmental dependence of galaxy properties for blue galaxies should be stronger than that for red galaxies. However, Figures 3–4 and Table 1 show that the environmental dependence of galaxy age is stronger for red galaxies, but is fairly weak for blue galaxies. [40] also found that the environmental dependence of the SFR and SSFR for blue galaxies is very weak, while the one for red galaxies is fairly strong. These results show that the correlation between galaxy morphology and color is not tight. Indeed, [76] and [43] observed that a significant fraction of red galaxies are not early-types, which means that early type galaxies are dominated by red ones, but red galaxies are not dominated by early types.

The color of galaxies is the galaxy property that is very predictive of its local environment (e.g., [32, 36]). Some works showed that at fixed color, the environmental dependence of galaxy other properties is greatly decreased ([36, 40, 43, 45]). [73] even argued that color is fundamental in correlations between galaxy properties and the environment and that much of the other galaxy properties-density relation are likely due to the relation between color and density. In this study, we note that at fixed color, the environmental dependence of galaxy age is substantially reduced.

3.3 Environmental dependence of galaxy age for High Stellar Mass (HSM) and Low Stellar Mass (LSM) galaxies

Following [77], we divide each volume-limited Main galaxy sample into two distinct families at a stellar mass of $3 \times 10^{10} M_{\odot}$: the High Stellar Mass (HSM) and the Low Stellar Mass (LSM). The luminous volume-limited Main galaxy

Table 1: The Kolmogorov-Smirnov (KS) test probabilities that the two independent distributions in each of Figures 1–6 are drawn from the same parent distribution.

The figure	p	The figure	P
Figure 1 (left panel)	5.91e-18	Figure 1 (right panel)	2.46e-38
Figure 2 (left panel)	1.43e-10	Figure 2 (right panel)	6.41e-37
Figure 3 (left panel)	3.14e-33	Figure 3 (right panel)	0.041
Figure 4 (left panel)	7.56e-16	Figure 4 (right panel)	8.49e-08
Figure 5 (left panel)	6.32e-06	Figure 5 (right panel)	8.31e-15
Figure 6 (left panel)	0.77	Figure 6 (right panel)	0

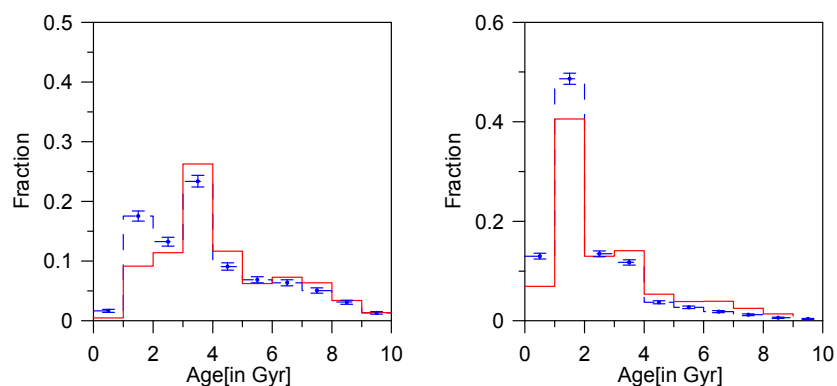


Figure 1: Age distribution at both extremes of density for early-types (left panel) and late-types (right panel) in the luminous volume-limited Main galaxy sample: red solid line for the sub-sample at high density, blue dashed line for the sub-sample at low density. The error bars of the blue lines are 1σ Poissonian errors. The error-bars of the red lines are omitted for clarity.

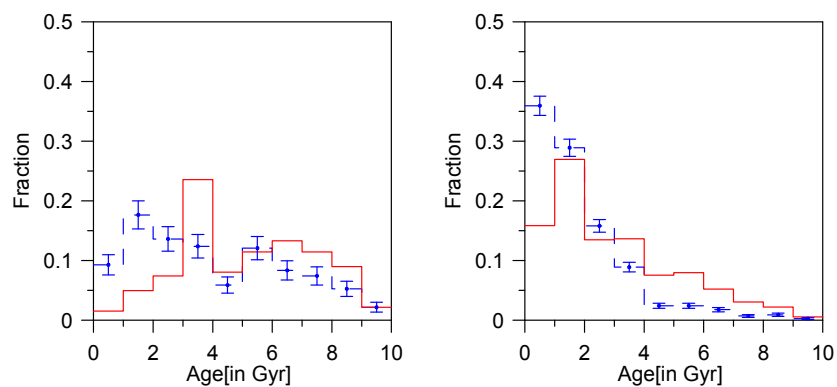


Figure 2: As Figure 1 but for age distribution at both extremes of density for early-types (left panel) and late-types (right panel) in the faint volume-limited Main galaxy sample.

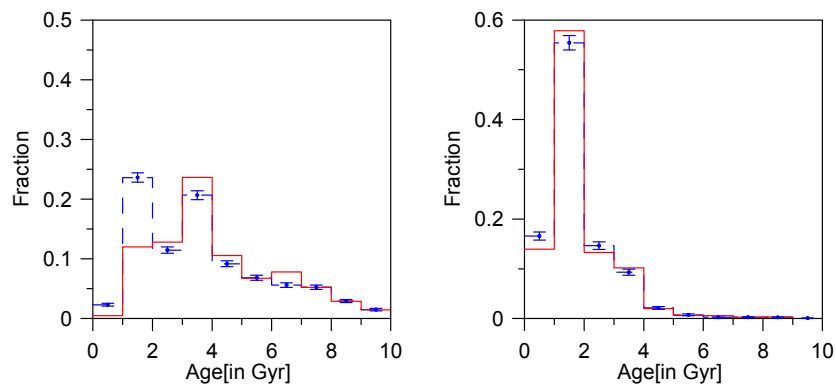


Figure 3: As Figure 1 but for age distribution at both extremes of density for the red galaxies (left panel) and blue galaxies (right panel) in the luminous volume-limited Main galaxy sample.

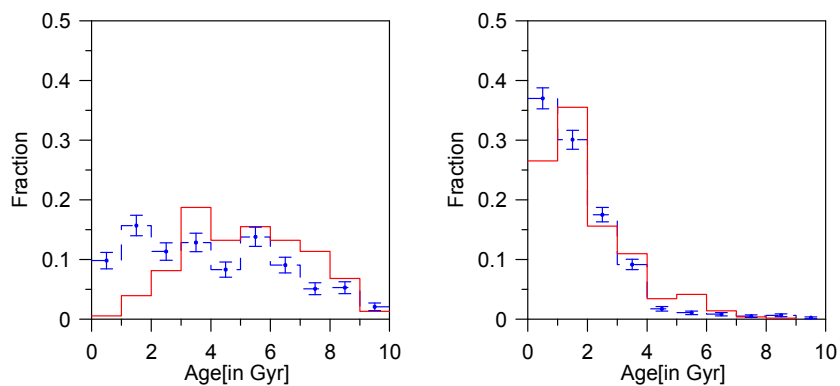


Figure 4: As Figure 1 but for age distribution at both extremes of density for the red galaxies (left panel) and blue galaxies (right panel) in the faint volume-limited Main galaxy sample.

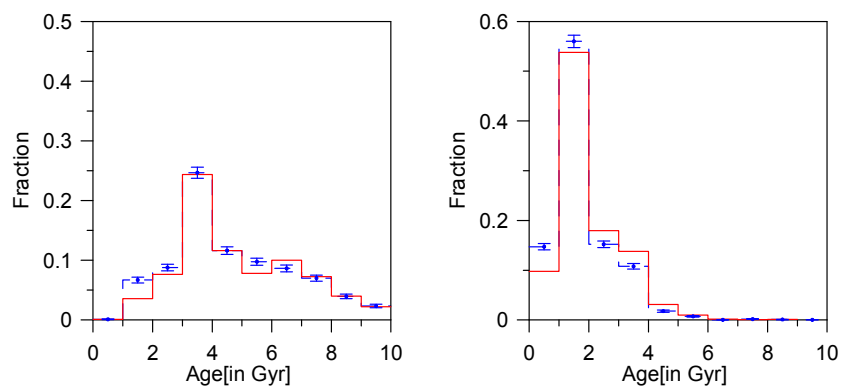


Figure 5: As Figure 1 but for age distribution at both extremes of density for the HSM galaxies (left panel) and LSM galaxies (right panel) in the luminous volume-limited Main galaxy sample.

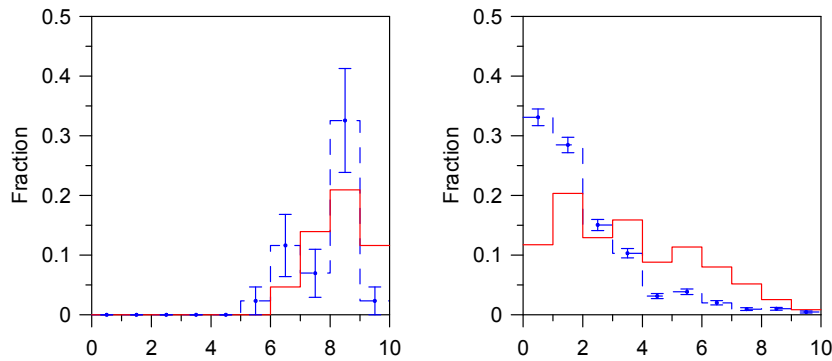


Figure 6: As Figure 1 but for age distribution at both extremes of density for the HSM galaxies (left panel) and LSM galaxies (right panel) in the faint volume-limited Main galaxy sample.

sample contains 56788 HSM galaxies and 72727 LSM galaxies, the faint volume-limited Main galaxy sample includes 857 HSM galaxies and 33716 LSM galaxies.

The environmental dependence of galaxy properties at fixed stellar mass is somewhat complicated. Some authors reported that at fixed stellar mass, color, star formation and nuclear activity still are strongly correlated with local density, while morphology, size and concentration weakly depend on environment (e.g., [31, 35]). [39] divided a volume-limited Main galaxy sample of the SDSS into two sub-samples: HSM galaxies and LSM galaxies, and found that for HSM and LSM galaxies, color, morphologies and star formation activities still very strongly depend on environment, but size is weakly correlated with environment. [42] performed the comparative studies between HSM galaxies and LSM galaxies in two volume-limited Main galaxy samples of the SDSS and demonstrated that the environmental dependence of the SFR and SSFR for luminous HSM galaxies and faint LSM galaxies remains very strong, while the one for luminous LSM galaxies is substantially reduced. [42] also found that the fraction of AGNs in HSM galaxies decreases with increasing density, while the one in LSM galaxies is almost independent of on local density. In the apparent-magnitude limited Main galaxy sample, [45] showed that the abnormal environmental dependence of u-band luminosity for LSM galaxies is fairly strong in the redshift range $0.03 \leq z \leq 0.09$, while the one for HSM galaxies is very weak in nearly all redshift bins. One possible explanation is that the majority of LSM galaxies corresponds to late-types.

Figures 5–6 present the age distribution at both extremes of density for HSM galaxies and LSM galaxies in the luminous and faint volume-limited Main galaxy sam-

ples. In the faint volume-limited sample, the number of HSM galaxies is only 857, which results in large error bars of the left panel of Figure 6. As shown by Figures 5–6 and Table 1, the environmental dependence of galaxy age for LSM galaxies remains very strong, especially in the faint volume-limited sample, while the one for HSM galaxies is fairly weak. Nearly all galaxies in the faint volume-limited sample are LSM galaxies. Therefore, the environmental dependence of galaxy age for faint LSM galaxies should be close to the one in the entire faint volume-limited sample. [15] reported that in the faint volume-limited Main galaxy sample, K-S probability of the galaxy age distributions at both extremes of density is nearly 0.

4 Summary

Using two volume-limited samples constructed from the Main galaxy data of SDSS DR10, we examine the environmental dependence of galaxy age at fixed parameters or for different galaxy families. We measure the three-dimensional density within the distance to the 5th nearest neighbor, proceed with the same approach as used by [56] did, and compare distribution of age in the lowest density regime with that in the densest regime. The main results can be summarized as follows:

1. The environmental dependence of galaxy age is stronger for late type galaxies, but can still be observed for the early types, similar to the behavior of many other properties.
2. At fixed color, the environmental dependence of galaxy age is substantially reduced. The environmental dependence of galaxy age is stronger for red galax-

ies, but is fairly weak for blue galaxies. Considering the environmental dependence of galaxy age at fixed morphology, this further shows that the correlation between galaxy morphology and color is not tight.

3. The environmental dependence of galaxy age for LSM galaxies remains very strong, especially in the faint volume-limited sample, while the one for HSM galaxies is fairly weak, which can be explained by an age-density relation at fixed morphology and a strong morphology-stellar mass relation.

When exploring the environmental dependence of u-band luminosity and stellar velocity dispersion at fixed parameters or for different galaxy families, [45] and [59] applied the apparent-magnitude limited Main galaxy sample of the SDSS. [45] found that the abnormal environmental dependence of u-band luminosity for late-type galaxies and Low Stellar Mass (LSM) galaxies is fairly strong in the redshift range $0.03 \leq z \leq 0.09$, while the one for early-type galaxies, High Stellar Mass (HSM) galaxies, red galaxies and blue galaxies is very weak in nearly all redshift bins. [59] demonstrated that the environmental dependence of the stellar velocity dispersion for red galaxies is very strong in certain redshift bins. This dependence can still be observed in some redshift bins for late-type galaxies, HSM galaxies and LSM galaxies, but is fairly weak in all redshift bins for early-type galaxies and blue galaxies. These results show that the environmental dependence of galaxy properties at fixed parameters or for different galaxy families is very complicated, which needs further investigation.

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