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INVESTIGATION OF THE ENVIRONMENTAL DEPENDENCE OF GALAXY AGE IN THE CMASS GALAXY SAMPLE OF SDSS DR12

XIN-FA DENG

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In this study, I investigate the environmental dependence of galaxy age in the CMASS sample of the Sloan Digital Sky Survey Data Release 12 (SDSS DR12). It is found that galaxy age is very weakly correlated with the local environment. Considering the weak stellar mass-density relation of CMASS galaxies, it has been suggested that it is likely a combination of a strong age-stellar mass relation and a weak stellar mass-density relation.

Keywords: *galaxy: fundamental parameters - galaxies: statistics*

1. *Introduction*. In the past, many studies showed that in the local Universe, galaxies in low-density environments are generally younger than galaxies in high-density environments [1-14]. Proctor et al. [5] and Mendes de Oliveira et al. [6] reported that the galaxies in compact groups are generally older than field galaxies. Thomas et al. [7] demonstrated that massive early-type galaxies in low-density environments appear younger (on average ≈ 2 Gyr) than their counterparts in high-density environments, which is qualitatively consistent with the predictions from semianalytic models of galaxy formation [15]. In mock galaxy catalogs, Reed et al. [11] found that older mock galaxies significantly are more clustered. Their results also suggested that the clustering-age dependence is manifested in real galaxies. Rakos et al. [12] argued that there is a significant correlation between the galaxies mean age and their distance from the cluster center: older galaxies inhabit the core. When investigating the variation in stellar population ages of Coma cluster galaxies as a function of projected cluster-centric distance, Smith et al. [14] noted a clear distinction between the giant and dwarf galaxies. The age of red-sequence giants only has a weak environmental dependence, while the age of red-sequence dwarfs has strong trends with projected cluster-centric radius. The average age of dwarfs at the boundary of their sample on 2.5 Mpc is approximately half that of dwarfs near the cluster centre. The current hierarchical assembly paradigm predicts that galaxies are younger in lower density environments [16-17].

In the local Universe, galaxy colors are strongly correlated with environments

[18-23], but in intermediate and high redshift regions, the color-density relation is too weak [24-26]. Similarly, the environmental dependence of stellar mass is quite strong in the local Universe [27-30], but it is too weak in the SDSS luminous red galaxy sample and galaxy samples in the Baryon Oscillation Spectroscopic Survey (BOSS) [31-32]. At intermediate redshifts, Grützbauch et al. [25] also found a weak environmental dependence of stellar mass. These studies showed that the environmental dependence of galaxy properties is likely different in different redshift regions. Thus, it would be of great interest to explore the environmental dependence of galaxy age in intermediate and high redshift regions.

The BOSS is one of four surveys in the SDSS-III project [33]. It is carrying out a redshift survey of 1.5 million luminous red galaxies at $0.15 < z < 0.8$ over 10000 square degrees. The BOSS is designed to measure the baryon oscillation signature in the correlation function of galaxies [34-37]. Meanwhile, using the BOSS galaxy sample, some authors also explored many other galaxy issues [32,38-45]. Masters et al. [38] studied the morphology and size of BOSS galaxies. Applying principal component analysis, Chen et al. [39] calculated some parameters of BOSS galaxies, such as stellar masses, mean stellar ages, star formation histories (SFHs), dust extinctions and stellar velocity dispersions, and investigated the correlation between the fraction of galaxies with active star formation and stellar mass. Maraston et al. [40] explored the uniformity of mass sampling as a function of redshift. Deng [42] performed comparative studies of properties of star forming galaxies and active galactic nuclei between two BOSS galaxy samples of SDSS Data Release 9 [46]. Deng [43] and Deng, Zou [32,44] examined the environmental dependence of colors, stellar mass and all five band luminosities for BOSS galaxy samples.

The BOSS galaxy sample can be divided into two principal samples at $z \approx 0.4$: a Low Redshift (LOWZ) sample and a Constant Mass (CMASS) sample. The LOWZ sample, a low redshift sample with a median redshift of $z = 0.3$, is a simple extension of the SDSS I and II luminous red galaxy samples [47] and can be used for comparison with them. The CMASS sample, a high redshift sample with a redshift of $0.43 < z < 0.7$, selects galaxies with roughly a constant stellar mass, and is a nearly complete sample of massive galaxies above $z \approx 0.4$. Such a sample is a good representative of intermediate-redshift galaxy samples. The primary goal of this study is to investigate the environmental dependence of the age of CMASS galaxies. My paper is organized as follows. In section 2, I describe the data used. The environmental dependence of age of CMASS galaxies is discussed in section 3. My main results and conclusions are summarized in section 4.

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

2. *Data*. Data Release 12 (DR12) [48] of the SDSS is the final public release of spectroscopic data from the SDSS-III BOSS, which includes the first spectra of the Multi-object APO Radial Velocity Exoplanet Large-area Survey(MARVELS), additional data from the APO Galactic Evolution Experiment(APOGEE) and additional sky coverage and better galaxy parameter estimates from BOSS. In this work, the data was downloaded from the Catalog Archive Server of SDSS Data Release 12 [48] by the SDSS SQL Search. Because most CMASS galaxies are located between $0.43 < z < 0.7$, I extract 858977 CMASS galaxies with a redshift of $0.43 \le z \le 0.7$.

Maraston et al. [40] employed two template fittings (passive and star-forming) and two adopted Initial Mass Functions (IMFs) (Salpeter and Kroupa). The passive model does not include the possibility of a non-zero SFR (star formation rate). The selection of the star-forming template and the Kroupa IMF leads to the largest number of non-zero SFR galaxies. Considering that further investigation would likely shed light on the SFR of galaxies, we use the best-fit age of galaxy (in Gyr) obtained with the star-forming template and the Kroupa IMF [40]. The data set of age measurement is from the StellarMassStarFormingPort table.

3. *Environmental dependence of age in the CMASS galaxy sample*. When using the CMASS galaxy sample, some authors restricted their analysis to the redshift range $0.43 < z < 0.7$ [34,36,38,41]. For example, Reid et al. [41] examined the anisotropic clustering of BOSS galaxies in the redshift range $0.43 < z < 0.7$. Masters et al. [38] investigated the morphology and size of the luminous and massive galaxies at $0.3 < z < 0.7$. However, Deng & Zou [32] demonstrated that the CMASS sample with a redshift of $0.43 \le z \le 0.7$ seriously suffers from the radial selection effect. In the CMASS sample with a redshift of $0.43 \le z \le 0.7$, an abnormal trend is observed: high mass galaxies exist preferentially in low density regions of the universe, while low mass galaxies are located preferentially in the densest regions. Deng & Zou [32] argued that this is likely due to the radial selection effect in this CMASS sample.

Dawson et al. [49] and Anderson et al. [34] demonstrated that the radial selection effect of CMASS galaxies is fairly serious at redshift $z > 0.6$. However, BOSS is a mass-uniform sample over the redshift range 0.2 to 0.6 [40]. Thus, Deng & Zou [32] constructed a CMASS sample with a redshift of $0.44 \le z \le 0.6$. Deng & Zou [32] believed that this CMASS sample should be a relatively uniform sample, in which the radial selection effect is less important. In this CMASS sample, Deng & Zou [32] found that the environmental dependence of the stellar mass of CMASS galaxies is fairly weak.

In this work, I measure the projected local density $\sum_5 = N/\pi d_5^2$ (Galaxies Mpc^{-2}) where d_5 is the distance to the 5th nearest neighbor within $\pm 1000\,\mathrm{km\,s^{-1}}$ in redshift [50-52]. Following Deng et al. [21], I arrange galaxies in a density order from the smallest to the largest, select approximately 5% of the galaxies, construct two subsamples at both extremes of density according to the density, and compare the distribution of age in the lowest density regime with that in the densest regime. Fig.1 shows age distribution at both extremes of density for the CMASS galaxy sample with a redshift of $0.44 \le z \le 0.6$, which contains 656087 galaxies. As shown by this figure, the age of CMASS galaxies is nearly independent of the local environment.

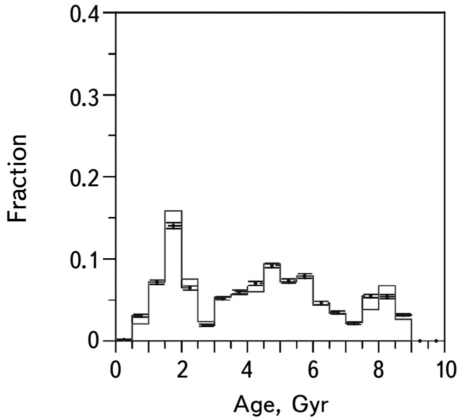

Fig.1. Age distribution at both extremes of density for the CMASS sample with the redshift $0.44 \le z \le 0.6$: solid line represents the subsample at high density, dashed line represents the subsample at low density. The error bars of the dashed lines are 1σ Poissonian errors. The error bars of the solid lines are omitted for clarity.

It is important to keep in mind that the CMASS sample with a redshift of $0.44 \le z \le 0.6$ still suffers from the radial selection effect. A good choice for removing this effect is to use the volume-limited galaxy sample. However, it is difficult to construct an ideal volume-limited sample from the CMASS galaxy sample because it is not simply flux-limited. The statistical method of Deng [53] can substantially reduce the influence of the radial selection effect on statistical results. In order to make the maximum use of observational data, Deng [53] used the apparent-magnitude limited sample, divided the entire galaxy sample into subsamples with a redshift binning size of $\Delta z = 0.01$ and focused on a statistical analysis of the subsamples in each redshift bin. Deng [53] argued that in each redshift bin, the radial selection effect is less important. It is noteworthy that in such a study, the environmental dependence of galaxy properties in each subsample is likely to be greatly decreased, due to each subsample being limited to a small redshift range, $\Delta z = 0.01$. However, some works demonstrated that in the redshift bin $\Delta z = 0.01$, the environmental dependence of galaxy properties can still be observed if it exists [30,53,54].

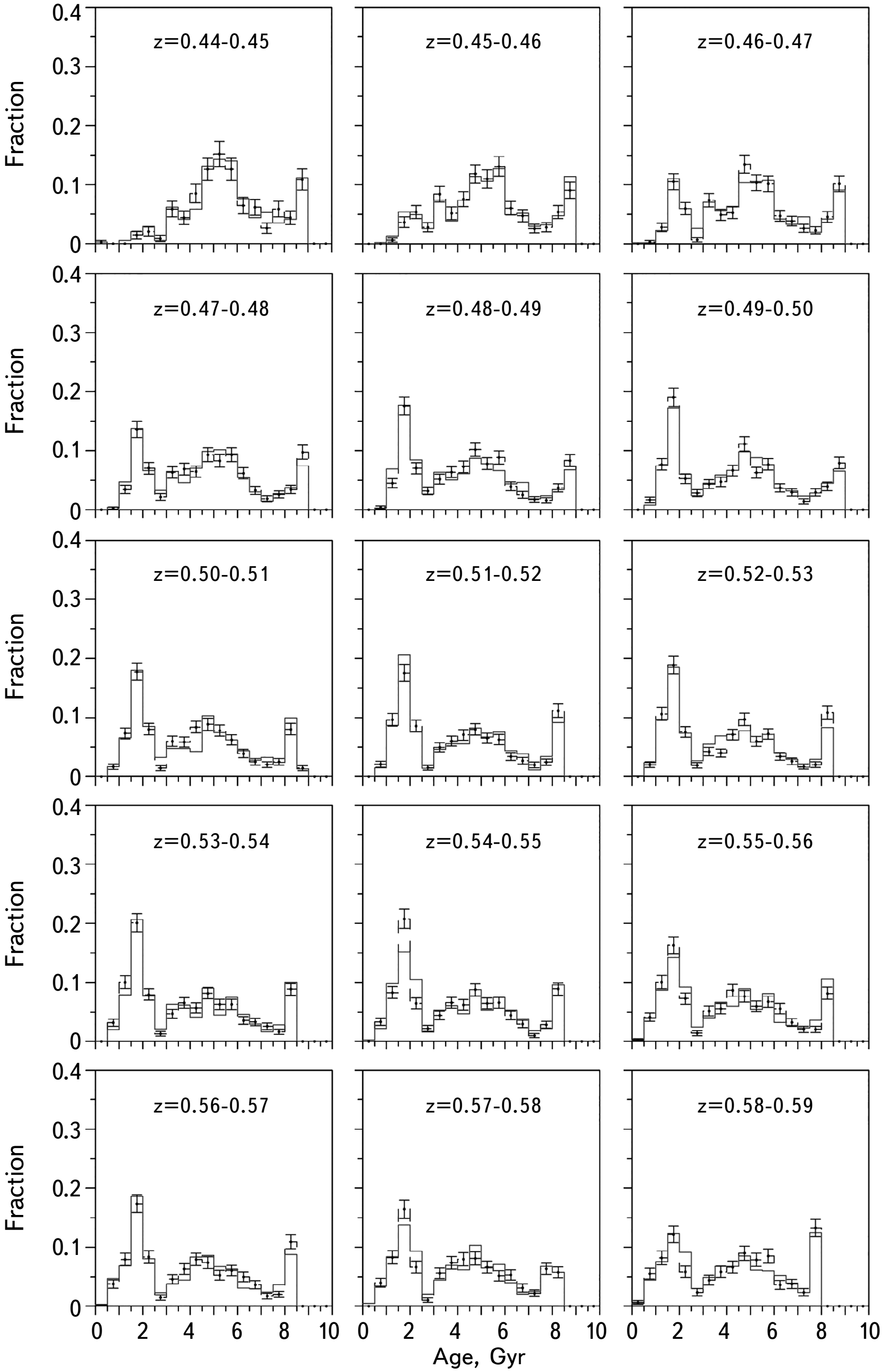

Fig.2. Age distribution at both extremes of density in different redshift bins: solid line represents the sample at high density, dashed line represents the sample at low density. The error bars of the dashed lines are 1σ Poissonian errors. The error-bars of the solid lines are omitted for clarity.

Following Deng [43,53], I extract a galaxy sample from the CMASS DR12 that comprises 621837 CMASS galaxies with a redshift of $0.44 \le z \le 0.59$ and divide this sample into subsamples with a redshift binning size of $\Delta z = 0.01$, and then analyze the environmental dependence of age of subsamples in each redshift bin. Fig.2 show age distribution at both extremes of density in different redshift bins for this CMASS galaxy sample. The level of significance of the difference between two distributions is nearly within 1σ in most bins, which indicates that the age of CMASS galaxies is almost independent of the local environment in all redshift bins.

I performed the Kolmogorov-Smirnov (KS) test that investigates if two independent distributions are similar or different, by calculating a probability value. If two independent distributions in a figure completely differ, its KS probability should be close to 0. The KS probability of Fig.1 is 0.00136, which is much larger than 0. This KS probability indeed is quite large, compared with those of strong environmental dependence. Table 1 also lists the KS probability in all redshift bins, which is much larger than that obtained by Deng [53], Deng et al. [30] and Deng et al. [54] (see Table 1 of Deng [53] and Deng et al. [30]) and even is much larger than 0.05 (5%, is the standard in statistical analysis). Such a result shows that two independent distributions in these two figures are very similar. It is in good agreement with the conclusion obtained by the histogram figures.

Table 1

KS PROBABILITIES OF Fig.2 IN EACH REDSHIFT BIN THAT TWO SAMPLES AT BOTH EXTREMES OF DENSITY ARE DRAWN FROM THE SAME DISTRIBUTION

Redshift bins	Galaxy number	P	Redshift bins	Galaxy number	P
0.44-0.45	20651	0.976	0.52-0.53	49030	0.528
0.45-0.46	27825	0.954	0.53-0.54	47301	0.579
0.46-0.47	34481	0.917	0.54-0.55	46175	0.268
0.47-0.48	41165	0.759	0.55-0.56	44768	0.334
0.48-0.49	44988	0.462	0.56-0.57	43058	0.876
0.49-0.50	48574	0.719	0.57-0.58	38843	0.928
0.50-0.51	50037	0.238	0.58-0.59	35896	0.679
0.51-0.52	49045	0.993			

Grützbauch et al. [25] demonstrated that stellar mass is weakly correlated with the environment at intermediate redshifts. They also found that at redshifts $0.4 < z < 0.7$, galaxy color has a weak environmental dependence, and claimed that such a weak color-density relation is a combination of a strong color-stellar mass relation and a weak stellar mass-density relation. Grützbauch et al. [26] further showed that the colors of galaxies are strongly dependent on the stellar mass at redshifts up to $z \approx 3$ and argued that stellar mass is the most important factor in determining the colors of galaxies and that the environment likely has a small additional effect. Grützbauch et al. [26] argued that a possible interpretation for this is that the environmental processes that exert the main influence on galaxy properties proceed slowly over cosmic time.

Fig.3 shows averaged stellar mass as a function of age for the CMASS sample with a redshift of $0.44 \le z \le 0.6$. In Fig.3, I observe a tight correlation between stellar mass and age. This suggests that the weak age-density relation obtained in this work is likely a combination of a strong age-stellar mass relation and a weak stellar mass-density relation [55]. Stellar mass is also the most important factor in determining the age of galaxies.

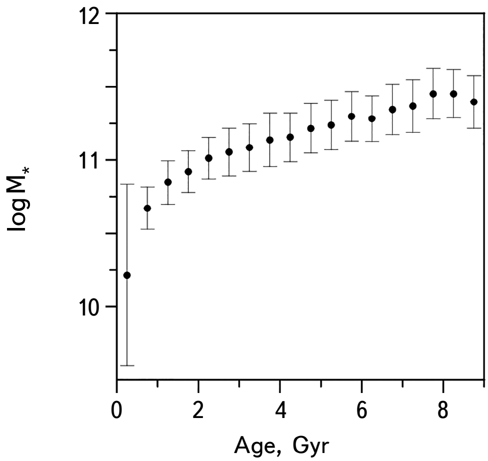

Fig.3. Averaged stellar mass as a function of age for the CMASS sample with the redshift $0.44 \le z \le 0.6$. Error bars represent standard deviation in each redshift bin.

4. *Summary*. In the local Universe, galaxy age strongly depends on the local environment [56]. I note that the strong environmental dependence of some typical galaxy properties (such as colors and stellar mass) in the local Universe cannot extend to intermediate- and high-redshift regions. Thus, it is necessary to explore the environmental dependences of galaxy age in intermediate and high redshift regions.

In this work, I investigate the environmental dependence of age in the CMASS sample of the SDSS DR12 [48]. Considering the radial selection effect in the CMASS sample, I use a CMASS sample with a redshift of $0.44 \le z \le 0.6$, which is a mass-uniform sample. To further decrease the influence of the radial selection effect, following Deng [53], I also divide the CMASS sample with a redshift of $0.44 \le z \le 0.59$ into several subsamples with a redshift binning size of $\Delta z = 0.01$

and I analyze the environmental dependence of age of subsamples in each redshift bin. Statistical results show that galaxy age is very weakly correlated with the local environment. Due to the weak stellar mass-density relation of CMASS galaxies [55], such a weak age-density relation of CMASS galaxies is likely a combination of a strong age-stellar mass relation and a weak stellar mass-density relation.

Apparently, the environmental dependence of age in the CMASS sample is inconsistent with that obtained in the local Universe. A possible interpretation of this result is that stellar mass essentially influences on age of galaxies and that the environment likely has a small additional effect only at the most extreme dense regions. The environmental processes that exert the main influence on galaxy properties proceed slowly over cosmic time. Some of the most influential high-density environments may still be in the process of developing and cannot yet affect galaxy age.

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School of Science, Nanchang University, Jiangxi, China, 330031,
e-mail: xinfadeng@163.com

ИССЛЕДОВАНИЕ ЗАВИСИМОСТИ ВОЗРАСТА ГАЛАКТИК ОТ ОКРУЖАЮЩЕЙ СРЕДЫ В ВЫБОРКЕ CMASS ГАЛАКТИК SDSS DR12

КСИН-ФА ДЭНГ

В работе исследована зависимость возраста галактик от окружающей среды в выборке CMASS из 12-го выпуска данных цифрового обзора неба Sloan (SDSS DR12). Установлено, что возраст галактик очень слабо коррелирует с локальной средой. Рассматривая слабую связь звездной массы и плотности галактик CMASS, предположено, что она, вероятно, является комбинацией сильной связи возраст-звездная масса и слабой связи звездная масса-плотность.

Ключевые слова: *фундаментальные параметры - галактики: статистика*

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