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# THE ENVIRONMENTAL DEPENDENCE OF GALAXY AGE AND STELLAR MASS IN THE REDSHIFT REGION $0.6 \leq z \leq 0.75$

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ABSTRACT

In this work, I construct a LRG (Luminous Red Galaxy) sample with redshifts $0.6 \leq z \leq 0.75$ from the Sloan Digital Sky Survey Data Release 15 (SDSS DR15), which contains 184172 CMASS LRGs and 27158 eBOSS LRGs, and examine the environmental dependence of galaxy age and stellar mass in this galaxy sample. I divide this LRG sample into subsamples with a redshift binning size of $\Delta z = 0.01$, and analyze the environmental dependence of galaxy age and stellar mass for these subsamples in each redshift bin. Overall, galaxy age and stellar mass in the LRG sample with redshift $0.6 \leq z \leq 0.75$ are very weakly correlated with the local environment, which shows that minimal environmental dependence of galaxy parameters can continue to larger redshifts.

RESUMEN

En este trabajo se compila una muestra de galaxias luminosas rojas (LRG) con corrimientos al rojo $0.6 \leq z \leq 0.75$ extraída del Sloan Digital Sky Survey Data Release 15 (SDSS DR15), que contiene 184172 CMASS LRGs y 27158 eBOSS LRGs. Se estudia la dependencia ambiental de las edades de las galaxias de esta muestra y de las masas estelares. Se divide la muestra de LGRs en submuestras usando una $\Delta z = 0.01$ y se analiza la dependencia ambiental de las edades de las galaxias y las masas estelares en cada intervalo de $z$. En general, la correlación de las edades galacticas y las masas estelares en la muestra LRG con $0.6 \leq z \leq 0.75$ con el medio ambiente local es leve, lo que muestra que la mínima dependencia ambiental de los parámetros galácticos puede extenderse a corrimientos al rojo mayores.

*Key Words:* galaxies: fundamental parameters — galaxies: statistics

## 1. INTRODUCTION

In the past, many works have shed light on the environmental dependence of galaxy parameters. The extended Baryon Oscillation Spectroscopic Survey (eBOSS) of the Sloan Digital Sky Survey IV (SDSS-IV) aims to map the galaxy, quasar, and neutral gas distributions between $z \simeq 0.6$ and 3.5 (Dawson et al. 2016). The LRG component of SDSS-IV /eBOSS will obtain spectroscopy of a sample of luminous early-type galaxies in the redshift range $0.6 < z < 1.0$ (median redshift 0.71) (Prakash et al. 2016). The SDSS-IV /eBOSS LRGs will cover a volume either not probed, or not probed at high density, by SDSS-III /BOSS, and will provide a powerful extension of SDSS-III /BOSS for many studies of galaxies at high redshifts. The primary goal of this study is to explore the environmental dependence of galaxy age and stellar mass in the redshift range $0.6 \leq z \leq 0.75$.

In the local Universe, galaxy age and stellar mass strongly depend on the environment: galaxies in high density regions are generally older and more-massive than galaxies in low density regions (e.g., Bernardi et al. 1998; Trager et al. 2000; Kuntschner et al. 2002; Terlevich & Forbes 2002; Kauffmann et al. 2004; Proctor et al. 2004; Mendes de Oliveira et al. 2005; Thomas et al. 2005; Gallazzi et al. 2006; Li et al. 2006; Sánchez-Blázquez et al. 2006; Sil'chenko 2006; Reed et al. 2007; Rakos et al. 2007; Wegner & Grogin 2008; Deng et al. 2011, 2012a; Smith et al. 2012). Proctor et al. (2004) and Mendes de Oliveira et al. (2005) noted that field galaxies are generally younger than member galaxies of compact groups. Rakos et al. (2007) showed the correlation between galaxy mean age and distance from the cluster center: older galaxies inhabit the core. Kauffmann et al. (2004) reported that galaxies in high-density environments have larger masses than galaxies in low-density environments. Li et al. (2006) found that more-massive galaxies cluster more strongly than less-massive galaxies. But some studies demonstrated the environmental dependence of galaxy age and stellar mass becomes weak with increasing redshift. Deng et al. (2012b) argued that the stellar mass of SDSS LRGs with redshifts $0.16 \leq z \leq 0.3$ is nearly independent of local environments. Grützbauch et al. (2011a) claimed that galaxies at intermediate redshifts also have only a weak dependence of stellar mass on environment. Deng & Zou (2014) and Deng (2015, 2019) found that galaxy age and stellar mass in the CMASS sample of SDSS-III/BOSS (Eisenstein et al. 2011) are very weakly correlated with environment. To demonstrate the variation of the environmental dependence of galaxy age and stellar mass with redshift, it is important to examine the environmental dependence of these two galaxy parameters in the higher redshift region.

The outline of this paper is as follows. In § 2, I describe the galaxy sample. I present statistical result in § 3 and a discussion in § 4. I summarize my main results and conclusions in § 5.

In calculating the distance, I 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 $H_0$=70km$\cdot$s$^{-1}\cdot$ Mpc$^{-1}$.

## 2. SAMPLE

The Constant Mass (CMASS) sample SDSS-III/BOSS (Eisenstein et al. 2011) is a high redshift sample with a redshift of $0.43 < z < 0.7$. Anderson et al. (2012) and Dawson et al. (2013) claimed that the BOSS galaxies are selected to have approximately uniform comoving number density only out to a redshift $z = 0.6$. Maraston et al. (2013) also showed that BOSS is a mass-uniform sample over the redshift range 0.2 to 0.6. Thus, in my previous works, the CMASS sample was limited to the redshift region of $0.44 \leq z \leq 0.59$ (Deng 2015, 2019). I hope to extend studies for the environmental dependence of galaxy age and stellar mass to a higher redshift region. In this work, the data of the galaxy sample was downloaded from the Catalog Archive Server of SDSS Data Release 15 (Aguado et al. 2019) by the SDSS SQL Search (`https://www.sdss.org/dr15/`). I extracted 194380 CMASS LRGs (with SDSS flag: BOSS_TARGET1&128>0) and 48131 eBOSS LRGs (with SDSS flag: eBOS _TARGET1 & $(2 \mid 4 \mid 8) > 0$) in the redshift region of $0.6 < z < 1.0$. Because the number of galaxies at redshifts $z > 0.75$ is too small to ensure an ideal statistical analysis, I constructed a LRG sample with redshift of $0.6 \leq z \leq 0.75$, which contains 184172 CMASS LRGs and 27158 eBOSS LRGs.

## 3. STATISTICAL RESULTS

Like Deng (2012) did, I measure the projected local density $\Sigma_5 = N/\pi d_5^2$ (Galaxies Mpc$^{-2}$) where $d_5$ is the distance to the 5th nearest neighbor within $\pm$1000 km s$^{-1}$ in redshift (e.g., Goto et al. 2003; Balogh et al. 2004a, 2004b), and divide the LRG sample with redshifts of $0.6 \leq z \leq 0.75$ into subsamples with a redshift binning size of $\Delta z = 0.01$. Table 1 lists the density ranges in each redshift bin. As shown by Table 1, the projected local density in this sample is much smaller than the one in the CMASS sample of SDSS-III/BOSS (Eisenstein et al. 2011) with redshifts of $0.44 \leq z \leq 0.59$ (see Table 1 of Deng 2014), which is consistent with the results of Dawson et al. (2013) and Anderson et al. (2012). Dawson et al. (2013) and Anderson et al. (2012) showed that the number-density of CMASS galaxies dramatically drops with increasing redshifts at $z > 0.6$.

In each subsample, I arrange galaxies in density order from the smallest to the largest, select approximately 5% of the galaxies, construct two samples at both extremes of density according to the density, and compare the distribution of galaxy age and stellar mass in the lowest density regime with those in the densest regime.

Following Deng (2012), Deng (2015, 2019) divided a CMASS sample of SDSS-III/BOSS (Eisenstein et al. 2011) with redshifts $0.44 \leq z \leq 0.59$ into subsamples with a redshift binning size of $\Delta z = 0.01$, and then analyzed the environmental dependence of age and stellar mass of subsamples in each redshift bin. The result of Deng (2015, 2019) demonstrated that age and stellar mass of CMASS galaxies are very weakly correlated with the local environment in all redshift bins. Figures 1-2 show the age and stellar mass distributions at both extremes of density in different redshift bins for the CMASS + eBOSS LRG sample with redshifts $0.6 \leq z \leq 0.75$. As shown by these two figures, age and stellar mass of LRGs with redshifts $0.6 \leq z \leq 0.75$ are nearly independent of the local environment in all redshift bins.

TABLE 1

K-S PROBABILITIES OF GALAXY AGE AND STELLAR MASS*

| Redshift bins | Number of Galaxies | Projected local density range (Galaxies $\mathrm{M\,pc^{-2}}$) | $P$(age) | $P$(stellar mass) |
|---|---|---|---|---|
| 0.60-0.61 | 27622 | $2.55 \times 10^{-5} \longrightarrow 94.78$ | 0.110 | 0.0130 |
| 0.61-0.62 | 25835 | $1.67 \times 10^{-5} \longrightarrow 22.47$ | 0.329 | 0.261 |
| 0.62-0.63 | 23002 | $1.57 \times 10^{-5} \longrightarrow 19.64$ | 0.0612 | 0.140 |
| 0.63-0.64 | 20378 | $2.42 \times 10^{-5} \longrightarrow 73.91$ | 0.375 | 0.763 |
| 0.64-0.65 | 18037 | $4.55 \times 10^{-5} \longrightarrow 5.39$ | 0.843 | 0.251 |
| 0.65-0.66 | 16001 | $1.40 \times 10^{-5} \longrightarrow 5.19$ | 0.859 | 0.0435 |
| 0.66-0.67 | 14474 | $2.08 \times 10^{-5} \longrightarrow 50.81$ | 0.887 | 0.0248 |
| 0.67-0.68 | 12443 | $1.45 \times 10^{-5} \longrightarrow 5.85$ | 0.499 | 0.129 |
| 0.68-0.69 | 11062 | $1.47 \times 10^{-5} \longrightarrow 5.37$ | 0.141 | 0.00270 |
| 0.69-0.70 | 9623 | $1.97 \times 10^{-5} \longrightarrow 2.54$ | 0.174 | 0.000348 |
| 0.70-0.71 | 8532 | $1.45 \times 10^{-5} \longrightarrow 9.49$ | 0.174 | 0.350 |
| 0.71-0.72 | 7440 | $1.14 \times 10^{-5} \longrightarrow 2.70$ | 0.313 | 0.00996 |
| 0.72-0.73 | 6362 | $1.23 \times 10^{-5} \longrightarrow 3.16$ | 0.863 | 0.00123 |
| 0.73-0.74 | 5514 | $1.24 \times 10^{-5} \longrightarrow 2.00$ | 0.799 | 0.0713 |
| 0.74-0.75 | 5005 | $7.92 \times 10^{-6} \longrightarrow 3.73$ | 0.817 | 4.754e-05 |

*The two samples at both density extremes are drawn from the same distribution.



The step figures can directly present some properties of the statistical result. But this procedure is not ideal because the error bars in the step figures may change with binning sizes. The Kolmogorov-Smirnov (KS) test is well-suited for a quantitative comparison, which demonstrates the degree of similarity or difference between two independent distributions by calculating a probability value. Table 1 lists the K-S probabilities of each panel in Figures 1-2. As shown by Table 1, the K-S probabilities of the CMASS + eBOSS LRG sample with redshifts $0.6 \le z \le 0.75$ are much larger than those obtained by Deng (2012) and Deng et al. (2012a) (see Table 1 of Deng 2012 and Deng et al. 2012a) and even in many redshift bins much larger than 0.05 (5% is the standard in a statistical analysis). This is in good agreement with the conclusion obtained by the step figures.

The weak environmental dependence of some galaxy parameters in intermediate and high redshift regions is likely due to the color-density relation and the tight correlations between colors and other galaxy parameters. In the local Universe, Deng et al. (2013) concluded that color is fundamental in correlations between galaxy properties and the environment and that a large part of the other galaxy properties-density relation is likely due to the relation between color and density. Grützbauch et al. (2011a) observed a weak environmental dependence of galaxy color at $0.4 < z < 0.7$. Deng (2014) also reported that all five colors in the CMASS sample with redshifts $0.44 \le z \le 0.59$ are very weakly correlated with the local environment. A possible interpretation for this is that the environmental processes that exert the essential influence on galaxy properties proceed slowly over cosmic time. Some of the most influential high-density environments may still be in the process of being built up and cannot yet affect galaxy colors (Grützbauch et al. 2011b). The weak environmental dependence of age and stellar mass in intermediate and high redshift regions is likely due to weak color-density relation and tight correlations between colors and these two parameters. For example, Grützbauch et al. (2011a,b) remarked that there is a strong correlation between galaxy color and stellar mass in these redshift regions.

## 4. DISCUSSION

These results demonstrate that the strong environmental dependence of galaxy age and stellar mass in the local Universe cannot be extended to intermediate- and high-redshift regions. Cucciati et al. (2006) also reported that the color-density relation at $0.25 < z < 0.60$ progressively disappears at

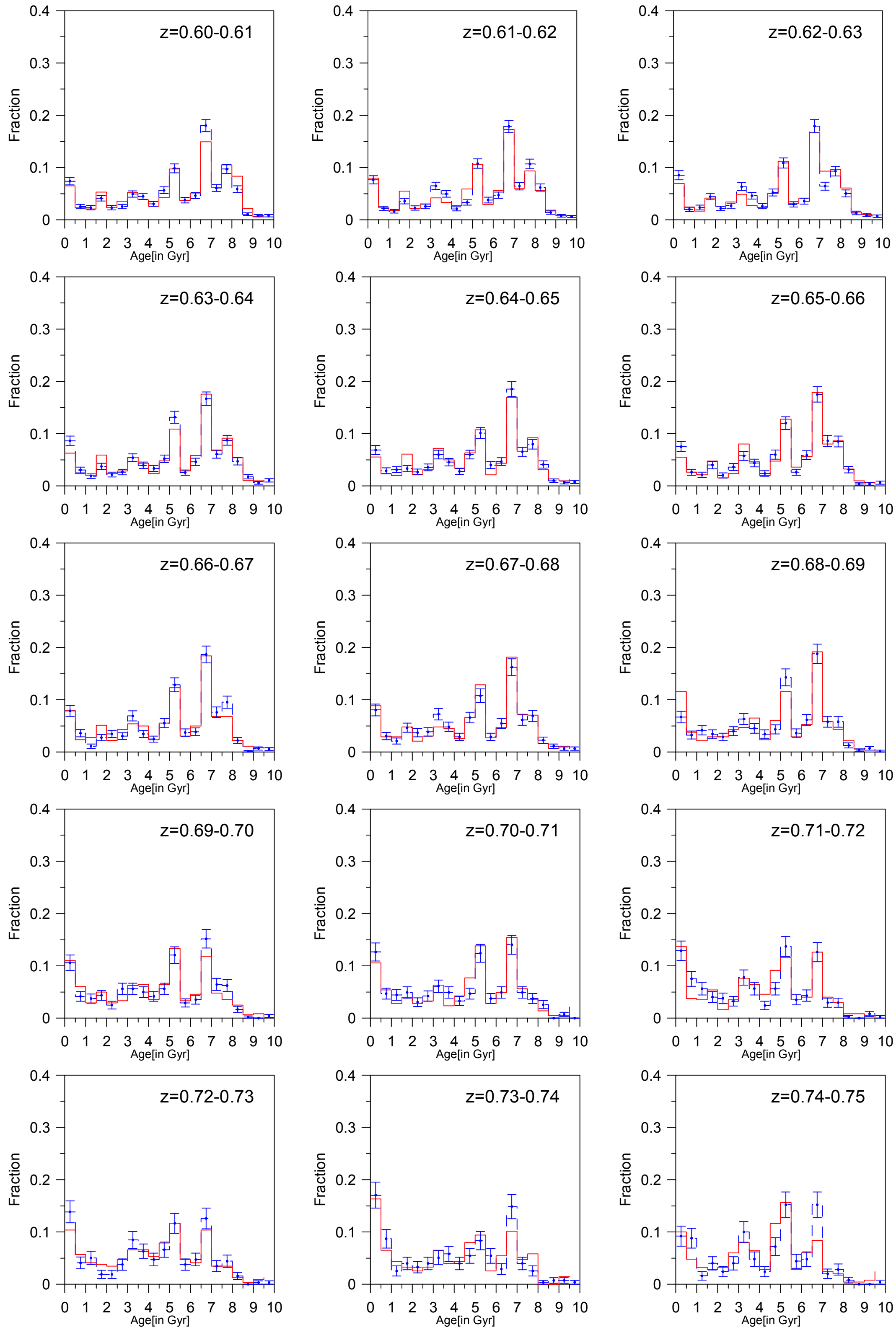


Fig. 1. Age distribution at both extremes of density in different redshift bins: the red solid line represents the sample at high density, the blue dashed line represents the sample at low density. The error bars of the blue lines are 1 $\sigma$ Poissonian errors. The error-bars of the red lines are omitted for clarity. The color figure can be viewed online.

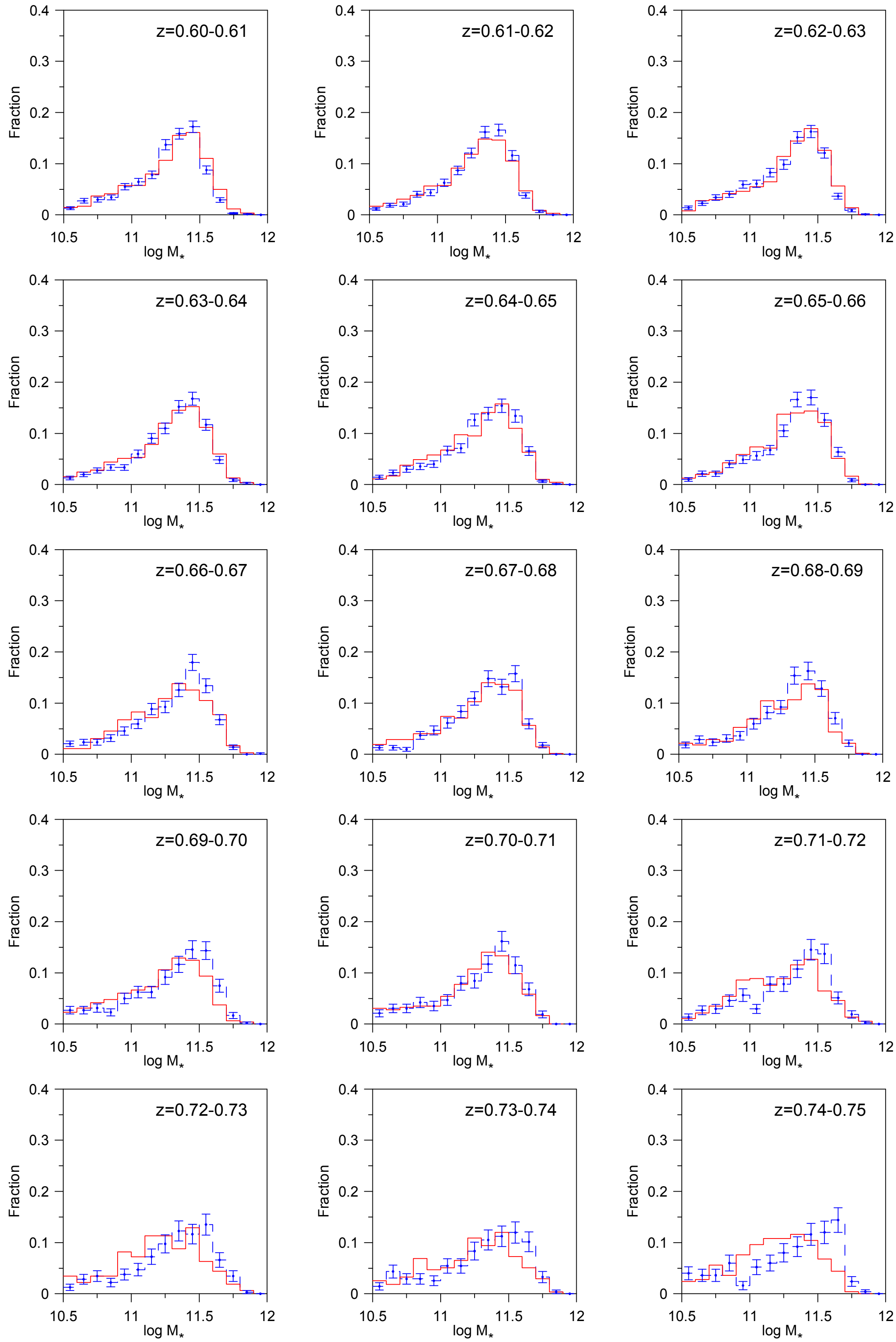


Fig. 2. Same as Figure 1, but for the stellar mass distribution at both density extremes in different redshift bins. The color figure can be viewed online.

higher redshift until it is undetectable at $z \simeq 0.9$. The method of Deng (2012) is well-suited for exploring the variation of the environmental dependence of galaxy properties with redshift. Using this method, Deng et al. (2012a) noted that the environmental dependence of galaxy properties becomes weak with increasing redshifts in the apparent magnitude-limited Main Galaxy Sample (Strauss et al. 2002) and argued that this is likely due to a selection effect, i.e., galaxies at the higher end of a redshift region are restricted to a fairly narrow high-luminosity region due to the Malmquist bias (Malmquist 1920; Teerikorpi 1997), which consequently leads to the limitation of other galaxy properties to within a narrow region. However, such a phenomenon is also likely due to a real physical effect, which subsequently leads to the variation of the environmental dependence of galaxy properties with redshift. The Main(Strauss et al. 2002), LOWZ and CMASS galaxy samples of SDSS can be used to demonstrate the variation of the environmental dependence of galaxy properties with redshift in a fairly wide redshift region. For example, Deng et al. (2017) explored the environmental dependence of K-band luminosity in the Main, LOWZ and CMASS Galaxy Samples of the SDSS. The environmental dependence of K-band luminosity in the LOWZ Galaxy Sample becomes weak with increasing redshift, like the one in the apparent magnitude-limited Main Galaxy Sample does. In the LOWZ Galaxy Sample, the K-band luminosity of galaxies shows substantial correlation with the local environment only in the redshift region $0.16 \leq z \leq 0.21$, which seemingly is a continuation of that in the apparent magnitude-limited Main Galaxy Sample, while minimal environmental dependence of the K-band luminosity in the high redshift region in the LOWZ galaxy sample continues as far as the CMASS sample can reach. The result of this work shows that minimal environmental dependence of galaxy parameters can continue to higher redshifts.

## 5. SUMMARY

To demonstrate the variation of the environmental dependence of galaxy age and stellar mass with redshift, I construct a LRG sample with redshifts of $0.6 \leq z \leq 0.75$, which contains 184172 CMASS LRGs and 27158 eBOSS LRGs, and examine the environmental dependence of these two galaxy parameters in this sample. Following Deng (2012), I divide this LRG sample into subsamples with a redshift binning size of $\Delta z = 0.01$, and analyze the environmental dependence of galaxy age and stellar mass for these subsamples in each redshift bin. As shown by Table 1 and Figures 1-2, overall, galaxy age and stellar mass in LRG sample with the redshifts $0.6 \leq z \leq 0.75$ are very weakly correlated with the local environment, which shows that minimal environmental dependence of galaxy parameters can continue to higher redshifts.

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