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Local Environmental Dependence of Galaxy Properties in a Volume-Limited Sample of Main Galaxies *

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Abstract Using a volume-limited sample of Main Galaxies from SDSS Data Release 5, we investigate the dependence of galaxy properties on local environment. For each galaxy, a local three-dimensional density is calculated. We find that the galaxy morphological type depends strongly on the local environment: galaxies in dense environments have predominantly early type morphologies. Galaxy colors have only a weak dependence on the environment. This puts an important constraint on the process of galaxy formation.

Key words: galaxy: distances and redshifts — galaxies: statistics

1 INTRODUCTION

Numerous studies have shown that the properties of galaxies seem to correlate with the environment, for example, galaxies in dense environments (i.e., clusters or groups) have a higher proportion of early type morphologies (e.g., Oemler 1974; Dressler 1980; Whitmore, Gilmore & Jones 1993; Deng et al. 2007) and low SFRs (e.g., Balogh et al. 1997, 1999; Poggianti et al. 1999). Many authors have investigated the correlations between the environment and properties of galaxies such as morphological type (e.g., Postman & Geller 1984; Dressler et al. 1997; Hashimoto & Oemler 1999; Fasano et al. 2000; Tran et al. 2001; Goto et al. 2003; Helsdon & Ponman 2003; Treu et al. 2003), star formation rate (e.g., Hashimoto et al. 1998; Lewis et al. 2002; G'omez et al. 2003; Balogh et al. 2004a; Tanaka et al. 2004; Kelm, Focardi & Sorrentino 2005), and colour (e.g., Tanaka et al. 2004; Balogh et al. 2004b; Hogg et al. 2004). In order to explain these correlations, various physical mechanisms have been proposed, including rampressure stripping (Gunn & Gott 1972; Kent 1981; Fujita & Nagashima 1999; Quilis, Moore & Bower 2000), galaxy harassment (Moore et al. 1996, 1999), cluster tidal forces (Byrd &Valtonen 1990; Valluri 1993; Gnedin 2003), and interaction/merging of galaxies (Icke 1985; Lavery & Henry 1988; Mamon 1992; Bekki 1998). In their study of the relations between morphology and density and between morphology and distance to the cluster centre, Goto et al. (2003) measured the local galaxy density in the following way. For each galaxy, they calculated the projected distance to the 5th nearest galaxy (r'_5, say) within $\pm 1000\,\mathrm{km\,s^{-1}}$ in redshift. The local galaxy density was defined as the number of galaxies ($N = 5$) within the distance to the circular surface area with the radius of the distance to the 5th nearest galaxy. It was found that the fraction of early-type galaxies increase (and that of late-type galaxies decreases) with increasing local density.

If redshift is taken as a pure distance measure, then we can modify Goto et al. (2003)'s procedure and measure the local galaxy density in the following way. For each galaxy, we calculate the three-dimensional distance to the 5th nearest galaxy (r_5, say). The local three-dimensional galaxy density is defined as the number of galaxies ($N = 5$) within this distance to the volume of the sphere within the radius of the distance to the 5th nearest galaxy. We will make a comprehensive investigation of the correlations between the environment and various galaxy properties. Our paper is organized as follows. In Section 2 we describe

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the data to be used. The correlations between galaxy properties and local galaxy density are discussed in Section 3. Our main results and conclusions are summarized in Section 4.

2 DATA

The SDSS observes galaxies in five photometric bands (u, g, r, i and z) centered at (3540, 4770, 6230, 7630 and 9130 Å). York et al. (2000) have provided a technical summary of the SDSS. The imaging camera was described by Gunn et al. (1998), while the photometric system and the photometric calibration of the SDSS imaging data were separately outlined by Fukugita et al. (1996), Hogg et al. (2001) and Smith et al. (2002). Pier et al. (2003) described the methods and algorithms involved in the astrometric calibration of the survey, and presented a detailed analysis of the accuracy achieved. Many of the survey properties were discussed in detail in the Early Data Release paper (Stoughton et al. 2002). The spectroscopic target selection was implemented by two algorithms. The MAIN Galaxy sample (Strauss et al. 2002) comprise galaxies brighter than $r_p < 17.77$ (r-band apparent Petrosian magnitude). Most of the galaxies have redshifts in the range $0.02 \leq z \leq 0.2$, a few have $z > 0.25$. The sample median redshift is 0.10.

We used the Main galaxy sample in our work. The data were downloaded from the Catalog Archive Server of SDSS Data Release 5 (SDSS5, Adelman-McCarthy et al. 2007) with the SDSS SQL Search (with SDSS flag: bestPrimtarget=64) with high-confidence redshifts ($Z\mathrm{warning} \neq 16$ and $Z\mathrm{status} \neq 0, 1$ and redshift confidence level: $z$conf>0.95) (*http://www.sdss.org/dr5/*). From this sample, we selected 332412 Main galaxies in the redshift range $0.02 \leq z \leq 0.2$.

In calculating the distances we used a cosmological model with a matter density $\Omega_0 = 0.3$, cosmological constant $\Omega_A = 0.7$, Hubble's constant $\mathrm{H}_0 = 100h\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$ with $h = 0.7$.

We intend to construct a volume-limited sample from the Main galaxy sample of SDSS5. This choice reduces the number of galaxies, but it has several important advantages: the radial selection function being approximately uniform, the only variation in the space density with the radial distance is due to clustering. Thus, the analysis is more straightforward. The volume-limited sample is defined by choosing appropriate minimum and maximum absolute magnitude limits.

According to the distribution of absolute magnitudes for the Main galaxy sample, we chose the maximum absolute magnitude limit $M_{\max} = -22.40$. The absolute magnitude M_r is calculated from the r-band apparent Petrosian magnitude, using a polynomial fit formula (Park et al. 2005a) for the K-correction (Blanton et al. 2003a) within $0 < z < 0.3$:

$$K(z) = 2.3537(z - 0.1)^2 + 1.04423(z - 0.1) - 2.5\log(1 + 0.1). \quad (1)$$

The minimum absolute magnitude limit was defined as the absolute magnitude of a galaxy having r-band apparent Petrosian magnitude $r = 17.77$ (the r-band apparent Petrosian magnitude limit of the Main galaxy sample) at the redshift limit $Z_{\max}$. Figure 1 shows the number of galaxies in the volume-limited sample as a function of the redshift limit, $Z_{\max}$. As seen from this figure, there is a high platform in the redshift region $0.089 \leq z \leq 0.12$. When constructing a volume-limited sample, we mainly consider two factors: the luminosity range of the volume-limited sample be as large as possible, and the size of the galaxy sample be as large as possible. Thus, we construct a volume-limited sample that extends to $Z_{\max} = 0.089$, and is limited to the absolute magnitude region $-22.40 \leq M_r \leq -20.16$. This sample contains 67907 galaxies, and has a mean galaxy density of about $2.2649\times10^{-3}\,\mathrm{Mpc}^{-3}$. Figure 2 displays the redshift and absolute magnitude distributions with dashed lines marking the limits defining the volume-limited sample. We use the concentration index $c_i = R_{90}/R_{50}$ to separate early-type (E/S0) galaxies from late-type (Sa/b/c, Irr) galaxies (Shimasaku et al. 2001), where R_{50} and R_{90} are the radii enclosing 50% and 90% of the Petrosian flux, respectively. The proportion of early-type galaxies in different luminosity bins (bin size $\Delta M_r = 0.4$) for the whole Main galaxy sample is shown in Figure 3. As is well-known, the galaxy morphology is closely correlated with many other parameters, such as color and concentration index. Naturally, these parameters can be used as tools for the morphology classification (e.g., Park & Choi 2005b; Yamauchi & Goto 2005; Abraham, van den Bergh & Nair 2003; Strateva et al. 2001; Shimasaku et al. 2001). The concentration parameter is a good and simple morphological parameter. Nakamura et al. (2003) showed that c_i=2.86 separates galaxies at S0/a with a completeness of about 0.82 for both late and early types. As can be seen from Figure 3, the proportion of early-type galaxies rapidly increases with increasing luminosity from about $M_r = -20.20$, corresponding to 0.29 magnitude fainter than the value of M^* for the overall

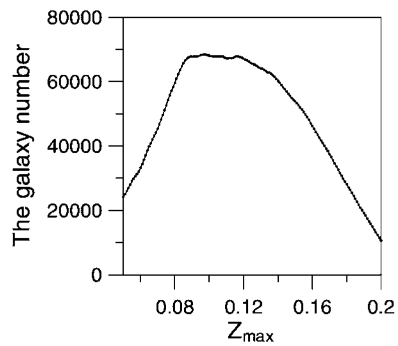

Fig. 1 Number of galaxies in a volume-limited sample as a function of redshift limit $Z_{\max}$.

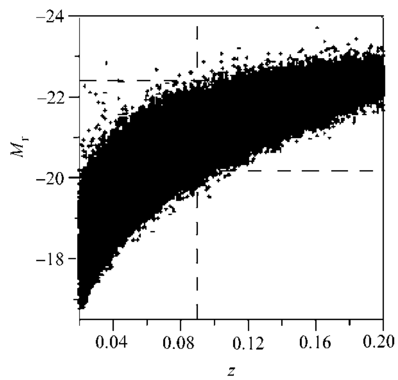

Fig. 2 Redshift z vs. luminosity M_r for the Main galaxy sample. The vertical dashed line marks the redshift limit $Z_{\max}$ of the volume-limited sample, The two horizontal dashed lines mark the minimum and maximum absolute magnitude limits of the volume-limited sample.

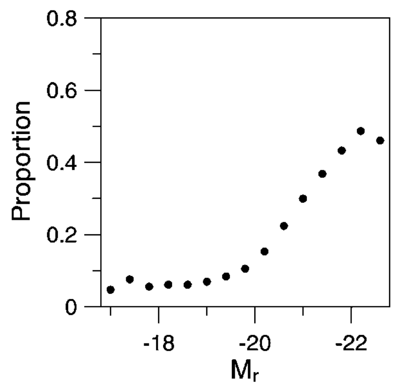

Fig. 3 Proportion of early-type galaxies in different luminosity bins for the whole Main galaxy sample.

Schechter fit to the galaxy luminosity function (Ball et al. 2006). So, this volume-limited sample is good for investigating the correlation between galaxy morphological types and luminosities.

3 CORRELATIONS BETWEEN GALAXY PROPERTIES AND LOCAL GALAXY DENSITY

For each galaxy, we calculate the three-dimensional distance to the 5th nearest galaxy, r_5, say. The local three-dimensional galaxy density is defined as the number of galaxies ($N = 5$) within this distance to the volume of the sphere with radius r_5. In this paper, we express the local galaxy density as a relative density LRD, the ratio of the local three-dimensional density to the mean density of galaxies in the volume-limited sample. Figure 4 shows a histogram of the LRD distribution in the volume-limited sample.

Figure 5 displays the fraction of early-type ($c_i \geq 2.86$) galaxies as a function of the local relative density LRD (logarithmic scale). We bin the sample in steps of about 0.08 over the range 0$<$ log LRD $<$ log 40 ≈ 1.6. The dashed line marks the overall fraction of early-type galaxies in the volume-limited sample. As seen from this figure, the fraction of early type galaxies clearly increases with increasing local density. This result is in qualitative agreement with the previous conclusion that galaxies in dense environments (clusters or groups) contain higher proportions of early type morphologies (e.g., Oemler 1974; Dressler

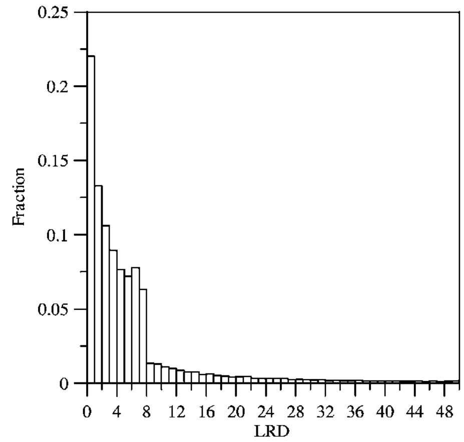

Fig. 4 Distribution of the local relative density LRD in the volume-limited sample.

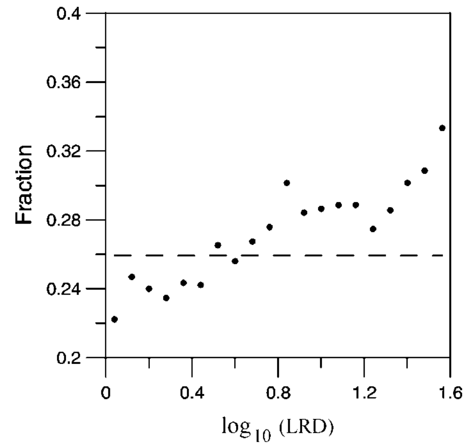

Fig. 5 Fraction of early-type galaxies as a function of the local relative density LRD. The dashed line marks the overall fraction in the volume-limited sample.

1980; Whitmore, Gilmore & Jones 1993; Deng et al. 2007), while galaxies in the low density regions (isolated galaxies) have lower proportions of early-type galaxies (e.g., Deng et al. 2006).

From the projected correlation function $w_p(r_p)$, Zehavi et al. (2002) found that the more luminous galaxies are more strongly clustered. Using the photometry and spectroscopy of 144,609 galaxies from the SDSS, Blanton et al. (2003b) investigated the dependence on the local galaxy density (smoothed over $8\,\mathrm{h}^{-1}$ Mpc scales), of seven galaxy properties comprising four optical colors, the surface brightness, the shape of the radial profile as measured by the S'ersic index and the absolute magnitude. They found that the luminosity depends strongly on the local density, that the most luminous galaxies exist preferentially in the densest regions of the universe. These results are similar to those found in a number of earlier studies (Davis et al. 1988; Hamilton 1988; Park et al. 1994; Loveday et al. 1995; Guzzo et al. 1997; Benoist et al. 1998; Norberg et al. 2001). In the left panel of Figure 6, we present the mean luminosity as a function of the LRD (logarithmic). The error bars mark the standard deviation in each density bin. As seen from this figure, we do not observe any correlation between the galaxy luminosity and the local density. This result agrees with that found by Deng et al. (2007). Norberg et al. (2002) investigated the dependence of galaxy clustering on luminosity and spectral type using the 2dF Galaxy Redshift Survey (2dFGRS). The galaxies were divided into two broad spectral classes: early-types and late-types. They calculated the projected correlation functions of both spectral types, and found that for both the early and late types, the clustering strength has approximately the same dependence on the luminosity. These results demonstrated that both luminosity and morphological type impact on the galaxy clustering. According to the above analyses, our results show that the morphological types of galaxies are strongly correlated with the local density, while there is no significant correlation between the galaxy luminosity and the local density. Note however, since we are using a volume-limited sample where the galaxies are restricted to a relative small luminosity range, the lack of luminosity dependence may change if very bright and faint galaxies are included.

We also present the mean size as a function of the LRD in the right panel of Figure 6. The r-band $R_{90,r}$ is selected as the parameter of galaxy size. As shown , there is no significant correlation between the galaxy size and the local density. As is well-known, the galaxy size is correlated with the luminosity (Kormendy 1977; Shen et al. 2003). These results are naturally explained since the galaxy luminosity does not depend on the environment.

Galaxy colors are an important quantity that characterizes the stellar content of the galaxy. Some studies showed that the clustering of galaxies depends on the color (Brown et al. 2000; Zehavi et al. 2002). Blanton et al. (2003b) also found that the local density is a strong function of all the colors. In this paper we intend

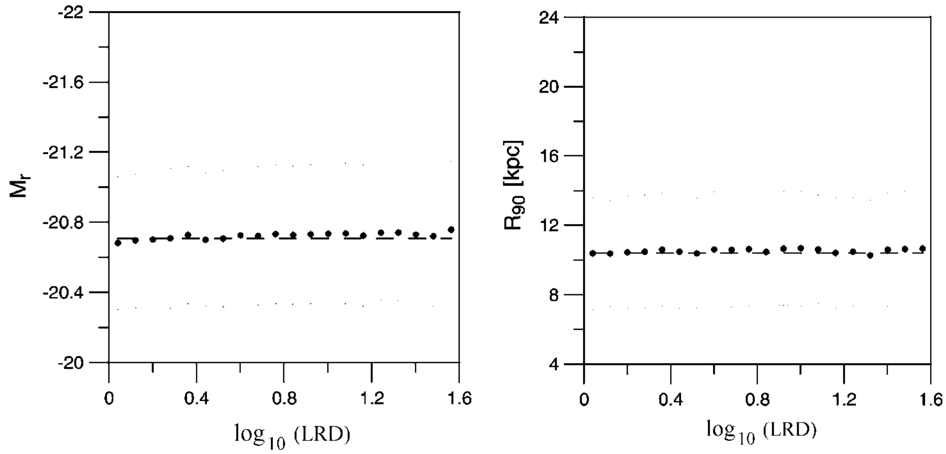

Fig. 6 Mean luminosity (left panel) and mean size (right panel) as a function of the LRD. The dashed line marks the mean value of the whole volume-limited sample. Error bars are the standard deviation in each density bin.

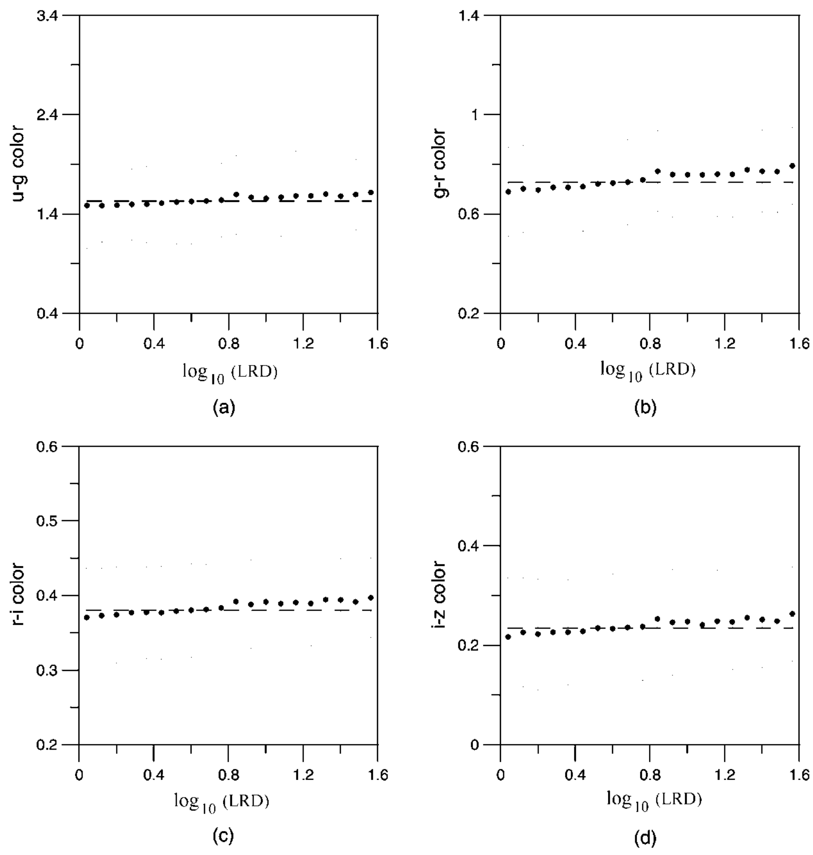

Fig. 7 Mean color as a function of the LRD. The dashed line marks the mean color of the whole volume-limited sample. Error bars are the standard deviation in each density bin (a) $u - g$ color, (b) $g - r$ color, (c) $r - i$ color and (d) $i - z$ color.

to investigate the correlation between the color and the local environment. Figure 7 presents four optical mean colors as functions of the LRD. A few galaxies in the volume-limited sample have abnormal colors, for example, the galaxy, located at redshift $z = 0.081$, right ascension RA= 259.2084° and declination DEC= 64.62785°, has an abnormally large $g - r$ color: $g - r = 7.945$. In our work, such galaxies (110 galaxies in all) are excluded from the volume-limited sample in order to avoid especially wild values. As shown in Figure 7, we only observe a weak dependence of the colors on the local density. This result is similar to that found by other authors (Bernardi et al. 2003; Balogh et al. 2004b; Hogg et al. 2004). Hogg et al. (2004) showed that although the most luminous galaxies reside preferentially in the highest density regions, red color galaxies are independent of the environment. By analyzing the $u - r$ color distribution of galaxies as a function of luminosity and environment, Balogh et al. (2004b) found that at fixed luminosity the mean color of blue galaxies or red galaxies is nearly independent of the environment, but the fraction of red galaxies increases with density in a similar way to the fraction of early type galaxies, increasing from ≈10%–30% of the population in the lowest density environments, to ≈70% at the highest densities. So, they inferred that most star-forming galaxies today evolve at a rate which is determined primarily by their intrinsic properties, regardless of their environment, and that the transformation from late to early types must be either sufficiently rapid, or sufficiently rare, to keep the overall color distribution unchanged.

For each galaxy, we also calculate the local three-dimensional galaxy density within the distance to the 10th nearest galaxy (LRD_10, say). Figure 8 shows the distribution of LRD_10 for the volume-limited sample. Figures 9 and 10 respectively show the fraction of early type galaxies and four optical mean colors as functions of the LRD_10 (logarithmic). As seen from these figures, these results are very similar to those for local density within the distance to the 5th nearest galaxy.

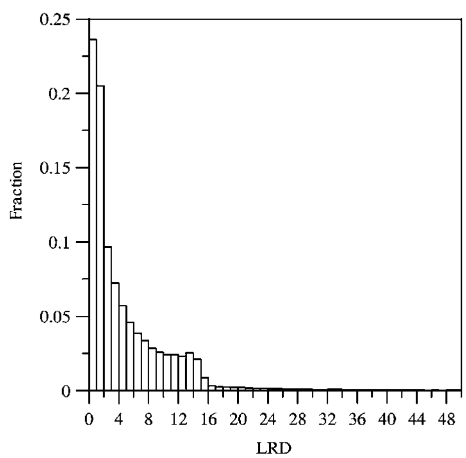

Fig. 8 Distribution of LRD_10 for the volume-limited sample.

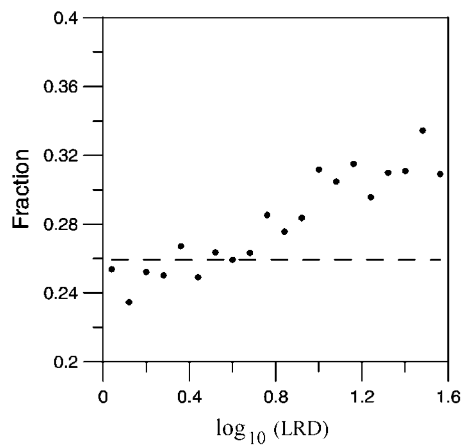

Fig. 9 Fraction of early-type galaxies as a function of LRD_10 (logarithmic). The dashed line represents the proportion of early-type galaxies in the whole volume-limited sample.

We note that the galaxy morphological types strongly depend on local environments: galaxies in dense environments are predominantly early types, a result amply confirmed by other studies. This suggests that in dense environments late-type galaxies are transformed into early types. Various physical mechanisms, such as galaxy harassment (Moore et al. 1996), rampressure stripping (Gunn & Gott 1972) and galaxy-galaxy merging (Toomre & Toomre 1972), can explain such a transformation, but we also note that the other galaxy properties do not show any significant dependence on the local environment. Clearly, this puts an important constraint on proposed physical mechanisms when modeling the formation of galaxies.

Although we use the three dimensional LRD that is less liable to projection effects, it is important to recognize that this method did not take into account distortions in the redshift space. So, we also use the Goto et al. (2003)'s method, to see if it changes the results in any way. The projected local density (PLD)

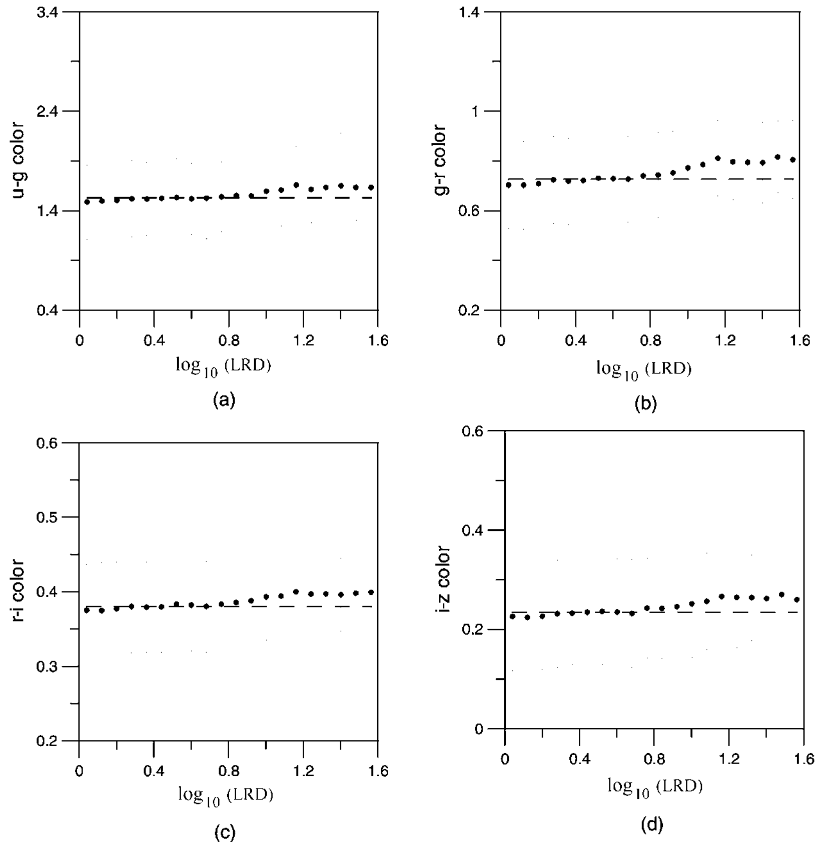

Fig. 10 Mean color as a function of LRD_10. The dashed line represents the mean color of the whole volume-limited sample. Error bars are the standard deviation in each density bin (a) $u-g$ color, (b) $g-r$ color, (c) $r-i$ color and (d) $i-z$ color.

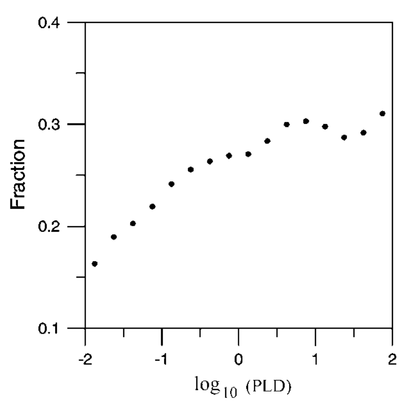

Fig. 11 Fraction of early-type galaxies as a function of the PLD (within 5th) of galaxies. The dashed line represents the proportion of early-type galaxies of the volume-limited sample.

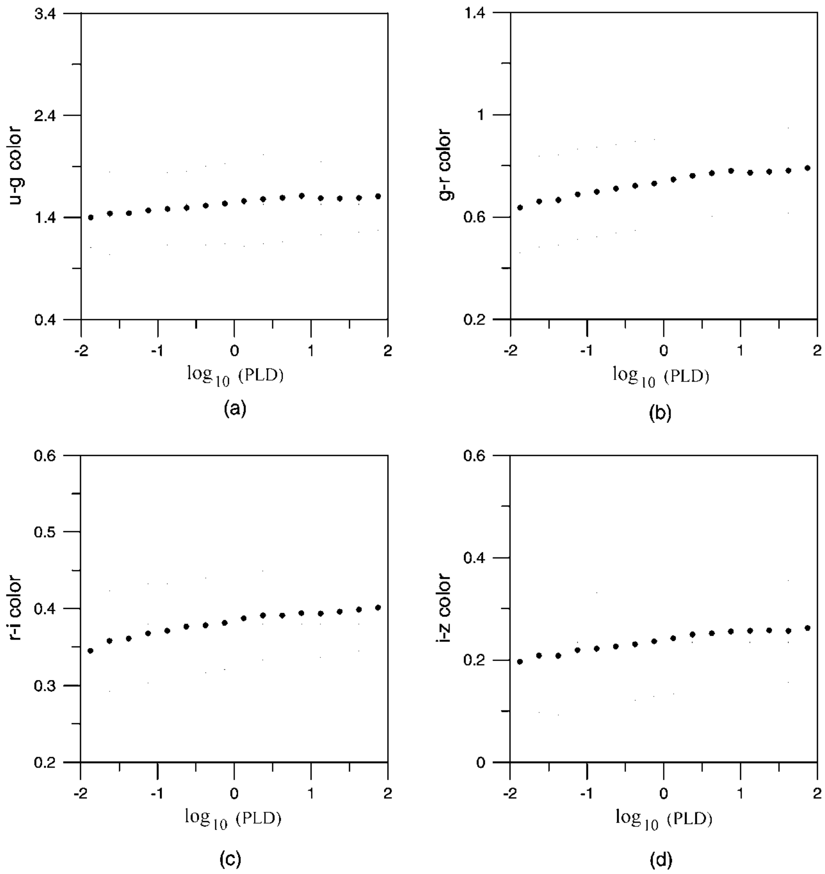

Fig. 12 Mean colors as functions of the PLD (within 5th) of galaxies. The dashed line represents the mean colors of the volume-limited sample. Error bars are standard deviation in each density bin (a) $u-g$ color, (b) $g-r$ color, (c) $r-i$ color and (d) $i-z$ color.

is given by PLD= N/πd_5^2 where d_5 is the distance to the 5th nearest neighbour within $\pm$1000 km s^{-1} in redshift. We bin the sample in steps of 0.25 over the range –2 < log PLD < 2, a factor of 10000 in density. Figures 11 and 12 respectively show the fraction of early type galaxies and four optical mean colors as functions of the PLD. As seen from these figures, the correlation of galaxy morphologies with the projected local density is stronger than that with the three-dimensional local density, and the galaxy colors also show stronger correlations with the projected local density. This difference comes from a combination of redshift distortion and projection effects.

4 SUMMARY

In order to investigate the dependence of galaxy properties on the local environment, we calculated the local three-dimensional galaxy density within the distance to the 5th nearest galaxy for each galaxy. Because the Main galaxy sample is an apparent-magnitude limited sample, we constructed a volume-limited sample that extends to $Z_{\rm max}$ =0.089, and limits the absolute magnitudes to the range –22.40$\leq M_r \leq$–20.16. This volume-limited sample contains 67907 galaxies, and has a mean galaxy density of about 2.2649$\times 10^{-3}$ Mpc^{-3}. We found that galaxy morphologies strongly depend on the local environment: galaxies in dense environments have predominantly early type morphologies, as is expected in many physical mechanisms. However, we also note that the other galaxy properties such as galaxy colors do not present significant dependence on the local environment. Additionally, we also explore the dependence of galaxy properties on the local three-dimensional galaxy density within the distance to the 10th nearest galaxy. Results are almost the same as those with the local density within the distance to the 5th nearest galaxy.

We also use the Goto et al. (2003) method, and compute the PLD according to PLD= $N/\pi d_5^2$ where d_5 is the distance to the 5th nearest neighbor within $\pm$ 1000 km s^{-1} in redshift. We found that the correlation of galaxy morphologies with the PLD is stronger than with the three-dimensional local density, and the colors of galaxies also show stronger correlations with the PLD. We did not find any local density dependence for galaxy luminosity and size, but this is largely due to the selections (luminosity cut) in the volume-limited sample.

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