THE LUMINOUS RED GALAXY (LRG) GROUPS FROM THE SDSS DATA RELEASE 5

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At the linking length $R = 0.2\,\bar{n}^{-1/3} \approx 6.3$ Mpc ($\bar{n}$ is the mean galaxy density), we have extracted 540 groups from a approximately volume-limited LRG sample of the SDSS Data Release 5. In order to investigate the correlations between galaxy properties and environment, we compare basic properties of member galaxies of groups with those of field galaxies in different redshift bins, and find that these properties of LRGs are nearly independent of environment.

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1. Introduction

For a long time, galaxy groups have been a very important issue about the large-scale structure of the Universe. The information obtained from these systems allows us to understand many important issues better: properties of the large-scale structure, galaxy formation and evolution, environmental studies, studies of dark matter and others. The first sizeable sample of groups was constructed by Geller and Huchra (Geller, Huchra 1982), who identified 176 groups with three or more galaxies from the CfA galaxy redshift survey. Most group catalogs were constructed by means of the friends-of-friends (FOF) algorithm (Huchra, Geller 1982) or slightly modified versions. These group catalogs and their members provide a basis for statistical studies of the large-scale distribution of groups and their physical properties. In recent years, some large catalogs of groups have been compiled from different redshift surveys (Merchán, Maia, Lambas 2000; Giuricin *et al.* 2000; Tucker *et al.* 2000; Carlberg *et al.* 2001; Ramella *et al.* 2002; Merchán, Zandivarez 2002; Eke *et al.* 2004; Gerke *et al.* 2005; Merchán, Zandivarez 2005; Berlind *et al.* 2006). Many authors also performed various studies involving groups, ranging from local physical properties (Martínez *et al.* 2002; Domínguez *et al.* 2002; Ragone *et al.* 2004) to large scale structure (Zandivarez, Merchán, Padilla 2003; Padilla *et al.* 2004).

Galaxy properties are strongly correlated with environment, for example, galaxies in dense environments (*i.e.*, clusters or groups) have high proportion of early type morphologies *e.g.*, (Oemler 1974; Dressler 1980; Whitmore, Gilmore, Jones 1993; Deng *et al.* 2007a) and low SFRs *e.g.*, (Balogh *et al.* 1997, 1999; Poggianti *et al.* 1999). Many authors have investigated correlations between environment and galaxy properties, such as the correlation between environment and morphology *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), between environment and star formation rate *e.g.*, (Hashimoto *et al.* 1998; Lewis *et al.* 2002; Gómez *et al.* 2003; Balogh *et al.* 2004a; Tanaka *et al.* 2004; Kelm, Focardi, Sorrentino 2005), and between environment and colors *e.g.*, (Tanaka *et al.* 2004; Balogh *et al.* 2004b; Hogg *et al.* 2004).

Groups represent dense systems in the distribution of galaxies. They are often used for exploring the dependence of galaxy properties on local environment. Some studies showed that the median physical properties of galaxies in groups are significantly different from those in the field *e.g.*, (Hickson 1982; Williams, Rood 1987; Sulentic 1987; Hickson *et al.* 1988; Rood, Williams 1989; Prandoni *et al.* 1994; Lee *et al.* 2004). For example, by exploring morphology-environment effects in the SDSS compact groups, Lee *et al.* (Lee *et al.* 2004) found that the rest-frame colors of galaxies in compact groups indeed differ from those of field galaxies — at least for $M_{u*} - M_{g*}$, $M_{g*} - M_{r*}$, and even $M_{r*} - M_{i*}$, and concluded that the SDSS compact groups contain a relatively higher fraction of elliptical galaxies than the field galaxies. N-body simulations pioneered by Toomre (Toomre 1977) showed that the end-product of merging spirals can be an elliptical galaxy. So, Lee's *et al.* (Lee *et al.* 2004) results finally illustrated that there is strong evidence of interactions and mergers within a significant fraction of the SDSS compact groups. Interactions within the group environment may have important effects on the properties of member galaxies. Thus, investigating the dependence of galaxy properties on their group environment is a key step in understanding galaxy formation and evolution.

Luminous Red Galaxies (LRGs) are among the most luminous galaxies in the Universe, and are strongly correlated with clusters. This makes the LRG sample an astrophysically interesting one. The aim of this work is to construct a group catalog from the Luminous Red Galaxy (LRG) sample (Eisenstein *et al.* 2001) of the Sloan Digital Sky Survey (SDSS) Data Release 5 (Adelman-McCarthy *et al.* 2007) and investigate the correlations between LRG properties and environment. The group identification is performed using the three-dimensional friends-of-friends (FOF) algorithm developed by Davis *et al.* (Davis *et al.* 1985). Our paper is organized as follows. In Section 2, we describe the data to be used. The group identification algorithm is discussed in Section 3. In Section 4, we study the correlations between LRG properties and environment. Our main results and conclusions are summarized in Section 5.

2. Data

The SDSS observes galaxies in five photometric bands (u, g, r, i, z) centered at (3540, 4770, 6230, 7630, 9130 Å). York *et al.* (York *et al.* 2000) provided the technical summary of the SDSS. The imaging camera was described by Gunn *et al.* (Gunn *et al.* 1998), while the photometric system and the photometric calibration of the SDSS imaging data were roughly described by Fukugita *et al.* (Fukugita *et al.* 1996), Hogg *et al.* (Hogg *et al.* 2001) and Smith *et al.* (Smith *et al.* 2002) respectively. Pier *et al.* (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). In our work, the data is downloaded from the Catalog Archive Server of SDSS Data Release 5 (Adelman-McCarthy *et al.* 2007) by the SDSS SQL Search (`http://www.sdss.org/dr5/`).

The Luminous Red Galaxy (LRG) algorithm (Eisenstein *et al.* 2001) selects galaxies to $r_{\rm petro} < 19.5$ that are likely to be luminous early-types, based on the observed colors. These LRGs are intrinsically red and at higher redshift. In order to extract LRGs, Eisenstein *et al.* (Eisenstein *et al.* 2001) used different selection cuts above and below $z \approx 0.4$: cut I (the low-redshift cut) and cut II (the high-redshift cut). Cut I, which accounts for the most (80–85%) of the targets, not only imposes a flux cut $r_{\rm petro} < 19.2$ but also sets the luminosity threshold as a function of redshift, while cut II sample is simply a flux-limited one. Eisenstein *et al.* (Eisenstein *et al.* 2001) showed that the LRG spectroscopic sample contains luminous and red galaxies with early-type spectra out to $z \approx 0.55$, and strongly advised the researcher that LRGs should be selected at $z > 0.15$. Thus, in redshift region $0.16 \leq z \leq 0.55$, we extract 81392 LRGs (with SDSS flag: Primtarget_Galaxy_Red, redshift confidence level: $z_{\rm conf} > 0.95$): 73707 cut I LRGs and 7685 cut II LRGs. At $z \leq 0.3$ the LRG sample contains many galaxies that are bright enough to be in the Main galaxy sample (Strauss *et al.* 2002). Eisenstein *et al.* (Eisenstein *et al.* 2001) suggested the author that the choice of sample-LRGs with and without MAIN sample contributions should be clear from the context. Our LRG sample contains 19849 Main galaxies which are also classified as LRGs. Fig. 1 shows the redshift distributions for all LRGs, cut I LRGs, cut II LRGs, and Main galaxies which are also classified as LRGs, respectively. We notice that in the redshift region $0.16 \le z \le 0.24$ most objects of the LRG sample are Main galaxies, and that cut II LRGs are mostly located at redshift $z \ge 0.4$. Fig. 2 also illustrates the comoving number density of galaxies as a function of redshift z for the LRG sample of the SDSS5.

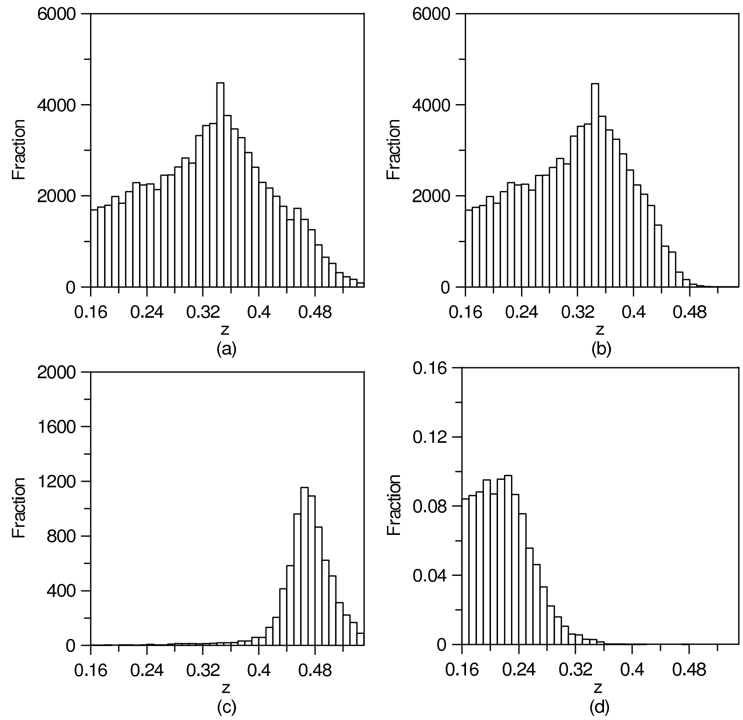

Fig. 1. The redshift distributions for (a) all LRGs, (b) cut I LRGs, (c) cut II LRGs, and (d) Main galaxies which are also classified as LRGs.

It is difficult to construct an ideal volume-limited sample from the LRG sample because it is not simply a flux-limited one. Eisenstein *et al.* (Eisenstein *et al.* 2001) showed that the LRG sample appears to have approximately constant passively evolved selection, physical size, and comoving number density out to $z \approx 0.4$. From this, the LRG sample can be called an approximately volume-limited one. In addition, we also notice that the flux-limited cut II sample is mainly located at redshift $z \ge 0.4$, and that at redshift $z \approx 0.4$ the number-density of galaxies begins to drop with increasing the redshift dramatically. Thus, we extract LRGs with the redshift $0.16 \le z \le 0.4$ and construct a approximately volume-limited sample which contains 64198 LRGs.

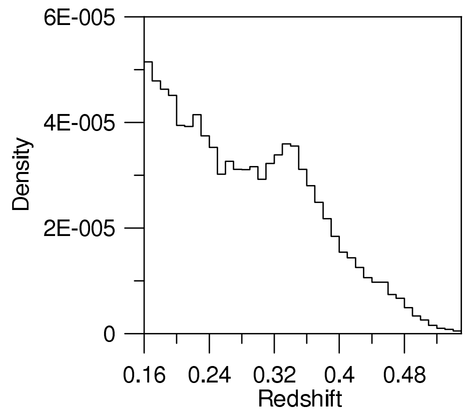

Fig. 2. Comoving number density of galaxies as a function of redshift z for the LRG sample of the SDSS5.

In calculating the comoving distance we use a cosmological model with a matter density $\Omega_0 = 0.3$, cosmological constant $\Omega_\Lambda = 0.7$, Hubble's constant $H_0 = 100\,h\ \mathrm{km\,s^{-1}\,Mpc^{-1}}$ with $h = 0.7$.

Because the LRG sample spans a wide range of redshifts, the interpretations of the sample often require the application of K-corrections and stellar population evolution corrections ($K{+}e$ corrections) for comparison of photometry at different redshifts. As described in Appendix B of Eisenstein *et al.* (Eisenstein *et al.* 2001), we use the measured redshift and the observed r^*_{petro} magnitude to construct the rest-frame, passively evolved g^*_{petro} absolute magnitude M^*_g. In this paper, we have selected the "nonstar-forming" model presented in Appendix B of Eisenstein *et al.* (Eisenstein *et al.* 2001) and normalized to M^*_g at $z = 0$.

3. The group-finding algorithm

For group identification, the friend-of-friend (FOF) algorithm developed by Huchra and Geller (Huchra, Geller 1982) was the most frequently applied method for redshift surveys. By allowing a longer linking length in the radial direction, the Huchra-Geller's FOF algorithm actually accounted for the redshift space distortion. But we notice that the criterion of radial distance adopted by most authors is far larger than that of the projected separation. If the ratio of the criterion of radial distance to that of the projected separation is far larger than the proper ratio for correcting the redshift-space distortion, groups identified by such a method are seriously contaminated by background/foreground galaxies. In this paper, we use the friends-of-friends (FOF) algorithm of Davis *et al.* (Davis *et al.* 1985) which defines the three-dimensional linking length as $b\,\bar{n}^{-1/3}$ where $\bar{n}$ is the mean particle density, in order to identify groups within N-body simulations. An attractive feature of this method is that it does not impose any fixed shape on groups. For relatively large values of b, the resulting groups are often quite irregular with several separate centers of concentration, while smaller values of b tend to identify groups with a well-defined center and relatively regular structure. Davis *et al.* (Davis *et al.* 1985) used $b = 0.2$ for identifying dark matter groups. Jenkins' *et al.* (Jenkins *et al.* 2001) study showed that this choice of linking length yield a halo mass function that is independent of redshift and Ω_0, and thus provides a good definition of the underlying dark matter haloes.

Though Davis' *et al.* (Davis *et al.* 1985) algorithm became three dimensional and thus less subject to the projection effect, it is important to recognize that this algorithm did not take into account the stretching of groups in redshift space along the radial direction — the redshift space distortion. But as seen from above analyses, there is existence of serious projection effect in previous many works. We may face the choice of two effects: the projection effect or the redshift space distortion. Most authors selected the former, while we will select the latter here. Undoubtedly, it is of interest to explore the properties of groups using independent and different methods.

In this study, we also use $b = 0.2$, corresponding to the linking length $R \approx 6.3$ Mpc (for the LRG sample, the mean galaxy density is about 3.2×10^{-5} Mpc^{-3}), in order to identify LRG groups. At the linking length $R = 0.2\,\bar{n}^{-1/3} \approx 6.3$ Mpc, we totally extract 540 LRG groups with the richness $N \geq 4$ (N is the number of member galaxies in each group), in which the richest group only contains 20 LRGs. The whole group sample contains

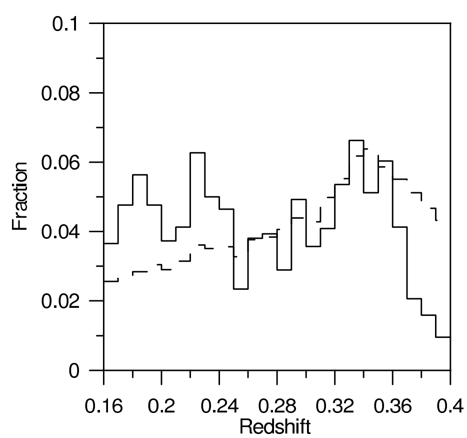

Fig. 3. The redshift distributions of the approximately volume-limited LRG sample (dashed line) and member galaxies of LRG groups (solid line).

2520 LRGs. Fig. 3 shows the redshift distributions of the LRG sample and member galaxies of LRG groups. We notice that LRG groups are mostly small systems in the LRG sample, 458 groups with the richness $N = 4$ or 5, and only 3 groups with the richness $10 < N \leq 20$. This indicates that LRGs are highly clustered on smaller scales (Eisenstein *et al.* 2005; Zehavi *et al.* 2005; Deng *et al.* 2006a).

4. Correlations between LRG properties and environment

From the approximately volume-limited LRG sample, we remove member galaxies of LRG groups and construct a field sample which contains 61678 LRGs. In order to investigate the correlations between LRG properties and environment, we will compare physical properties of member galaxies of LRG groups with those of field galaxies.

It has been known for a long time that many properties of galaxies depend strongly on luminosity *e.g.* (de Vaucouleurs 1961; Kormendy 1977; Bower *et al.* 1992; Blanton *et al.* 2003; Shen *et al.* 2003; Baldry *et al.* 2004; Balogh *et al.* 2004b; Kelm *et al.* 2005), for example, more luminous galaxies are redder. Because LRG selection cuts impose a flux cut, the number of bright galaxies increases with increasing redshift z, and the mean luminosity and many other properties of galaxies change with redshift z. In this study, we divide the whole redshift region into 24 bins of width 0.01, and focus the analysis on the statistical differences of physical properties between member galaxies of LRG groups and field galaxies in each redshift bin, to unveil the effects of galaxy environment on galaxy properties.

Clustering properties of galaxies strongly depend on galaxy luminosity: the most luminous galaxies exist preferentially in the densest regions of the Universe (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; Norberg *et al.* 2002; Zehavi *et al.* 2002; Blanton *et al.* 2003). Applying the projected correlation functions $w_p(r_p)$, Zehavi *et al.* (Zehavi *et al.* 2002) found that more luminous galaxies more strongly cluster. Using photometry and spectroscopy of 144,609 galaxies from the Sloan Digital Sky Survey, Blanton *et al.* (Blanton *et al.* 2003) investigated the dependence of local galaxy density (smoothed on 8 h^{-1} Mpc scales) on seven galaxy properties: four optical colors, surface brightness, radial profile shape as measured by the Sérsic index, and absolute magnitude. Their results indicated that local density is a strong function of luminosity, and the most luminous galaxies exist preferentially in the densest regions of the Universe. By calculating the projected correlation functions of galaxies with different spectral types, Norberg *et al.* (Norberg *et al.* 2002) further showed that luminosity, and not type, is the dominant factor of galaxy clustering.

If structure in the Universe grows due to the subsequent mergers of dark matter halos, and massive galaxies are the result of merging of smaller ones, then high density of galaxies seems helpful to produce a bright galaxy. In Fig. 4, we present the mean luminosity(g-band) as a function of redshift z for member galaxies of LRG groups and field galaxies (dashed line). Error bars (1σ) represent standard deviation for member galaxies of LRG groups. We note that the statistical difference of luminosity between member galaxies of LRG groups and field galaxies is very small ($< 0.36\sigma$). This shows that the luminosity of LRGs is not strongly correlated with the environment.

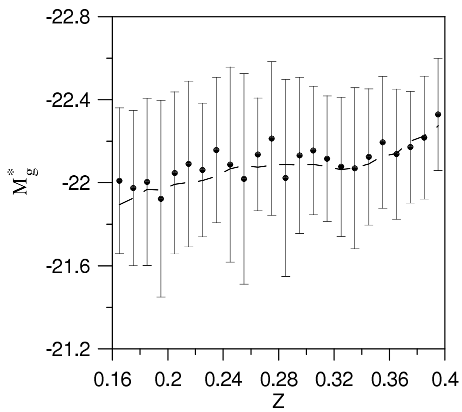

Fig. 4. The mean luminosity as a function of redshift z for member galaxies of LRG groups and field galaxies (dashed line). Error bars represent standard deviation for member galaxies of LRG groups.

Deng *et al.* (Deng *et al.* 2007a) compared statistical properties of galaxy luminosity in the compact Main galaxy group sample with those in random group sample, and found that there is no significant difference between them. In order to investigate the influence of the super-large-scale dense environment (the Great Wall of galaxies) on galaxy properties, in each redshift bin, Deng *et al.* (Deng *et al.* 2007b) performed the comparative studies of galaxy properties among the Sloan Great Wall (Gott *et al.* 2005; Deng *et al.* 2006b), isolated galaxies and the Main galaxy subsample located in the same redshift region as the Sloan Great Wall, and also found that the statistical properties of galaxy luminosity have no strong correlation with the super-large-scale dense environment. Apparently, these results are not consistent with previous conclusions.

Due to the flux cut of LRG selection cuts, mean properties of galaxies change with redshift z. In such a sample, faint galaxies are mainly located in the low redshift region, while bright galaxies are predominantly located in the high redshift region. Thus, when we explore the difference of clustering of bright and faint galaxies, it is not easy to determine whether it is due to different redshift region of bright and faint galaxies or their luminosity difference. In addition, when exploring the projected correlation functions of galaxies, it is important to recognize that there is the existence of serious projection effect in such analyses, due to the lack of radial distance information. In this study, we perform comparative study of galaxy properties in each redshift bin between galaxies located in different environments. In principle, our method may be more reasonable.

In this study, the r-band $R_{90}(R_{90,r})$ is selected as the parameter of galaxy size. As seen from Fig. 5, the mean size of member galaxies of LRG groups is almost the same as that of field galaxies (the statistical difference $< 0.33\sigma$). As is well-known, the galaxy sizes are strongly correlated with luminosity (Kormendy 1977; Shen *et al.* 2003). Due to a weak dependence of LRG luminosity on environment, we can explain this result naturally.

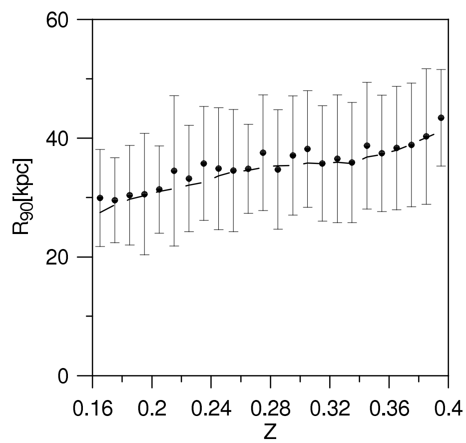

Fig. 5. The mean size as a function of redshift z for member galaxies of LRG groups and field galaxies (dashed line). Error bars represent standard deviation for member galaxies of LRG groups.

It is widely accepted that galaxy morphologies seem to correlate significantly with environment: galaxies in dense environments (*i.e.*, clusters or groups) have predominantly early type morphologies *e.g.*, (Oemler 1974; Dressler 1980; Whitmore, Gilmore, Jones 1993; Deng *et al.* 2007a; Deng *et al.* 2007b). For example, Deng *et al.* (Deng *et al.* 2007a) indicated that the proportion of early-type galaxies in compact groups is statistically higher than that in random groups. By exploring the influence of the super-large-scale dense environment on galaxy properties (luminosity, size, colors, morphology), Deng *et al.* (Deng *et al.* 2007b) found that the correlation between environment and morphology is the strongest. This suggests that in dense environments there is the existence of the transformation from late to early type. Many physical mechanisms, such as galaxy harassment (Moore *et al.* 1996), ram pressure stripping (Gunn, Gott 1972) and galaxy–galaxy merging (Toomre, Toomre 1972) can explain such a process. In this study, the concentration index $c_i = R_{90}/R_{50}$ is used to separate early-type (E/S0) galaxies from late-type (Sa/b/c, Irr) galaxies (Shimasaku *et al.* 2001). 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 the morphology classification tool *e.g.*, (Park, Choi 2005; Yamauchi, Goto 2005; Abraham, van den Bergh, Nair 2003; Strateva *et al.* 2001; Shimasaku *et al.* 2001). The concentration index is a good and simple morphological parameter. Nakamura's *et al.* (Nakamura *et al.* 2003) study showed that $c_i = 2.86$ separates galaxies at S0/a with a completeness of about 0.82 for both late and early types. Figure 6 illustrates that the early-type proportion as a function of redshift z for member galaxies of LRG groups and field galaxies. As seen from this figure, we do not find strong correlation between galaxy morphology and environment.

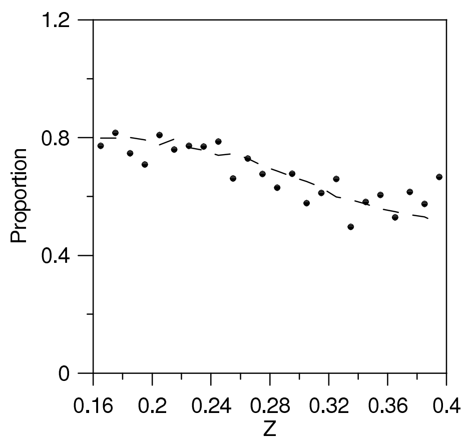

Fig. 6. The early-type proportion as a function of redshift z for member galaxies of LRG groups and field galaxies (dashed line).

Galaxy color is an important quantity that characterizes stellar contents of galaxies. Some studies showed that clustering of galaxies depends on color (Brown *et al.* 2000; Zehavi *et al.* 2002). Blanton *et al.* (Blanton *et al.* 2003) indicated that local density is a strong function of all colors. By exploring morphology-environment effects in SDSS compact groups, Lee *et al.* (Lee *et al.* 2004) found that the rest-frame colors of galaxies in compact groups indeed differ from those of field galaxies — at least for $M_{u*} - M_{g*}$, $M_{g*} - M_{r*}$, and even $M_{r*} - M_{i*}$. Deng's *et al.* (Deng *et al.* 2007c) results also showed that the mean colors of galaxies in compact Main galaxy groups are redder than those of galaxies in random groups. But in recent years there are also some different conclusions about the correlations between environment and colors *e.g.*, (Bernardi *et al.* 2003; Balogh *et al.* 2004b; Hogg *et al.* 2004). For example, Hogg's *et al.* (Hogg *et al.* 2004) study showed that red galaxy colors are independent of environment. Balogh *et al.* (Balogh *et al.* 2004b) found that at fixed luminosity the mean color of blue galaxies or red galaxies is nearly independent of environment, but at fixed luminosity the fraction of galaxies in the red distribution is a strong function of local density, increasing from ≈ 10–30% of the population in the lowest density environments, to ≈ 70% at the highest densities. They inferred that most star-forming galaxies today evolve at a rate which is determined primarily by their intrinsic properties, and independent of their environment, and that the transformation from late to early type must be either sufficiently

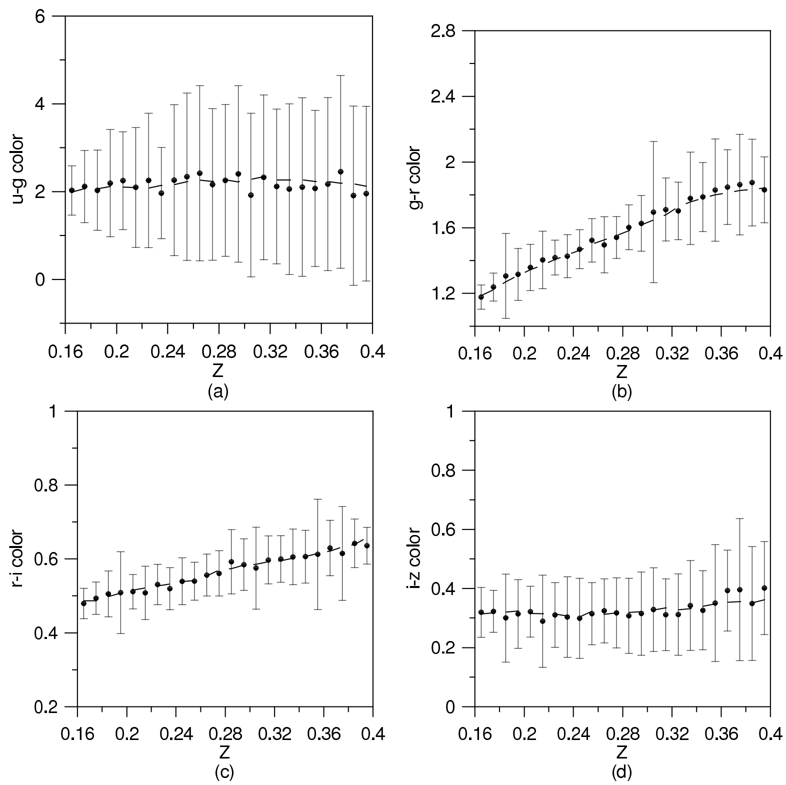

Fig. 7. Colors as a function of redshift z for member galaxies of LRG groups and field galaxies (dashed line). Error bars represent standard deviation for member galaxies of LRG groups (a) u–g color, (b) g–r color, (c) r–i color, (d) i–z color.

rapid, or sufficiently rare, to keep the overall color distribution unchanged. Figure 7 shows u–g, g–r, r–i and i–z colors as a function of redshift z for member galaxies of LRG groups and field galaxies. As seen in this figure, the mean color distributions of member galaxies of LRG groups with redshift z are almost the same as those of field galaxies. In addition, we also notice that g–r and r–i colors of LRGs apparently change with increasing redshift z, which means that these colors of LRGs are strongly correlated luminosity.

Our LRG group sample can be considered the closest systems in the LRG sample. According to above analyses, there are no significant differences between the basic properties of member galaxies of LRG groups and those of field galaxies. This indicates that basic properties of LRGs are not correlated with environment. The correlations between galaxy properties and environment ever suggested various physical mechanisms *e.g.*, (Gunn, Gott 1972; Moore *et al.* 1996; Bekki 1998; Gnedin 2003), for example, ram pressure stripping *e.g.*, (Gunn, Gott 1972) and galaxy harassment (Moore *et al.* 1996). Our results suggest that LRGs may have different formation and evolution mechanisms.

5. Summary

Using the three-dimensional friends-of-friends (FOF) algorithm developed by Davis *et al.* (Davis *et al.* 1985), we have extracted 540 close LRG groups with the number of member galaxies $N \geq 4$ from an approximately volume-limited LRG sample of the SDSS Data Release 5, in which the richest group only contains 20 LRGs. The linking length is defined as $R = 0.2\,\bar{n}^{-1/3} \approx 6.3$ Mpc, where $\bar{n}$ is the mean galaxy density. By constructing a LRG group catalog and a field sample, we intend to investigate the correlations between LRG properties and environment. Luminosity, size, morphology and colors of member galaxies of LRG groups are compared with those of field galaxies. Due to the radial selection effect, we divide the whole redshift region into 24 bins of width 0.01, and focus the analysis on the statistical differences of physical properties between member galaxies of LRG groups and field galaxies in each redshift bin, to unveil the effects of galaxy environment on galaxy properties. It is found that these properties of LRGs are not correlated with environment. The correlations between galaxy properties and environment for the Main galaxy sample were confirmed by many studies, which ever suggested various physical mechanisms. Our results show LRGs may have different formation and evolution mechanisms.

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