АСТРОФИЗИКА

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THE LUMINOSITY DEPENDENCE OF CLUSTERING PROPERTIES OF LUMINOUS RED GALAXIES (LRGs)

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From the approximately volume-limited Luminous Red Galaxy (LRG) sample of the Sloan Digital Sky Survey Data Release 6 (SDSS DR6), we construct three LRG samples with different luminosity, which have the nearly same number density, to investigate the luminosity dependence of clustering properties of LRGs. We preferentially conclude that the luminosity dependence of clustering properties of galaxies is fairly complicated, and that there is no single tendency for clustering properties of galaxies to change with luminosity.

Key words: *galaxies:fundamental parameters*

1. *Introduction.* It is widely accepted that galaxies with different luminosities cluster differently: luminous galaxies exhibit stronger clustering than faint galaxies [1-11]. In the past, correlation function was the most popular method for investigating this issue. Norberg et al. [8] measured the projected two-point correlation function of galaxies in a series of volume-limited samples drawn from the 2dFGRS, each with different absolute magnitude and redshift limits, and found that the clustering amplitude increases slowly with absolute magnitude for galaxies fainter than $M^{*}_{bJ} - 5\log_{10} h = -19.7$ (Folkes et al. [12]), but rises more strongly at higher luminosities, and that the slope of the best-fitting power law correlation function is independent of luminosity. Norberg et al. [8] further demonstrated the robustness of this study in two ways. First, they calculated the correlation function of galaxies in three disjoint absolute magnitude bins measured in the same volume (subject to the same large-scale structure fluctuations). A clear increase in clustering amplitude was found for the brightest galaxies in the volume (see Fig.1a of [8]). Secondly, they also explored the correlation function of galaxies in a fixed luminosity bin, but using samples taken from different volumes and gave consistent results (see Fig.1b of [8]). These results showed that the difference of clustering of galaxies in a series of volume-limited samples is due to their luminosity difference, not to different volumes, establishing the dependence of clustering on galaxy luminosity. Using SDSS data, Zehavi et al. [10,11] got the same conclusions. Zehavi et al. [13] investigated the intermediate-scale (0.3 to 40 h^{-1} Mpc) clustering of 35000 luminous early-type galaxies in the redshift region $0.16 \le z \le 0.44$ from the Sloan Digital Sky Survey and found

that clustering properties are dependent on the luminosity, more luminous LRGs being yet more strongly clustered. But using correlation function, we can not clearly understand the geometry of the distribution of galaxies. May be, we should try some new methods and use different galaxy samples, in order to get more informations about the luminosity dependence of clustering properties. Some works studied how the filaments depend on galaxy properties (Pandey & Bharadwaj [14-16]). Pandey & Bharadwaj [14] showed that the degree of filamentarity exhibits a luminosity dependence with the brighter galaxies having a more concentrated and less filamentary distribution as compared to the faint ones.

Cluster analysis (Einasto et al. [17]) is a method which has been widely applied to study the geometry of point samples and is more sensitive to the geometry of the distribution of galaxies. By this method, the galaxy sample can be separated into isolated galaxies, close double and multiple galaxies, galaxy groups or clusters and even superclusters which consist of clusters and strings of galaxies. Galaxy strings form bridges between superclusters and join all superclusters to a single infinite network. From the apparent-magnitude Main galaxy sample (Strauss et al. [18]) of the Sloan Digital Sky Survey Data Release 6 (SDSS DR6) (Adelman-McCarthy et al. [19]), Deng et al. [20] constructed three volume-limited samples with different luminosity and performed comparative studies of clustering properties between them, using cluster analysis. It is found that the luminosity dependence of clustering properties does not exhibit a single trend, which is different between samples fainter than the characteristic luminosity M^* of the Schechter luminosity function and ones brighter than M^*. In the galaxy samples brighter than M^*, the brighter galaxies have a more concentrated and less filamentary distribution as compared to the faint ones. But when performing comparative studies of the luminosity dependence of clustering properties between the sample fainter than M^* and the one brighter than M^*, an opposite trend is found.

The SDSS galaxy data contains two interesting samples: the Main galaxy sample [18] and the Luminous Red Galaxy (LRG) sample [21]. Main galaxies mostly are located within the redshift interval $0.02 \le z \le 0.2$, while LRGs are at higher redshift, intrinsically red and luminous early-types. In this study, we still use cluster analysis and investigate the luminosity dependence of clustering properties of Luminous Red Galaxies. Our paper is organized as follows. In section 2 we describe the data used. The cluster analysis is discussed in section 3. In section 4 we investigate the luminosity dependence of clustering properties of Luminous Red Galaxies. Our main results and conclusions are summarized in section 5.

2. *Data.* The Sloan Digital Sky Survey (SDSS) is one of the largest astronomical surveys to date. Many of the survey properties were discussed in

detail in the Early Data Release paper [22]. Galaxy spectroscopic target selection was implemented by two algorithms. The Main galaxy sample [18] comprises galaxies brighter than $r_{petro} < 17.77$, where r_{petro} is the apparent r-band Petrosian magnitude. This sample has a median redshift of 0.10. The Luminous Red Galaxy algorithm [21] selects galaxies to $r_{petro} < 19.5$ that are likely to be luminous early-types, based on their observed colors. In our work, the data was downloaded from the Catalog Archive Server of SDSS Data Release 6 [19] by the SDSS SQL Search (http://www.sdss.org/dr6/).

Eisenstein et al. [21] strongly advised the researcher that LRGs should be selected at $z > 0.15$ and 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 a approximately volume-limited one. Thus, we extract all LRGs with the redshift $0.16 \le z \le 0.4$ (with SDSS flag: Primtarget_Galaxy_Red, redshift confidence level: $z_{conf} > 0.95$) and construct an approximately volume-limited sample which contains 77148 LRGs. This sample is therefore the lower redshift regime of the LRGs and does not extend into the $z > 0.4$ regime of just brighter objects.

We suspect that when comparing samples with different number density, the difference of number density of samples may result in the difference of clustering properties between samples, even if dimensionless radii are used to express distances. This is not a physical effect. Thus, across different luminosity ranges, we construct three samples with the nearly same number density, labeled S1 to S3. S1 contains 25419 LRGs with the luminosity range $M_g \ge -21.96$, S2 includes 26169 LRGs with the luminosity range $-22.22 \le M_g < -21.96$, S3 has 25560 LRGs with the luminosity range $M_g < -22.22$.

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. Following Appendix B of Eisenstein et al. [21], 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 "nonstarforming" model presented in Appendix B (which describes the $K+e$ correction procedure) of Eisenstein et al. [21] and normalized to M_g at $z = 0$.

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

3. *Cluster analysis.* Cluster analysis [17] used here is actually the friends-of friends algorithm by which the galaxy sample can be separated into individual systems at a given neighbourhood radius R. Starting from one galaxy of the sample, we search all galaxies within a sphere of radius R around it and call these close galaxies "friends". These "friends" and the starting galaxy

are considered belonging to the same system. Around new neighbours, we continue above procedure using the rule "any friend of my friend is my friend". When no more new neighbours or "friends" can be added, then the procedure stops and a system is identified. Apparently, at small radii, most systems are some isolated single galaxies, the rest being close double and multiple galaxies. At larger radii groups and clusters of galaxies and even superclusters will be formed. Superclusters are the largest non-percolating galaxy systems which contain clusters and groups of galaxies with their surrounding galaxy filaments (Einasto et. al [23-26]). By selecting different neighbourhood radii, we can probe the structures at different scales.

The mean density of galaxies is $\overline{\rho} = N/V$ (N is the number of galaxies contained in the volume V). The Poisson radius (radius of the sphere with unit population) is $R_0 = (3/4\pi\overline{\rho})^{1/3}$. To compare samples with different number density we express all distances in dimensionless radii $r = R/R_0$. Poisson radii (comoving distance) are 28.25 Mpc for the S1 sample, 27.98 Mpc for the S2 sample and 28.20 Mpc for the S3 sample.

4. ***Luminosity dependence of clustering properties.*** According to the analysis of Einasto et al. [17], maximum lengths of the systems can be calculated by three different methods. In this study, the maximal length of a system is defined as the maximum distance between members of this system. The largest system has the longest one, but it often is not the richest system which contains the most member galaxies. Fig.1 shows the galaxy number N_{max} of the richest system and the maximal length D_{max} of the largest system as a function of the dimensionless radius r for three LRG samples with different luminosity. As Deng et al. [27], we define $L_0 = V^{1/3}$ (the edge length of the cube) as the rough estimate of the edge length of the sample volume V and express the maximal length of the largest system as dimensionless length $d_{max} = D_{max}/L_0$. The edge length L_0 of our LRG sample is 1339.10 Mpc. In the volume-limited Main galaxy sample, Deng et al. [20] did not find significant tendency for the galaxy number N_{max} of the richest system and the maximal length D_{max} of the largest system to change with luminosity. But in the LRG sample we note that richer and larger systems can be more easily formed in the S1 sample containing the faintest LRGs. In the dimensionless radius region $r \le 0.8$, the LRG systems identified by cluster analysis consist mostly of isolated galaxies, close double and multiple galaxies and few systems form groups. At dimensionless radius $r = 0.8$, the richest system contains 49 LRGs in the S1 sample, 27 LRGs in the S2 sample and 51 LRGs in the S3 sample; the maximal length of the largest system is 159.47 Mpc in the S1 sample, 143.51 Mpc in the S2 sample and 162.42 Mpc in the S3 sample. Even at dimensionless radius $r = 1.0$ (if the distribution of galaxies is uniform, all galaxies merge into a huge network at this radius), the richest system only contains 212 LRGs in the S1 sample, 127 LRGs in the S2 sample and 100 LRGs in the

S3 sample; the maximal length of the largest system is 398.29 Mpc in the S1 sample, 374.28 Mpc in the S2 sample and 358.87 Mpc in the S3 sample, while in the volume-limited Main galaxy samples with different luminosity, Deng et al. [20] found that the richest and largest systems identified at dimensionless radius $r = 0.70$ already are huge clusters. This indicates that LRGs show stronger clustering on smaller scales, which is in accord with the analysing results of correlation function [13,28]. The observed features of the galaxy distribution are undoubtedly important constraints on the models for the formation and evolution of the universe. Geller and Huchra [29] indicated that the cold dark matter model can successfully explain the clustering of galaxies on scales $\leq 10\,h^{-1}$ Mpc and the qualitative appearance of the large-scale galaxy distribution. However, the occurrence of super-large-scale structure in the distribution of galaxies is a serious challenge to the cold dark matter model. Geller and Huchra [29] claimed that hot dark matter model may be a good

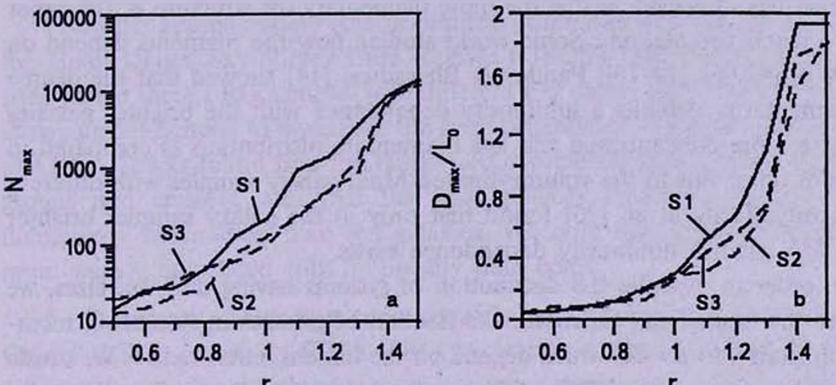

Fig.1. Clustering properties for the S1, S2 and S3 samples: a) the galaxy number N_{max} of the richest system, b) the maximal length D_{max}/L_0 of the largest system, as a function of the dimensionless radius r.

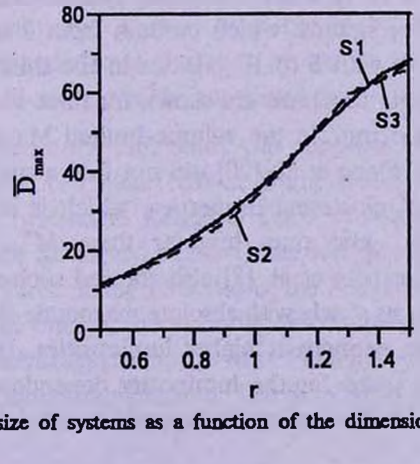

Fig.2. Average size of systems as a function of the dimensionless radius r for the S1, S2 and S3 samples.

alternative.

Fig.2 shows the average size of the systems (not including isolated galaxies) *vs.* dimensionless radii for LRG samples with different luminosity. The average size of the systems as a function of the dimensionless radius r is nearly the same for LRG samples with different luminosity.

With increasing neighbourhood radius various systems merge into strings and later into a string network. At a certain critical radius r_c, called the percolation radius, the largest string system reaches opposite sidewalls of the sample. In this study, the percolation radius r_c is defined as the radius at which the maximal length D_{max} of the largest system approximate to the edge length L_0: $r_c \approx 1.30$ for the S1 sample, $r_c \approx 1.32$ for the S2 sample and $r_c \approx 1.34$ for the S3 sample. There is a weak dependence of the percolation radius on the luminosity. As indicated in Einasto et al. [17], the percolation radius depends on two factors: the degree of clustering and the degree of concentration to the strings. It is evident that the more filamentary the structure is, the easier it is to reach percolation.. Some works studied how the filaments depend on galaxy properties [14-16]. Pandey & Bharadwaj [14] showed that the degree of filamentarity exhibits a luminosity dependence with the brighter galaxies having a more concentrated and less filamentary distribution as compared to the faint ones. But in the volume-limited Main galaxy samples with different luminosity, Deng et al. [20] found that only in the galaxy samples brighter than M^*, such a luminosity dependence exists.

In order to describe the distribution of systems having different sizes, we analyse the multiplicity functions: the fraction of galaxies in systems of membership from n to $n+dn$, which depend on the dimensionless radii r. We divide the interval from 1 to N (the total number of galaxies) into 7 subintervals: $n=1$; $2 \le n < 5$; $5 \le n < 20$; $20 \le n < 50$; $50 \le n < 100$; $100 \le n < 200$; $n \ge 200$ and then construct histograms of the multiplicity functions at different radii (r=0.7, r=0.8, r=0.9). In each histogram, systems which contain one galaxy are in the first bin, systems which contain from 2 to 4 galaxies are in the second bin, systems with 5 to 19 galaxies in the third bin and so on.

In Fig.3, the multiplicity functions are shown for three samples. The (1σ) error bars are Poissonian errors. In the volume-limited Main galaxy samples with different luminosity, Deng et al. [20] did not find a single trend for the luminosity dependence of clustering properties, which is different between samples fainter than M^* and ones brighter than M^*. The studies of correlation function by Norberg et al. [8] also showed such a difference: the clustering amplitude increases slowly with absolute magnitude for galaxies fainter than M^*, but rises more strongly at higher luminosities. In this study, we still do not find a single trend for the luminosity dependence of clustering properties of LRGs. May be, the luminosity dependence of clustering properties of galaxies is fairly complicated. There is no single tendency for clustering properties of galaxies to change with luminosity.

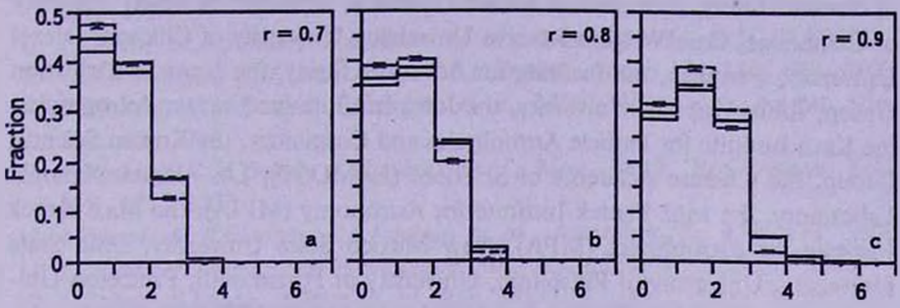

Fig.3. Histograms of multiplicity functions for the S1, S2 and S3 samples at different radii. a) at $r=0.7$. b) at $r=0.8$. c) at $r=0.9$. The error bars for the S2 sample are 1σ Poissonian errors. Error bars for the S1 and S3 samples are omitted for clarity.

From the approximately volume-limited Luminous Red Galaxy sample of the Sloan Digital Sky Survey Data Release 6 (SDSS DR6), Deng et al. [30] constructed three LRG samples with different $g-r$ color, which have the nearly same number density, to investigate the color dependence of clustering properties of LRGs. It was found that the bluest LRGs preferentially inhabit the dense groups and clusters, and that the blue galaxies seemingly have a more filamentary distribution than red galaxies. We note that galaxy clustering is more weakly correlated with luminosity than color.

5. *Summary*. From the approximately volume-limited Luminous Red Galaxy (LRG) sample of SDSS DR6, we construct three LRG samples with different luminosity, which have the nearly same number density, to investigate the luminosity dependence of clustering properties of LRGs. It is found that richer and larger systems can be more easily formed in the faintest sample. Our results also seemingly show that there is a weak dependence of the percolation radius on the luminosity. As seen from Fig.3, there is no a single trend for the luminosity dependence of clustering properties of LRGs. We also note that galaxy clustering is more weakly correlated with luminosity than color.

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ЗАВИСИМОСТЬ ОСОБЕННОСТЕЙ СКУЧИВАНИЯ ЯРКИХ КРАСНЫХ ГАЛАКТИК ОТ СВЕТИМОСТИ

ХИН-ФА ДЕНГ, ДЖИ-ШУ ХЕ, ДЖАН СОНГ,
ХИАО-ХИА КИАН, ПИНГ ВУ

Используя пространственно ограниченную выборку Ярких Красных Галактик (ЯКГ) из обзора SDSS DR6, составлены три ЯКГ выборки с различными светимостями, которые имеют примерно одинаковую плотность. Указанные выборки используются для исследования зависимости особенностей скучивания ЯКГ от светимости. Делается заключение, что эта зависимость довольно сложная и нет единой тенденции для ее изменения со светимостью.

Ключевые слова: *галактики:основные параметры*

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