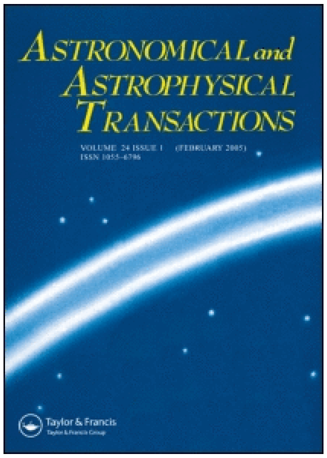

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Luminous red galaxy pairs from the SDSS data release 3

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Using cluster analysis, we selected three luminous red galaxy (LRG) pair samples and studied their various properties. We found that LRG pair samples, identifying at different radii, have the same properties: there is a tendency for pair galaxies to have similar luminosity and size. Additionally, LRG pairs have the same properties as whole and isolated LRGs.

Keywords: Cosmology; Galaxy pairs; Cluster

1. Introduction

In the process of galaxy evolution, galaxy interactions are frequent and play a crucial role in determining galaxy properties. Interacting and merging galaxies are among the most fascinating astronomical objects in the Universe. These galaxy systems span a wide range of configurations, from single distant encounters to close encounters, which may result in a single merged system. Typical morphologies include bridges between the interacting partners and tidal tails. These structures are usually associated with sites of strong star formation resulting in dense star clusters or even dwarf galaxy-sized objects.

A simple method of identifying isolated galaxy pairs was described by Karachentsev [1]. Two galaxies of angular diameter a_1 and a_2, whose separation is $x_{1,2}$, will satisfy the Karachentsev criterion, if

$$\frac{x_{1,i}}{x_{1,2}} \geq 5 \times \frac{a_i}{a_1}; \quad \frac{x_{2,i}}{x_{1,2}} \geq 5 \times \frac{a_i}{a_2}$$

where i indicates each of the neighbor galaxies whose diameter a_i is included in the intervals set by

$$\frac{1}{2}a_1 \leq a_i \leq 4a_1; \quad \frac{1}{2}a_2 \leq a_i \leq 4a_2$$

Using Zwicky *et al.* [1], *Catalogue of Galaxies and Clusters of Galaxies*, Karachentsev [2] identified 603 isolated pairs north of $\delta_{1950} = -3°$ for galaxies down to $m_{pg} = 15.7$. Due to its

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size, completeness and relatively unbiased selection, this catalog has been a popular sample for studies of isolated galaxy pairs [3–13].

Lambas *et al.* [14] studied galaxy pairs in the field selected from the 100 K public release of the 2dFgalaxy redshift survey. Galaxy pairs were selected by radial velocity (ΔV) and projected separation (r_p) criteria. They excluded pairs in high density regions by removing galaxies in groups and clusters, and analyzed the star formation activity in the pairs as a function of both relative projected distance and relative radial velocity. They found that star formation in galaxy pairs is significantly enhanced over that of isolated galaxies with similar redshifts in the field for $r_p < 25$ kpc and $\Delta V < 100$ km/s.

Allam *et al.* [15] presented a catalog of 1479 merging pairs of galaxies extracted from the approximately 462 sq deg of imaging data from the Sloan Digital Sky Survey Early Data Release (SDSS EDR) [16]. The selection algorithm, implementing a variation on the original Karachentsev [2] criteria, proved to be very efficient and fast. They only considered galaxies with g^*-band Petrosian magnitudes $16.0 \leq g^* \leq 21.0$. To obtain isolated pairs, they imposed the following criteria on any neighboring galaxy i:

$$\left|g^*_{1,2} - g^*_i\right| > 3.0$$
$$0.25 \times R_{petro,1} \leq R_{petro,i} \leq 4 \times R_{petro,1}(g^*\text{−band})$$
$$0.25 \times R_{petro,2} \leq R_{petro,i} \leq 4 \times R_{petro,2}(g^*\text{−band})$$

Finally, they classified each resulting galaxy pair by the separation of its two members:

merging pairs: $x_{1,2} \leq (\text{Rpetro}, 1 + \text{Rpetro}, 2)$

intermediate pairs: $(\text{Rpetro}, 1 + \text{Rpetro}, 2) < x_{1,2} \leq 3 \times (\text{Rpetro}, 1 + \text{Rpetro}, 2)$

wide pairs: $3 \times (\text{Rpetro}, 1 + \text{Rpetro}, 2) < x_{1,2} \leq 10 \times (\text{Rpetro}, 1 + \text{Rpetro}, 2)$

They concerned only with the merging pair sample. After all rejections and verifications, the final number of candidate merging pairs left for inclusion in this catalog was 1479.

We think that the above methods of identifying galaxy pairs are biased toward binaries with a small viewing angle but, perhaps, with a certain radial distance. This bias is due to the use of the galaxy diameter or projected separation criteria. In this paper, we identify galaxy pairs of luminous red galaxies (LRGs) by using three-dimensional cluster analysis [17]. LRGs are among the most luminous galaxies in the Universe and map large cosmological volumes. This makes LRGs an astrophysically interesting sample. Using cluster analysis, at very small radii, the sample mainly consists of single galaxies: few galaxies form close double and multiple systems. Here, these close double galaxies, identifying at very small radii, are considered galaxy pairs.

Our paper is organized as follows. In section 2, we describe the data to be used. In section 3, we discuss the cluster analysis. In section 4, we analyse the basic properties of galaxy pairs of LRGs. Finally, in section 5, we summarize our main results.

2. Data

The Sloan Digital Sky Survey (SDSS) [18] is one of the largest astronomical surveys to date. The SDSS was designed in scope and systematic control to permit the study of galaxy clustering over a wide range of scales and galaxy properties. Galaxy spectroscopic target selection proceeds by two algorithms. The primary sample [19], referred to here as the MAIN sample, targets galaxies brighter than $r < 17.77$ (r-band apparent Petrosian magnitude). The surface density of such galaxies is about 90 per square degree. This sample has a median redshift of 0.10 and few galaxies beyond $z = 0.25$. The LRG algorithm [20] selects 12 additional galaxies per square degree, using color-magnitude cuts in g, r, and i to select galaxies to $r < 19.5$ that are likely to be luminous early-types at redshifts up to 0.5. The selection is extremely efficient and the redshift success rate is very high. In detail, there are two sections of the LRG algorithm, known as Cut I and Cut II and described in Eisenstein *et al.* [20].

The SDSS sky coverage can separate three regions north of the Galactic plane: one region at the celestial equator and another at high declination south of the Galactic plane and a set of three stripes near the equator. Each of these areas covers a wide range of survey longitude. We downloaded data from the Catalog Archive Server of SDSS Data Release 3, using the SDSS SQL Search (http://www.sdss.org/), and select from it 26481 LRGs (with SDSS flag: Primtarget_Galaxy_Red, redshift confidence level: zconf > 0.95, redshift region: $0.2 \le z \le 0.4$) and construct our LRG sample.

In calculating the comoving distance, we used a cosmological model with a matter density $\Omega_0 = 0.3$, cosmological constant $\Omega_A = 0.7$ and Hubble's constant $h = 0.7$.

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.* [20], 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.* [20] and normalized to M^*_g at $z = 0$.

3. Cluster analysis

Cluster analysis [17] is a general method, which has found wide application in many sciences to study the geometry of point samples. The kernel of the method is an objective, automated procedure to separate the sample into individual systems. Let us draw a sphere of radius R around each sample point (in our case, galaxy). If within this sphere there are other galaxies, they are considered belonging to the same system. Call these close galaxies 'friends'. Now draw spheres around new neighbours and continue the procedure using the rule 'any friend of my friend is my friend'. The procedure stops when no more new neighbours or 'friends' can be added: a system is identified. So, finally, each system consists either of a single, isolated galaxy or of a number of galaxies, each having at least one neighbour at a distance not exceeding R. At very small radii, the sample mainly consists of single galaxies – few galaxies form close double and multiple systems.

4. The basic properties of galaxy pairs of Luminous Red Galaxies (LRGs)

Using cluster analysis, we select the LRG close double galaxies, identifying at radii $R = 1$ Mpc, $R = 1.5$ Mpc and $R = 2$ Mpc (in LRG sample, the radius of the sphere with unit population is $R_0 = 23.04$ Mpc, $R = 2$ Mpc is very small comparing to R_0), as three pair samples, respectively, referred to as Sample 1, Sample 1.5 and Sample 2. Sample 1 includes 376 LRGs (1.4% of the total galaxy number in LRG sample), Sample 1.5 includes 526 LRGs (2% of the total galaxy number) and Sample 2 includes 740 LRGs (2.8% of the total galaxy number). In figures 1 and 2, we analysed the size and luminosity M^*_g distributions of three pair samples. The two Petrosian radii listed in the Photo output, R_{50} and R_{90}, are the radii enclosing

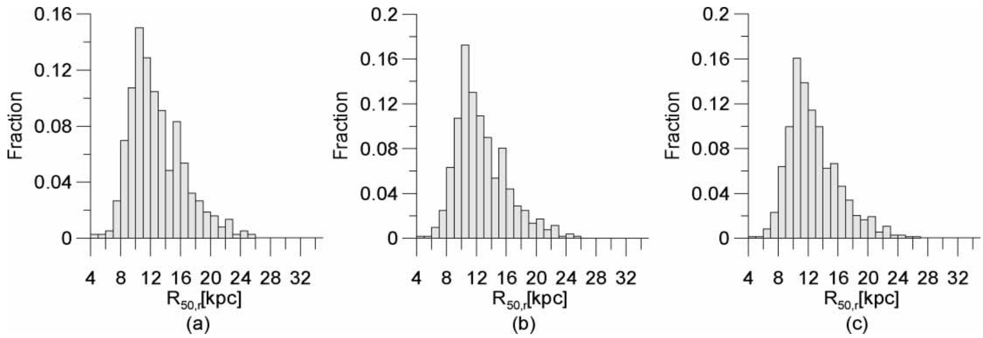

Figure 1. Histogram of the size distribution of galaxy pairs forming at R = 1 Mpc, R = 1.5 Mpc and R = 2 Mpc. (a) At R = 1 Mpc, (b) at R = 1.5 Mpc, (c) at R = 2 Mpc.

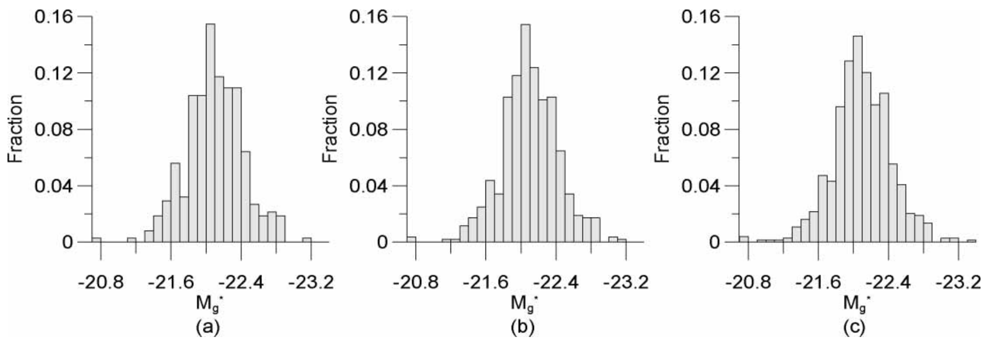

Figure 2. Histogram of the luminosity distribution of galaxy pairs forming at R = 1 Mpc, R = 1.5 Mpc and R = 2 Mpc. (a) At R = 1 Mpc, (b) at R = 1.5 Mpc, (c) at R = 2 Mpc.

50 and 90% of the Petrosian flux for each band, respectively. We selected the r-band R_{50} ($R_{50,r}$) as the parameter of galaxy size. The luminosity M_g^* is the g-band absolute magnitude, which has been k-corrected and passively evolved to rest-frame magnitudes at z = 0. To derive and compare quantitative parameters of the distributions, we fit all histograms. Available fits are normal distribution (Gaussian). Fit results are given in table 1. We found that the size and luminosity M_g^* distributions of three pair samples are almost the same. This demonstrates that close double galaxies, identifying at this radius region by cluster analysis, have definite basic properties and can be considered good galaxy pair samples.

At intermediate radii, some galaxies of the sample begin to form galaxy groups and clusters. At a large radius, most galaxies of the sample merge into less dense regions of groups and

Table 1. Gaussian fit results for figures 1 and 2.

	Sample	Average	Standard deviation
Histogram of size distribution (figure 1)	1	12.8165	3.58648
	1.5	12.6508	3.43462
	2	12.718	3.40163
Histogram of luminosity distribution (figure 2)	1	−22.1012	0.322291
	1.5	−22.1004	0.326495
	2	−22.0958	0.333256

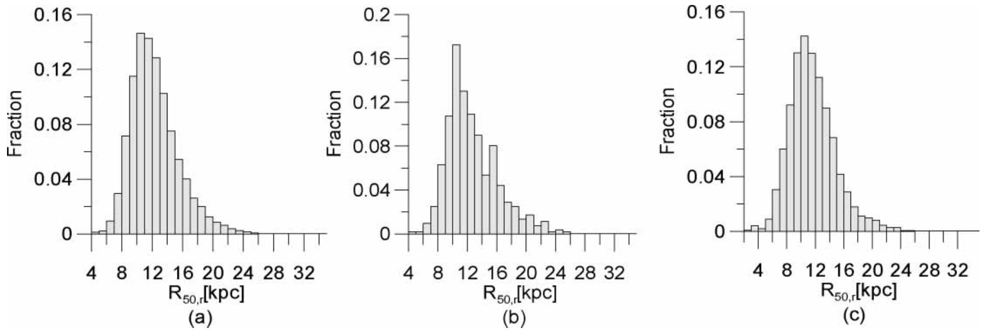

Figure 3. Histogram of the size distribution for all LRGs, galaxy pairs forming at R = 1.5 Mpc and isolated galaxies forming at r = 1.3. (a) For all LRGs, (b) for galaxy pairs forming at R = 1.5 Mpc, (c) for isolated galaxies forming at r = 1.3.

clusters, even a huge and less dense system. Few galaxies are isolated. These single galaxy systems can be considered real isolated galaxies in three-dimensional space. We selected the isolated LRGs, identifying at dimensionless radius r = 1.3 (dimensionless radius $r = R/R_0$ where R_0 is the radius of the sphere with unit population. Within redshift region: $0.2 \leq z \leq 0.4$, the calculated result of R_0 for LRG sample is 23.04 Mpc), as our isolated LRG samples. It includes 2239 LRGs (8.5% of the total galaxy number in the LRG sample). In figures 3 and 4, we compared the size and luminosity M_g^* distributions of pair sample, identifying at radius R = 1.5 Mpc, with that of whole LRG and isolated galaxy samples, identifying at dimensionless radius r = 1.3. The Gaussian fit results for figures 3 and 4 are given in table 2. We found that the basic properties of galaxy pairs, isolated galaxies and whole LRG sample are almost the same.

We believe that the member galaxies of physical pairs may have similar properties. So, we have calculated the luminosity difference $\Delta M_g^* = |M_{g,1}^* - M_{g,2}^*|$ and diameter ratio Pr ($R_{50,r}$ of large galaxy to that of small galaxy in pairs, $Pr \geq 1$) of member galaxies in pairs. Figure 5 shows the luminosity difference ΔM_g^* and diameter ratio Pr of each pair in three pair samples. We found that there is a tendency for pair galaxies to have similar luminosity and size. In three pair samples, most pairs have smaller luminosity difference ΔM_g^* and diameter ratio Pr close to 1; the average value of luminosity difference ΔM_g^* and diameter ratio Pr are: for Sample 1, $\overline{\Delta M_g^*} = 0.3151$, $\overline{Pr} = 1.3707$; for Sample 1.5, $\overline{\Delta M_g^*} = 0.3151$, $\overline{Pr} = 1.3562$; for Sample 2,

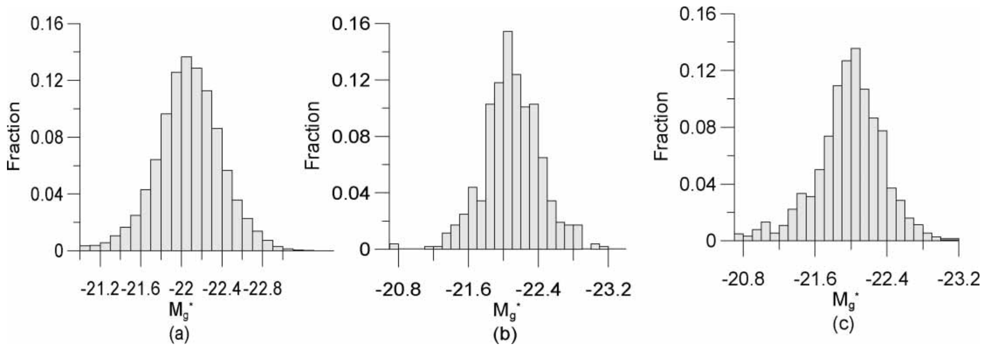

Figure 4. Histogram of the luminosity distribution for all LRGs, galaxy pairs forming at R = 1.5 Mpc and isolated galaxies forming at r = 1.3. (a) For all LRGs, (b) for galaxy pairs forming at R = 1.5 Mpc, (c) for isolated galaxies forming at r = 1.3.

Table 2. Gaussian fit results for figures 3 and 4.

	Sample	Average	Standard deviation
Histogram of size distribution (figure 3)	All LRGs	12.335	3.10408
	Galaxy pairs (sample 1.5)	12.6508	3.43462
	Isolated galaxies (forming at r = 1.3)	11.6262	3.1613
Histogram of luminosity distribution (figure 4)	All LRGs	−22.0762	0.315934
	Galaxy pairs (sample 1.5)	−22.1004	0.326495
	Isolated galaxies (forming at r = 1.3)	−21.9815	0.36669

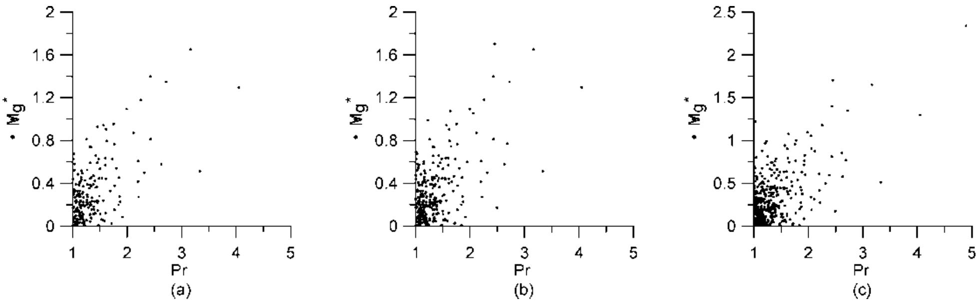

Figure 5. Luminosity difference ΔM_g^* and diameter ratio Pr of every galaxy pairs in three pair samples. (a) Forming at R = 1 Mpc, (b) forming at R = 1.5 Mpc, (c) forming at R = 2 Mpc.

$\overline{\Delta M_g^*} = 0.3247$, $\overline{Pr} = 1.3561$. Figure 5 also shows that some pairs have a large luminosity difference ΔM_g^* and they correspondingly have a large diameter ratio Pr. This demonstrates that the luminosity of member galaxies in pairs is correlated to their size. Additionally, we also noticed that the analysed results for three pair samples are almost the same.

5. Summary

In this paper, we identified LRG pairs using cluster analysis and studied the properties of LRG pair samples identifying at different radii. The whole LRG sample is limited in the redshift region: $0.2 \leq z \leq 0.4$ and includes 26 481 LRGs. We select three LRG pair samples: Sample 1, forming at radius R = 1 Mpc, includes 376 LRGs (1.4% of the total galaxy number in the LRG sample); Sample 1.5, forming at radius R = 1.5 Mpc, includes 526 LRGs (2% of the total galaxy number); Sample 2, forming at radius R = 2 Mpc, includes 740 LRGs (2.8% of the total galaxy number). The main results can be summarized as follows:

(1) The size and luminosity M_g^* distributions of three pair samples are almost the same. This demonstrates that close double galaxies, identifying at this radius region by cluster analysis, have definite basic properties and can be considered good galaxy pair samples.
(2) In figures 3 and 4, we compare the size and luminosity M_g^* distributions of pair sample, identifying at radius R = 1.5 Mpc, with that of whole LRG and isolated galaxy samples, identifying at dimensionless radius r = 1.3, and find that these basic properties of galaxy pairs, isolated galaxies and whole LRG sample are almost the same.
(3) We have calculated the luminosity difference $\Delta M_g^* = \left| M_{g,1}^* - M_{g,2}^* \right|$ and diameter ratio Pr of member galaxies in pairs. Figure 5 shows that there is a tendency for pair galaxies to have similar luminosity and size.

Acknowledgements

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