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Isolated Main Galaxy Pairs from the SDSS Data Release 4 *

Xin-Fa Deng[1], Yi-Qing Chen[2], Ping Wu[1], Cheng-Hong Luo[1] and Ji-Zhou He[1]

[1] Mathematics and Physics College, Nanchang University, Nanchang 330047; *xinfadeng@163.com*
[2] Management College, Nanchang University, Nanchang 330047

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Abstract From the Main galaxy data of the SDSS Data Release 4 (SDSS4), we have identified close galaxy pairs at neighbourhood radius $R = 100$ kpc by three-dimensional cluster analysis. Using the criterion that an "isolated galaxy pair" must be separated from its "nearest neighbor" by more than 500 kpc, we constructed an isolated galaxy pair sample of 1158 pairs. We also constructed a random pair sample by randomly selecting 1158 galaxy pairs from the Main galaxy sample, which has the same redshift distribution as the isolated galaxy pair sample, and in which the two components of any pair have the same redshifts. Comparative studies of luminosity and size between the members of the galaxy pairs are performed. We find and further confirm there is no tendency for paired galaxies to have similar luminosities or sizes. From the isolated pair sample we also selected a subsample with the magnitude limit of the primary raised by 2 magnitudes, so as to include pairs in which the secondary is 2 magnitudes fainter than the primary. This subsample contains 82 pairs. A random pair sample is similarly constructed.

Key words: galaxy: fundamental parameters– galaxies: interactions

1 INTRODUCTION

Galaxy pairs have long been an important subject of research and are also among the most fascinating objects in the universe. In the process of galaxy evolution, galaxy interactions frequently occur, causing a variety of interesting astrophysical phenomena, so they play a crucial role in the determination of galaxy properties. In many studies, close galaxy pairs are often defined as interacting and merging galaxies, and are used for studying galaxy interactions.

For paired galaxies, some properties may be correlated between the members. More than 40 years ago, Holmberg (1958) discovered that the colors of paired galaxies are closely correlated. This result was interpreted as reflecting a tendency for galaxies that form and evolve together to be of similar types. Allam et al. (2004) calculated the Holmberg Effect for 1479 merging pairs in the Sloan Digital Sky Survey Early Data Release (SDSS EDR, Stoughton et al. 2002). They noted that the level of significance of the correlation depend on the color index: it is the highest ($> 12\sigma$) for the $g^* - r^*$ color, and is the lowest ($< 2\sigma$) for the $i^* - z^*$ color. Zitelli et al. (2004) selected a sample of 84 isolated pairs of galaxies and found the projected separation between pair members to be $r < 200h^{-1}$ kpc, and the isolation criterion requires the pair to have no further companion within $R = 1h^{-1}$ Mpc distance. Morphological classification for both

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members is available for 57 pairs. Of these, nine are early-type (E+E) pairs, 29 late type (S+S) pairs, and 19 mixed (E+S) pairs. Thus, for 66.7% of the pairs the two members have the same morphological types. Applying the three-dimensional cluster analysis (Einasto et al. 1984), to the MAIN galaxy data of the SDSS Data Release 3 (Abazajian et al. 2005), Deng et al. (2005a) identified galaxy pairs. They compared the luminosities and sizes of the pair members and found there is a tendency for paired galaxies to have similar luminosities and sizes.

Many previous galaxy pair identification works were based on the two-dimensional projected sky separations and galaxy diameters (Karachentsev 1972; Lambas et al. 2003; Allam et al. 2004). The samples of galaxy pairs so identified are actually two-dimensional samples. In order to produce a real three-dimensional pair sample, we use three-dimensional cluster analysis and extract close galaxy pairs from the Main galaxy sample (Strauss et al. 2002) of the SDSS Data Release 4 (Adelman-McCarthy et al. 2006). The SDSS Data Release 4 provides a much deeper and wider galaxy sample with well-measured photometric and spectroscopic properties than almost any other wide-area catalog to date. From it, we can produce the largest galaxy pair sample and make ideal statistical analyses. We also perform comparative studies of some properties between the two members of galaxy pairs.

This paper is organized as follows. In Section 2, we describe the data to be used. The cluster analysis and selection criteria are discussed in Sections 3 and 4, respectively. In Section 5, we perform the comparative studies between the pair members. Our main results and conclusions are summarized in Section 6.

2 DATA

The Sloan Digital Sky Survey (SDSS) is one of the largest astronomical surveys. The completed survey will cover approximately 10 000 square degrees. York et al. (2000) provided a technical summary of the SDSS. The SDSS observes galaxies in five photometric bands (u, g, r, i and z) centered at (3540, 4770, 6230, 7630 and 9130 Å). The imaging camera was described by Gunn et al. (1998), while the photometric system and the photometric calibration of the SDSS imaging data were described by Fukugita et al. (1996), Hogg et al. (2001) and Smith et al. (2002), respectively. 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 galaxy spectroscopic target selection can be implemented by two algorithms. The primary sample (Strauss et al. 2002), referred to here as the MAIN sample, targets galaxies brighter than $r < 17.77$ (r-band apparent Petrosian magnitude). The surface density of the galaxies is about 90 per square degree. This sample has a median redshift of 0.10 and few galaxies beyond $z = 0.25$. The Luminous Red Galaxy (LRG) algorithm (Eisenstein et al. 2001) 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 SDSS has adopted a modified form of the Petrosian (1976) system of galaxy photometry, which is designed to measure a constant fraction of the total light independent of the surface-brightness limit. The Petrosian radius r_p is defined to be the radius where the local surface-brightness averaged in an annulus equals 20 percent of the mean surface-brightness interior to this annulus, i.e.,

$$\frac{\int_{0.8r_p}^{1.25r_p} dr2\pi rI(r)/[\pi(1.25^2 - 0.8^2)r^2]}{\int_0^{r_p} dr2\pi rI(r)/[\pi r^2]} = 0.2\,,$$

where $I(r)$ is the azimuthally averaged surface-brightness profile. The Petrosian flux F_p is then defined as the total flux within a radius of $2r_p$, $F_p = \int_0^{2r_p} 2\pi r dr I(r)$. With this definition, the Petrosian flux (magnitude) is about 98% of the total flux for an exponential profile and about 80% for a de Vaucouleurs profile. The other two Petrosian radii listed in the Photo output, R_{50} and R_{90}, are the radii enclosing 50% and 90% of the Petrosian flux, respectively.

In this paper, we use the SDSS Main galaxy sample. The data are downloaded from the Catalog Archive Server of SDSS Data Release 4 (Adelman-McCarthy et al. 2006) by the SDSS SQL Search (with SDSS flag: best Primtarget=64) with high-confidence redshifts ($z_{\rm warning} \neq 16$ and $z_{\rm status} \neq 0$, 1, redshift confidence level: $z_{\rm conf} > 0.95$) (*http://www.sdss.org/dr4/*). From this sample, we selected 260 928 Main galaxies in redshift range $0.02 \leq z \leq 0.2$.

For calculating the distances we use the following parameters: matter density $\Omega_0 = 0.3$, cosmological constant $\Omega_A = 0.7$ and Hubble constant $H_0 = 100\,\mathrm{hkm} \cdot \mathrm{s}^{-1} \cdot \mathrm{Mpc}^{-1}$ with $h = 0.7$.

3 CLUSTER ANALYSIS

Cluster analysis (Einasto et al. 1984), as a general method, has been widely applied to study the geometry of point samples in many fields. The key of this method is to separate the sample into individual systems by an objective and automatic procedure. We first draw a sphere of radius R around each sample point (in our case, galaxy). Within this sphere if there are other galaxies they are considered belonging to the same system and we 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". When no more new neighbours or "friends" can be added, then the procedure stops and a system is identified. As a result, each system consists of either a single, isolated galaxy or a number of galaxies which have at least one neighbour within a distance not exceeding R.

4 SELECTION CRITERIA

4.1 Selection Criteria for the Isolated Pair Sample

At small neighbourhood radii only close double and multiple galaxies, cores of groups and conventional clusters of galaxies form systems while the rest are isolated single galaxies. Apparently, close double systems identified at small neighbourhood radii are good candidates for galaxy pair sample. To define close pairs we have to choose a proper neighbourhood radius. Because we do not have a good priori criterion for this radius, we will first consider a certain range of neighbourhood radii and then analyse the properties of systems formed. Through this procedure we find the proper neighbourhood radius and then identify close pairs at this radius.

From the original CfA2 redshift survey, Barton et al. (2000) extracted a complete sample of 786 galaxies in pairs and N-tuples which were selected to have projected separations $r_p < 50\,h^{-1}$ kpc and velocity separations $\Delta V \leq 1000$ km s^{-1}. Lambas et al. (2003) studied galaxy pairs in a field selected from the 100 K public release of the 2dF galaxy redshift survey. Galaxy pairs were selected by the criteria of radial velocity difference ($\Delta V \leq 350\ \mathrm{km\,s}^{-1}$) and projected separation ($r_p \leq 100\,\mathrm{kpc}$). In Zitelli et al. (2004)'s volume-limited sample of 84 isolated pairs of galaxies, the projected separation between pair members is $r_p < 200\,h^{-1}$ kpc. Because we need to select close galaxy pairs, the range of above projected separation criteria can be selected as the analysis range of our neighbourhood radii. We analyse the clustering properties of the Main galaxy sample in the neighbourhood radius range $R = 60$–200 kpc, to find the appropriate neighbourhood radius for identifying galaxy pairs. At radius $R = 60$ kpc, only close double and triplet galaxies form systems (the number of triplet systems is nine, the number of galaxies in close double systems is 1374), the rest being isolated galaxies. These close double systems can be considered as good galaxy pair candidates. As we increase the neighbourhood radius the number of close double and multiple systems rapidly increases. At radius $R = 100$ kpc, 184 galaxies belong to multiple systems, and 3342 galaxies to double systems. It should be noted that some of the double systems formed at radius $R = 60$ kpc are now included in multiple systems. Figure 1 illustrates the increase in the number of galaxies containing in multiple systems with the increase in the neighbourhood radius.

Figure 2 shows the distribution of the r-band radius $R_{90,r}$ of all galaxies in the Main galaxy sample. We notice that few galaxies have $R_{90,r}$ above about 40 kpc. If we define 40 kpc as the upper limit of galaxy radius size (on this definition, 80 kpc is the minimum separation at which pairs can be reliably separated) and note that at larger neighbourhood radii some of the close double systems will be absorbed into multiple systems, we can set the value $R \approx 100$ kpc as an appropriate neighbourhood radius for identifying close galaxy pairs. Using this criterion, we obtained a galaxy pair sample containing 3342 galaxies (1.28% of the total number of galaxies).

The SDSS observes the spectra of targets, using a multi-object fiber spectrograph which can simultaneously observe 640 objects in a 3° diameter plate. Each plate can accommodate 640 fibers which are assigned to targets, about 50 of these are reserved for calibration targets, leaving around 590 fibers for scientific targets. The fiber diameter is 0.2 mm ($3''$ on the sky). Because of the cladding holding the fibers, the

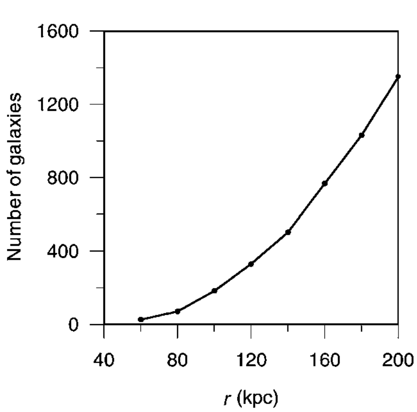

Fig. 1 Increase of the number of galaxies containing in multiple systems with the increase of the neighbourhood radius.

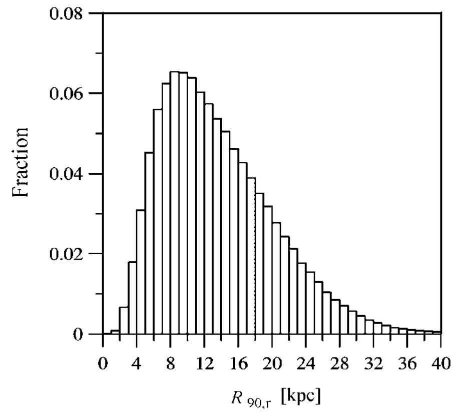

Fig. 2 Distribution of the r-band radius $R_{90,r}$ of all galaxies in the Main galaxy sample.

fibers cannot be located more closely than $55''$ on the sky; this corresponds to a distance of about 120 kpc at $z = 0.10$ (the median redshift of the Main galaxies). Roughly 8%–9% of selected objects are not observed for this reason, in regions covered by a single plate. Both members of a pair of objects closer than $55''$ can be observed spectroscopically only if they lie in the overlapping regions of adjacent plates, about 30% of the sky is covered by such overlaps (Stoughton et al. 2002). Apparently, this minimum fiber separation is a real hindrance for the study of the close pairs of SDSS. We hope that future surveys can observe a higher fraction of galaxies in close pairs by placing plate overlaps in regions continuing a high density of close pairs. This incompleteness of the pair sample is a serious drawback when we study the large-scale distribution of the pairs. The effect is not crucial when we study other properties such as the size, luminosity M_r and concentration index c_i of the pairs.

To test our criterion for the close pair sample, we calculated the separation between each pair and its nearest neighbor galaxy. This separation is called "nearest-neighbor distance" of pairs and is a measure of the "isolatedness" of the pairs. We have analysed the distribution of "nearest-neighbor distance" of pairs for the pair sample. In our pair sample, the three–dimensional separation between the two members of pairs is $R \leq 100$ kpc. We divide the range of the "nearest-neighbor distances" into five subranges, 100 kpc$< r_n \leq$ 200 kpc, 200 kpc$< r_n \leq 300$ kpc, 300 kpc$< r_n \leq 400$ kpc, 400 kpc$< r_n \leq 500$ kpc, and $r_n > 500$ kpc. Figure 3 is a histogram showing the fraction of pairs in each subrange or bin, labelled 1 to 5. It shows that 69.3% of the pairs are in Bin 5, and only about 10.17% in Bin 1. Defining now an "isolated galaxy-pair" as one whose nearest neighbour is more than 500 kpc away, we construct an isolated galaxy-pair sample containing 1158 pairs. Because the redshifts in the Main galaxy sample have an accuracy of 30 km s $^{-1}$ rms, the two components of a pair have the same redshifts by our selection criteria.

4.2 Comparison with a Random Pair Sample

Figure 4 shows the redshift distributions in the isolated pair sample and in the whole Main galaxy sample. We note that the isolated pair sample has a higher proportion of lower redshifts ($0.02 \leq z \leq 0.08$). Because the Main galaxy sample is an apparent-magnitude limited sample, the number of faint galaxies decreases with increasing redshift z . Figure 5 shows the distribution of space density of galaxies with redshift z for the whole Main galaxy sample. It shows clearly that the space density decreases with increasing redshift z. This incompleteness of the parent sample will have certain influence on the result of identification of galaxy pairs. Furthermore, in the denser region (low redshift region $0.02 \leq z \leq 0.08$) there are actually more galaxy pairs.

From the Main galaxy sample, we randomly select 1158 pairs of galaxies and construct a random pair sample. Because of the flux-limited nature of the parent sample, our isolated pair sample only includes

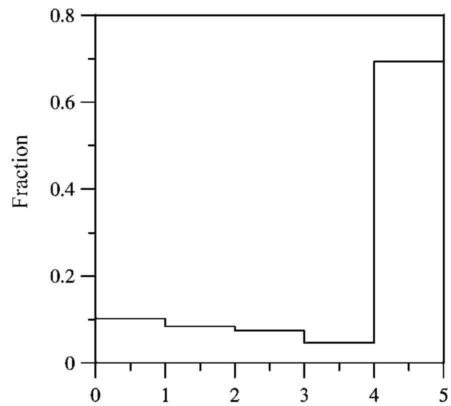

Fig. 3 Distribution of "nearest-neighbor distance" of pairs for the pair sample.

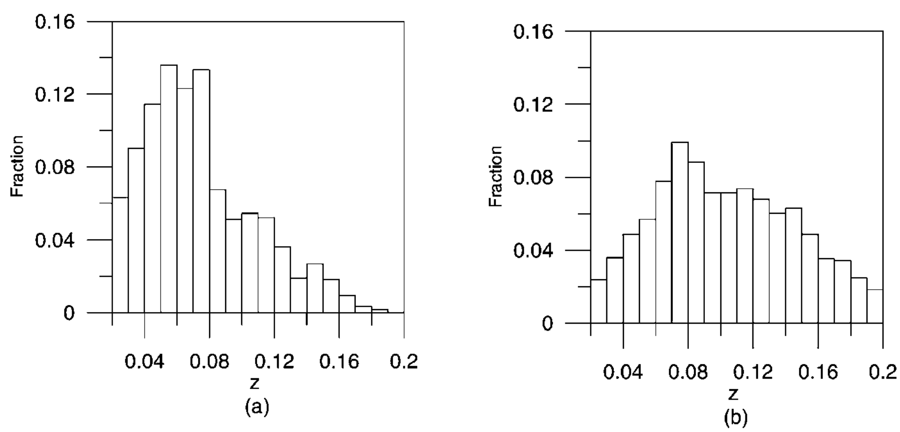

Fig. 4 Histogram of the redshift distribution of galaxies. (a) isolated pair sample; (b) whole Main galaxy sample.

pairs with both components brighter than the flux limit, while those with the primary brighter than the limit but the secondary fainter than the limit have been dropped. The missing secondaries are perhaps the most important source of incompleteness of a pair sample (Xu et al. 2004). This bias means that most pairs are composed of galaxies with magnitudes close to the magnitude limit, which are biased to have similar r magnitudes. In order to decrease the influence exerted by this bias, we make the random pair sample to be affected by the same bias as that affecting the isolated pair sample. This requires that the random pairs are composed of galaxies with the same redshifts, and the z distribution of the random pair sample is the same as that of isolated pair sample.

Luminosity, size and morphological type are the most basic properties of a galaxy. Study of the distribution of galaxies with respect to these properties is crucial to our understanding of the formation and evolution of the galaxy population. We select r-band radius, $R_{50,r}$, as the parameter of galaxy size. The luminosity M_r is the r-band absolute magnitude. We have ignored the K-correction (Blanton et al. 2003). Figures 6 and 7 show respectively the luminosity and size distribution histograms for the isolated pair sample, the random pair sample and the whole Main galaxy sample. As seen from these figures, the isolated pair sample has almost the same distributions as the random pair sample. Table 1 lists the mean luminosity and size of each sample. We note that the mean luminosity and size of the isolated pair sample is almost the same as that of the random pair sample, but smaller than that of the whole Main galaxy sample.

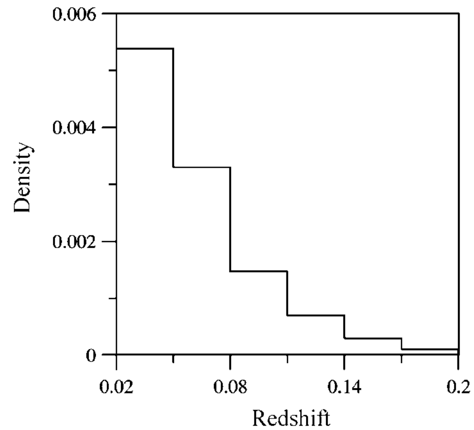

Fig. 5 Distribution of space density of galaxies with redshift z for the whole Main galaxy sample.

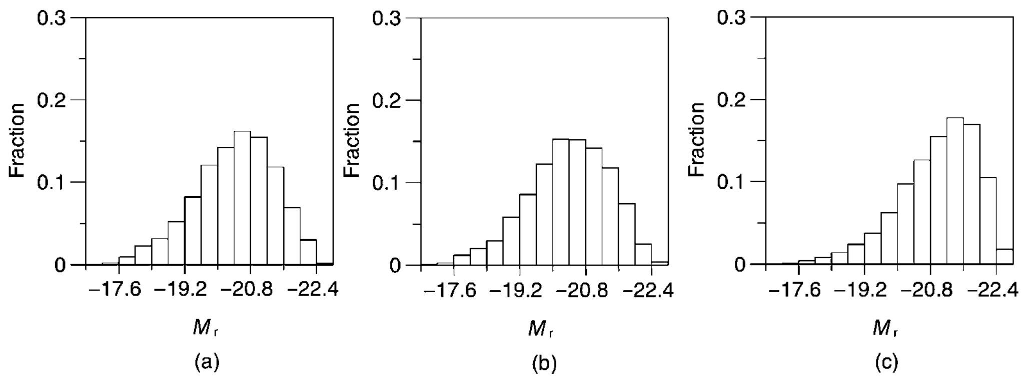

Fig. 6 Histograms of the luminosity distribution of galaxies. (a) isolated pair sample; (b) random pair sample; (c) whole Main galaxy sample.

Table 1 Mean luminosity, size, and the proportion of early-type galaxies for the isolated pair sample, the random pair sample and the whole Main galaxy sample.

Samples	Mean luminosity	Mean size	Proportion of early-type galaxies
The isolated pair sample	-20.41 ± 0.97	3.89 ± 2.03	24.74%
The random pair sample	-20.38 ± 0.98	4.01 ± 2.07	21.29%
The whole Main galaxy sample	-20.98 ± 0.94	5.28 ± 2.60	28.45%

We have calculated the concentration index $c_i = R_{90}/R_{50}$ which can be used to separate early-type (E/S0) galaxies from late-type (Sa/b/c, Irr) galaxies (Shimasaku et al. 2001). Using about 1500 galaxies with eye-ball classification, Nakamura et al. (2003) confirmed that $c_i = 2.86$ separates galaxies at S0/a with a completeness of about 0.82 for both late and early types. Table 1 lists the proportion of early-type ($c_i > 2.86$) galaxies for each sample. In the isolated pair sample and the random pair sample there are fewer early-type galaxies than in the whole Main galaxy sample.

Because the Main galaxy sample is an apparent-magnitude limited sample, many statistical properties of the galaxies change with the redshift z. To explore this change, Deng et al. (2005b) analysed the luminosity, size and c_i distributions for the Main galaxy subsamples in different redshift bins. It turned out that, on

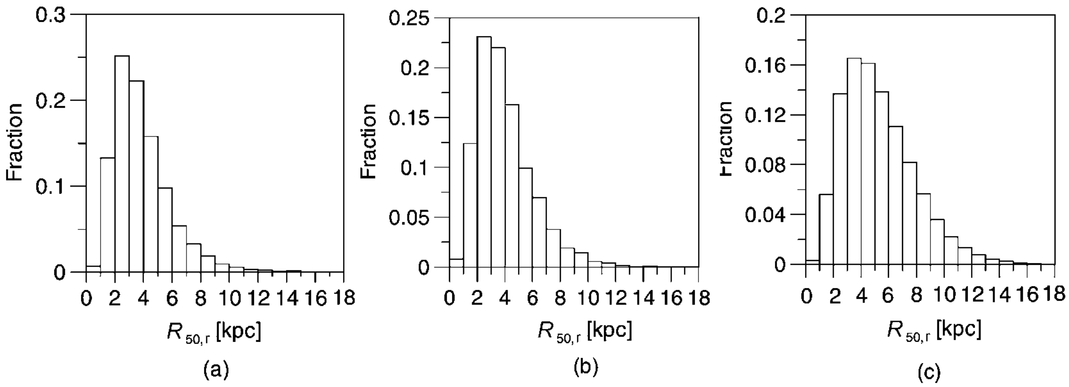

Fig. 7 Histograms of the size distribution of galaxies. (a) isolated pair sample; (b) random pair sample; (c) whole Main galaxy sample.

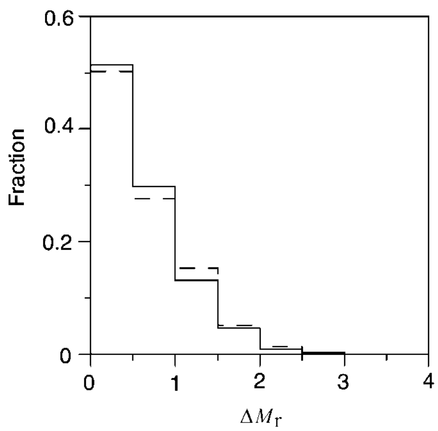

Fig. 8 Distribution of the luminosity difference ΔM_r for the isolated pair sample (dashed line) and the random pair sample (solid line).

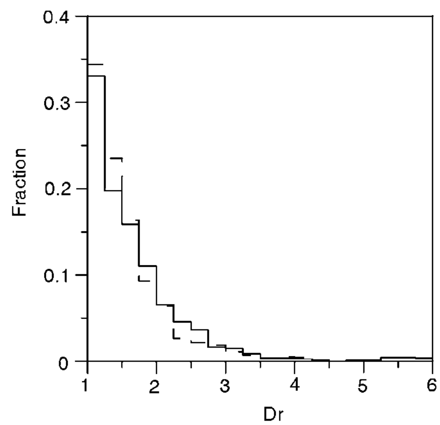

Fig. 9 Distribution of the diameter ratio Dr for the isolated pair sample (dashed line) and the random pair sample (solid line).

average, the luminosities and sizes of the galaxies and the proportion of early-type galaxies increase with increasing redshift z. According to above analysis, the isolated pair sample has the same redshift distribution as the random pair sample, but contains more galaxies with low redshifts than does the whole Main galaxy sample. So, the mean luminosity, mean size and the proportion of early-type galaxies of the isolated pair sample are almost the same as those of the random pair sample, but are smaller than those of the whole Main galaxy sample.

5 COMPARISONS OF SOME PROPERTIES OF MEMBERS OF GALAXY PAIRS

To explore correlation in basic properties between the members of galaxy pairs, we calculated the luminosity difference $\Delta M_r = |M_{r,1} - M_{r,2}|$ and the diameter ratio Dr ($R_{50,r}$ of the larger to that of the smaller galaxy (Dr ≥ 1)) in all the pairs. Figure 8 shows the distribution of ΔM_r for the isolated pair sample and the random pair sample. We further calculated the mean of the luminosity differences ΔM_r for each pair sample: we found, $\overline{\Delta M_r} = 0.62 \pm 0.50$ for the isolated pair sample and $\overline{\Delta M_r} = 0.60 \pm 0.47$ for the random pair sample. Figure 9 illustrates the distribution of Dr for the isolated pair sample and the random pair sample. The mean of the diameter ratios is: $\overline{\mathrm{Dr}} = 1.57 \pm 0.57$ for the isolated pair sample

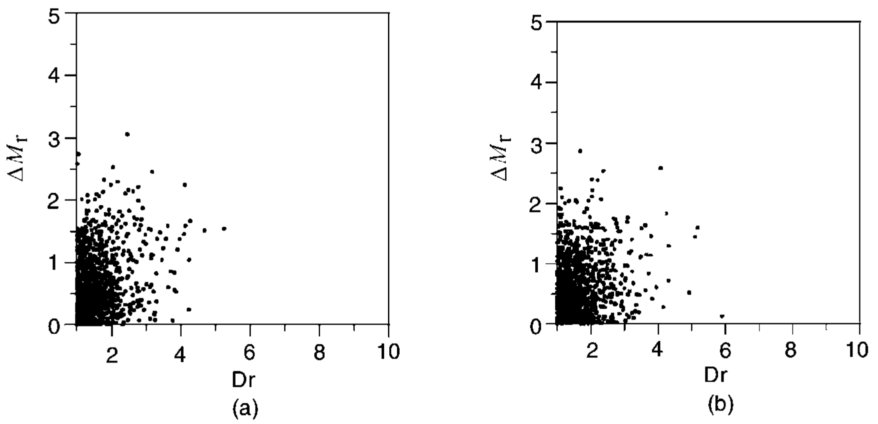

Fig. 10 Luminosity difference ΔM_r versus diameter ratio Dr plot. (a) isolated pair sample; (b) random pair sample.

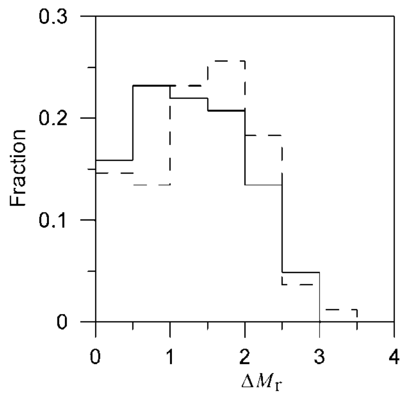

Fig. 11 Distribution of the luminosity difference ΔM_r for the subsample (dashed line) and the random pair sample (solid line).

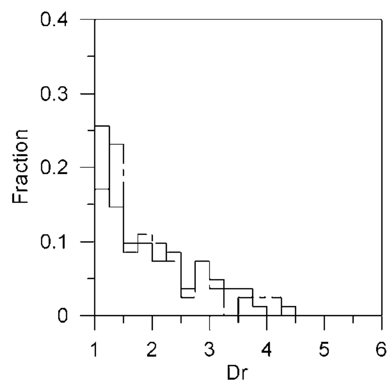

Fig. 12 Distribution of the diameter ratio Dr for the subsample (dashed line) and the random pair sample (solid line).

and $\overline{\text{Dr}} = 1.63 \pm 0.62$ for the random pair sample. Figure 10 shows the luminosity difference ΔM_r versus diameter ratio Dr plot for the same two pair samples. We note results of the isolated pair sample are almost the same as those of the random pair sample. This indicates there is no correlation of basic properties between the members of galaxy pairs. However, we also note that above mentioned bias actually affects both pair samples. This may reduce the real signal significantly.

In order to get rid of the above bias, we extract a subsample of isolated pairs by raising the magnitude limit of the primary (2 magnitude above the limit of the parent sample). So pairs with the secondary 2 magnitudes fainter than the primary can be included in the subsample. This subsample contains 82 pairs. At the same time, we similarly construct a random pair sample which has the same redshift distribution as the subsample, and the two components of each pair having the same redshifts. Figures 11 and 12 show the distributions of the luminosity difference ΔM_r, and the diameter ratio Dr for the subsample and the random sample. The mean luminosity difference and diameter ratio are: $\overline{\Delta M_r} = 1.40 \pm 0.70$, $\overline{\text{Dr}} = 1.96 \pm 0.83$ for the subsample and $\overline{\Delta M_r} = 1.31 \pm 0.68$, $\overline{\text{Dr}} = 1.99 \pm 0.82$ for the random pair sample. We find that the mean luminosity difference of the subsample (1.40) is much larger than that of the isolated pair sample. We also notice there is no significant difference between the results of the subsample and the random sample. These results further confirm there is no tendency for paired galaxies to have similar luminosities and sizes. Our studies also show that in a flux limit sample a large number of galaxy pairs with the primary above, but the secondary below the observational limit may have been missed, so that most of the pairs are biased to have similar r magnitudes (close to the magnitude limit). This incompleteness results in an apparent tendency for paired galaxies to have similar luminosities and sizes. So, when we carry out comparative studies between the members of galaxy pairs, this bias must be borne in mind.

The galaxy sizes are found to be correlated with the luminosities (Kormendy 1977; Shen et al. 2003). Shen et al. (2003) showed that the dependence of the galaxy sizes $R_{50,r}$ on the luminosity is quite different for early- and late-type galaxies: for early-type galaxies ($c_i > 2.86$), $R_{50,r} \propto L^{0.6}$; for late-type galaxies ($c_i < 2.86$), $R_{50,r} \propto L^{0.21}$ at the faint end ($L \ll L_0, L_0$ being the luminosity corresponding to $M_0 = -20.52$), and $R_{50,r} \propto L^{0.53}$ at the bright end ($L \gg L_0$).

In Figure 10, we note that some pairs have large luminosity differences, and correspondingly large diameter ratios. This further shows the correlation between the luminosity and size of the galaxies.

6 SUMMARY

Using the MAIN galaxy data from the SDSS Data Release 4 (SDSS4), we have identified close galaxy pairs by three-dimensional cluster analysis, and carried out comparative studies of the luminosities and sizes of members of galaxy pairs. The Main galaxy sample is limited in the redshift region: $0.02 \leq z \leq 0.2$ and contains 260 928 Main galaxies. Galaxy pairs are identified at neighbourhood radius $R = 100$ kpc. Using a criterion which requires "isolated pairs" to have "nearest-neighbor distance" $r_n > 500$ kpc, we finally constructed a sample of isolated galaxy pairs, containing 1158 isolated pairs. Additionally, we randomly selected 1158 pairs of galaxies from the Main Galaxy sample of SDSS Data Release 4 and constructed a random pair sample. Because of the flux-limited nature of the Main galaxy sample, our isolated pair sample only includes pairs with both components brighter than the data flux limit, while those with the primary brighter than the limit but the secondary fainter than the limit are missed. In order to decrease the effect of this bias, we required that the random pairs are composed of galaxies with the same redshifts, and the z distribution of the random pair sample is the same as that of the isolated pair sample.

Our main results are:

(1) Figures 6 and 7 show, respectively, the histograms of luminosity and size of the galaxies in the isolated pair sample, the random pair sample and the whole Main galaxy sample. As shown by these histograms, the isolated pair sample has almost the same distributions as the random pair sample. The mean luminosity and size of the isolated pair sample are almost the same as those of the random pair sample, but smaller than those of the whole Main galaxy sample. This is due to the higher proportion of galaxies with low redshifts in the isolated pair sample and the random pair sample.

(2) In our comparative studies of luminosity and size between both members of galaxy pairs, we compared the results of the isolated pair sample with those of the random pair sample. It turns out there is no tendency for paired galaxies to have similar luminosities or similar sizes.

(3) We extract a subsample of isolated pairs by raising the magnitude limit of the primary (2 magnitude above the limit of the parent sample), so as to include pairs where the secondary is 2 magnitudes fainter than the primary. This subsample contains 82 pairs. At the same time, we similarly constructed a random pair sample which has the same redshift distribution as that of the subsample, and in which the two components of a pair have the same redshifts. The results further confirm there is no tendency for paired galaxies to have similar luminosities or sizes.

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Participation Group, the Johns Hopkins University, the Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA),the New Mexico State University, the University of Pittsburgh, the Princeton University, the United States Naval Observatory, and the University of Washington.

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