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ARE GALAXY INTERACTIONS LINKED TO ENHANCED STAR FORMATION?

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RESUMEN

A partir de la muestra de galaxias limitada por magnitud aparente proveniente del Sloan Digital Sky Survey, versión 7 (SDSS DR7) construímos una muestra de pares de galaxias y una muestra de galaxias aisladas, y comparamos la tasa de formación estelar (SFR) y la tasa específica de formación estelar (SSFR) entre ambas muestras. Encontramos que las galaxias aisladas tienen SFRs y SSFRs mayores que las galaxias en pares. También investigamos la dependencia de la SFR y la SSFR de las separaciones tri-dimensionales entre los miembros de los pares de galaxias, pero no encontramos evidencia de que la SFR dependa de las separaciones.

ABSTRACT

From the apparent magnitude-limited main galaxy sample of the Sloan Digital Sky Survey Data Release 7 (SDSS DR7), we construct a paired galaxy sample and an isolated galaxy sample, and compare the star formation rate (SFR) and the specific star formation rate (SSFR) of paired galaxies with those of isolated galaxies. It is found that isolated galaxies preferentially have higher SFR and SSFR than paired galaxies. We also investigate the dependence of the SFR and SSFR on the three-dimensional separation between two members of pairs, but do not find evidence for the dependence of SFR enhancement on this separation.

Key Words: galaxies: interactions — galaxies: statistics

1. INTRODUCTION

In this work, we explore the influences of galaxy interactions on star formation. It has long been known that galaxy interactions likely lead to enhanced star formation (Toomre & Toomre 1972; Negroponte & White 1983; Barnes & Hernquist 1992; Mihos & Hernquist 1996; Struck 1999; Springel 2000; Tissera et al. 2002; Lambas et al. 2003; Meza et al. 2003; Nikolic et al. 2004; Kapferer et al. 2005; Cox et al. 2006; Smith et al. 2007; Woods & Geller 2007; Li et al. 2008a,b). Lambas et al. (2003) found that star formation in paired galaxies is significantly higher than that in isolated galaxies. The study of Li et al. (2008a) also clearly showed that mergers or interactions trigger enhanced star formation in galaxies. Such results are consistent with those obtained by N-body simulations, which show that interactions between galaxies can bring gas from the disk to the central regions of the galaxy, leading to enhanced star formation in the bulge (Negroponte & White 1983; Barnes & Hernquist 1992; Mihos & Hernquist 1996; Springel 2000; Tissera et al. 2002; Meza et al. 2003; Kapferer et al. 2005; Cox et al. 2006). However, some authors did not support this standpoint (Yee & Ellingson 1995; Patton et al. 1997; Bergvall et al. 2003; Brosch et al. 2004; Deng 2013; Deng & Zhang 2013). For example, Bergvall et al. (2003) showed that the global star formation rates of interacting/merging systems are not significantly different from those of isolated galaxies. Deng (2013) even found that isolated galaxies can have an enhanced SFR and SSFR compared with paired galaxies.

The physical mechanism of galaxy interactions on star formation also has been controversial. Smith et al. (2007) found an enhancement of the mass-normalized star formation rates (SFRs) and a central concentration of the Spitzer 24 μm fluxes in early-stage interacting pairs, compared with spirals. Smith et al. (2007) believed that tidal interactions lead to gas being concentrated into the inner regions of galaxies and fueling central star formation. On the other hand, Bitsakis et al. (2010) showed that galaxies in compact groups display low SSFRs, and argued that multiple past interactions had stripped significant amounts of gas out of galaxies, as well as made them to consume the remaining gas in order to built their stellar masses in the past. Boselli et al. (2008) demonstrated that in clusters, ram pressure stripping has as a result to remove substantial amounts of gas out of galaxies and hence to quench star formation in these systems.

Closely paired galaxies are often defined as interacting and merging galaxies when investigating the effect of galaxy interactions (e.g., Lambas et al. 2003; Alonso et al. 2004a), while isolated galaxies may have experienced no major interactions in billions of years. Thus, we perform comparative studies between galaxies in pairs and in isolation to determine the effects of interactions on star formation. The outline of this paper is as follows. § 2 describes the data used. In § 3 and § 4, we study the influences of galaxy interactions on star formation and the dependence of the SFR and SSFR on the three-dimensional separation between the two members of pairs, respectively. Our main results and conclusions are summarized in § 5.

In calculating the co-moving distance, we used a cosmological model with a matter density of $\Omega_0 = 0.3$, a cosmological constant of $\Omega_\Lambda = 0.7$, and a Hubble constant of H_0=70 km s^{-1}Mpc^{-1}.

2. DATA

2.1. *Summary of the data*

Most previous works have used small interacting/merging galaxy samples, making a statistically sound comparison between them difficult. It is clear that for such a study, a large galaxy sample with homogeneous characteristics is necessary. As one of the most ambitious and influential surveys in the history of astronomy, the Sloan Digital Sky Survey (SDSS) undoubtedly provides an excellent sample of this issue. In this study, we use the main galaxy sample of the SDSS DR7 (Abazajian et al. 2009). The main galaxy sample is an apparent magnitude-limited sample that suffers severely from the Malmquist bias (Malmquist 1920; Teerikorpi 1997). As a result, an observer will see an increase in the average luminosity with increasing distance because less luminous galaxies at large distances will not be detected. The Malmquist bias seriously affects statistical results. To decrease this effect, a simple alternative is to use the volume-limited galaxy sample, in which the radial selection function is approximately uniform. Using this approach, the only variation in the spatial density of galaxies with radial distance is due to clustering. Unfortunately, such an alternative results in a large fraction of the data not being used, which means too great a waste of the survey resources. In addition, Deng (2012) argued that the volume-limited galaxy sample is defined within a narrow luminosity region and with a redshift limit $Z_{\max}$ that cannot show the overall characteristics of the whole galaxy sample. To use the survey data to the fullest extent possible, we use the apparent magnitude-limited main galaxy sample of the SDSS DR7 (Abazajian et al. 2009). An advantage of the apparent magnitude-limited sample is the maximum use of observational data. However, we must consider how best to remove selection effects from the statistical results.

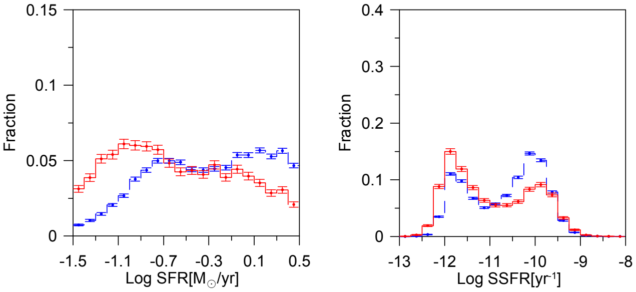

Fig. 1. SFR and SSFR distributions for paired and isolated galaxies: the red solid line represents paired galaxies, and the blue dashed line indicates isolated galaxies. The error bars are 1σ Poissonian errors.

Many of the survey properties of the SDSS have been discussed in detail in Stoughton et al. (2002). Similarly to Deng (2010), we used the main galaxy sample (Strauss et al. 2002) of the SDSS DR7 (Abazajian et al. 2009). The data were downloaded from the Catalog Archive Server of SDSS Data Release 7[1] using the SDSS SQL Search[2] with high-confidence redshifts[3]. We selected 565029 main galaxies in the redshift region $0.02 \leq z \leq 0.2$, and constructed an apparent magnitude-limited main galaxy sample. Figure 1 of Deng (2012) shows the galaxy number in each redshift bin ($\Delta z = 0.01$) and the comoving number density of galaxies as a function of redshift z for the apparent magnitude-limited main galaxy sample of the SDSS7. As seen in this figure, the comoving number density of galaxies dramatically decreases with increasing redshift.

2.2. *Galaxy pairs*

Many authors have developed different criteria to identify galaxy pairs (e.g., Karachentsev 1972; Barton et al. 2000; Lambas et al. 2003; Patton et al. 2005; Focardi et al. 2006; Kewley et al. 2006; Deng et al. 2006a, 2007, 2008a,b, 2010). For example, Lambas et al. (2003) selected galaxy pairs in the field using radial velocity ($\triangle V \leq 350\,\mathrm{km\ s^{-1}}$) and projected separation ($r_p \leq 100\,\mathrm{kpc}$) criteria. It is important to recognize that there is still no widely accepted criterion and that each criterion has drawbacks. For example, $r_p \leq 100\,\mathrm{kpc}$ and $\triangle V \leq 350\,\mathrm{km\ s^{-1}}$ can be defined as reliable upper limits for the relative radial velocity and projected distance criteria to select galaxy pairs with stronger specific star formation rates than average galaxies (Lambas et al. 2003; Alonso et al. 2004b, 2006, 2007). However, the main problem with this criterion is that it ignores the projection effect. To overcome the projection effect, Deng et al. (2006a, 2007,

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[1] `http://www.sdss.org/dr7/`.

[2] With SDSS flag: bestPrimtarget&64>0.

[3] Zwarning $\neq$ 16 and Zstatus $\neq$0.1 and redshift confidence level: zconf>0.95.

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2008a,b, 2010) used a three-dimensional distance criterion for identifying galaxy pairs. They applied three-dimensional cluster analysis (Einasto et al. 1984) by which the galaxy sample can be separated into various systems at a given three-dimensional neighborhood radius R. Close double systems identified at small neighborhood radii are good candidates for the galaxy pair sample.

Patton et al.(2005) extracted galaxy pairs using a projected separation of $r_p < 20h^{-1}$ kpc and a rest-frame relative velocity of $\triangle V \leq 500\,\mathrm{km\ s}^{-1}$. In the study by Barton et al. (2000), pairs and N-tuples were selected to have a projected separation of $r_p < 50\,h^{-1}$ kpc and a velocity separation of $\triangle V \leq 1000\,\mathrm{km\ s}^{-1}$. Lambas et al. (2003) identified galaxy pairs using radial velocity ($\triangle V \leq 350\,\mathrm{km\ s}^{-1}$) and projected separation ($r_p \leq 100\,\mathrm{kpc}$) criteria. In Focardi et al.'s (2006) volume-limited sample of 89 isolated pairs of galaxies, the projected separation between pair members is $r_p < 200\,h^{-1}$ kpc. Deng et al. (2010) noted that the projected galaxy separation adopted by most authors ranges from $20\,h^{-1}$ kpc to $200\,h^{-1}$ kpc, and then defined $R = 200$ kpc as their three-dimensional distance criterion to identify pairs. We also use this criterion in this study, and identify 3139 galaxy pairs in the apparent magnitude-limited main galaxy sample of the SDSS7.

It has long been known that fiber collisions are major sources of incompleteness in SDSS pair catalogs. When exploring the large-scale distribution of pairs, this incompleteness of the pair sample likely is a large drawback. In this study, however, the influence of this incompleteness is not critical because one can observe general trends of the entire sample from only a part of the galaxy pairs. In addition, the correction of some incompleteness will likely lead to new subjective biases or assumptions. For example, Berlind et al. (2006) corrected for fiber collisions by giving each collided galaxy the redshift of its nearest neighbor in the sky (usually the galaxy it collided with). Placing collided galaxies at the redshifts of their nearest neighbors will cause some nearby galaxies to be placed at high redshift, artificially increasing their estimated luminosities to very high values. Therefore, we do not correct for fiber collisions.

2.3. *Isolated galaxies*

Karachentseva (1973) made the first systematic compilation of isolated galaxies, which has since been used by many authors (e.g., Stocke et al. 2004; Verdes-Montenegro et al. 2005; Sulentic et al. 2006; Karachentsev et al. 2006; Lisenfeld et al. 2007; Verley et al. 2007a,b). Karachentseva's (1973) selection algorithm was as following: a galaxy i with angular diameter a_i is considered isolated if the projected sky separation $x_{i,j}$ between this galaxy and any neighboring galaxy j with angular diameter a_j satisfies the following two criteria: $x_{i,j} \geq 20 \times a_j$; $\frac{1}{4}a_j \leq a_i \leq 4 \times a_j$. However, Deng et al. (2009) demonstrated that approximately 35.36% of the isolated galaxies identified by Karachentseva's (1973) main criterion $x_{i,j} \geq 20 \times a_j$ lie in groups or clusters. Deng et al. (2009) argued that if considering that galaxies in groups or clusters and isolated galaxies are located at both extremes of density, the criteria used to identify isolated galaxies must ensure that isolated galaxies do not lie in groups or clusters. This shows that Karachentseva's (1973) selection algorithm has serious drawbacks.

Karachentseva (1973) only considered the galaxy angular distribution and did not use redshifts to identify isolated galaxies. When databases with redshifts became available, some authors added the criterion of radial distance (e.g., Colbert et al. 2001; Reda et al. 2004). For example, Colbert et al. (2001) extracted isolated galaxies using a projected radius of $1\,h_{100}^{-1}$ Mpc and $\pm 1000\,\mathrm{km\ s}^{-1}$. However, the radial distance criterion used by most authors is much larger than that of the projected separation, which leads to isolated galaxies continuing to be severely contaminated by background/foreground galaxies. Considering this factor, Deng et al. (2006b) applied three-dimensional cluster analysis (Einasto et al. 1984) to identify isolated galaxies and demonstrated that isolated galaxies identified at a dimensionless radius of $r \geq 1.2$ (dimensionless radii $r = R/R_1$, $R_1 = (3/(4\pi \times \bar{n}))^{1/3}$ is the radius of the sphere with the unit population where $\bar{n}$ is the mean number-density of galaxies) can be defined as genuinely isolated in three-dimensional space. Due to the radial selection function, we account for the change of the number-density of galaxies with redshift (see the right panel of Figure 1 of Deng 2012), and compute the radius of the sphere with the unit population $R_1 = (3/(4\pi \times n(r)))^{1/3}$ using the number-density of galaxies n(r) at a distance r from the observer. At a dimensionless radius r=1.4, we extract 20793 isolated galaxies from the apparent magnitude-limited main galaxy sample of the SDSS DR7.

3. CONNECTION BETWEEN GALAXY INTERACTIONS AND ENHANCED STAR FORMATION

As in Deng (2013), we use galaxy parameters derived by the MPA-JHU group[4]. The specific star formation rate (SSFR) is defined as the star formation rate per unit stellar mass. The star formation rate in this Web is determined based on the technique discussed in Brinchmann et al. (2004). Brinchmann et al. (2004) derived the SFR directly from the emission lines and also indirectly from the measured D4000 value. Inside the fibre, Brinchmann et al. (2004) applied different methods for different classes. Outside the fibre,

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[4] `http://www.mpa-garching.mpg.de/SDSS/DR7/`.

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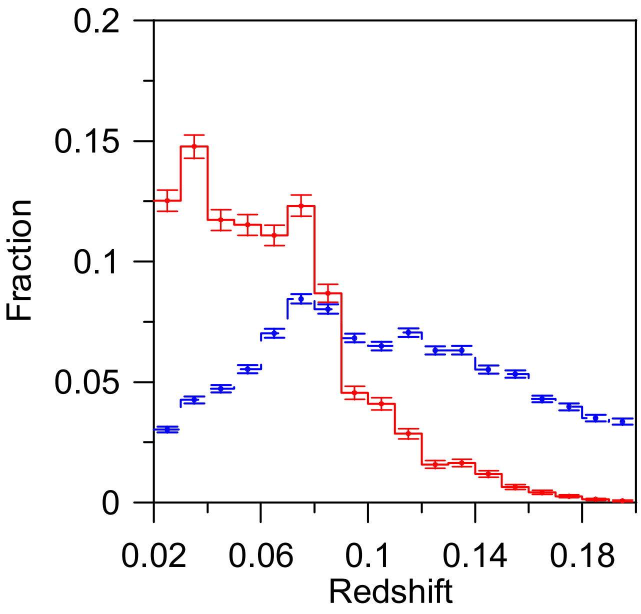

Fig. 2. Redshift distributions for paired and isolated galaxies: the red solid line represents paired galaxies, and the blue dashed line indicates isolated galaxies. The error bars are 1σ Poissonian errors. The color figure can be viewed online.

Brinchmann et al. (2004) used the color method to estimate the SFR. The stellar masses were obtained from fits to the photometry, hence not identically to Kauffmann et al. (2003) or Gallazzi et al. (2005) who use spectral indices. The differences are, however, very small.

We downloaded the total SFR and total specific SFR (SSFR). In this study, the MEDIAN estimate is used. Figure 1 shows the SFR and the SSFR distributions for paired and isolated galaxies. As seen in this figure, isolated galaxies preferentially have higher SFR and SSFR than paired galaxies. We also performed the Kolmogorov-Smirnov (K-S) test to check whether two independent distributions are similar or different by calculating a probability value. The K-S probabilities of the SFR and SSFR between paired galaxies and isolated galaxies are 0, indicating that the distributions of both the SFR and the SSFR completely differ.

The power-law star formation history model suggests that the SFRs of all galaxies evolve as follows: SFR$(z) \propto (1+z)^{\beta}$ (e.g., Baldry et al. 2002; Glazebrook et al. 2003; Brinchmann et al. 2004), where β is a fitting constant. We need to analyze the influence of this evolution effect of the SFR on the statistical results. Figure 2 shows redshift distributions for paired and isolated galaxies. As seen in this figure, a higher proportion of isolated galaxies is located at high redshift, which leads to enhanced star formation in isolated galaxies. The question naturally arises as to whether the above-mentioned conclusion can be attributed to such a selection effect. We divide the whole redshift region of the paired and isolated samples into 18 bins with a width of 0.01, and focus the analysis on the statistical differences in the SFR and the SSFR between paired and isolated galaxies in each redshift bin. In Figure 3, we see that, on the average, the SFR and the SSFR of the isolated galaxies are higher than those of the paired galaxies in each redshift bin. Therefore, our statistical conclusion should be a physical effect.

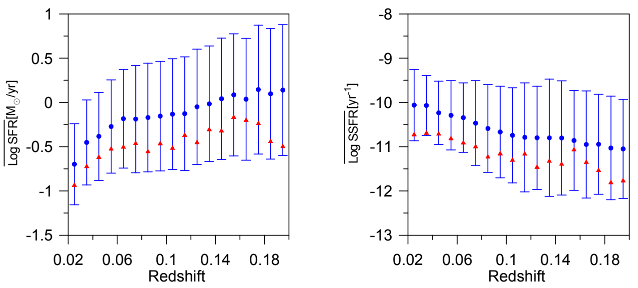

Fig. 3. Mean SFR and SSFR as a function of redshift z for paired galaxies (red triangle) and isolated galaxies (blue dot). Error bars of the blue dots represent the standard deviation in each redshift bin. The color figure can be viewed online.

We also consider that the 200 kpc separation may be too large for the selection of a pair sample. Thus, we limit the separation to 50 kpc, construct a pair sample with a three-dimensional separation of ≤ 50 kpc (containing 315 pairs), and again plot mean SFR and SSFR as a function of redshift z for paired galaxies and isolated galaxies. As shown in Figure 4, statistical results using the 50 kpc separation are the same as those obtained using the 200 kpc separation.

Deng (2013) also discussed a possible explanation for enhanced star formation in isolated galaxies based on the environmental dependence of the star formation rate (e.g., Hashimoto et al. 1998; Lewis et al. 2002; Gómez et al. 2003; Balogh et al. 2004; Tanaka et al. 2004; Kelm et al. 2005; Deng 2010). Most researchers would agree that galaxies in the lowest density regime preferentially have higher SFR and SSFR than galaxies in the densest regime. As a result, one can expect that isolated galaxies will have the highest SFR and SSFR. Some works have shown that interactions and mergers often occur in dense systems of galaxy samples (e.g., Rubin et al 1991; Mendes de Oliveira & Hickson 1994; Lee et al. 2004). Paired galaxies are also often located in dense systems, such as groups and clusters. Deng (2013) argued that if galaxies in dense systems have suppressed star formation rates, it would be impossible for star formation in galaxy pairs to be significantly enhanced over that of isolated galaxies.

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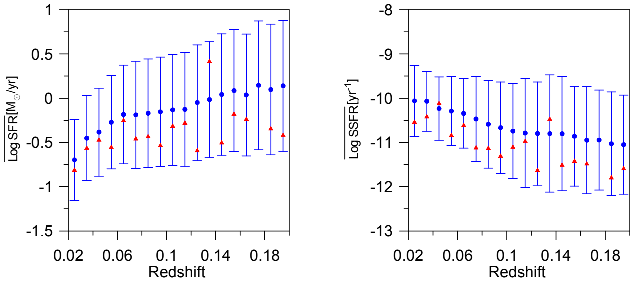

Fig. 4. Mean SFR and SSFR as a function of redshift z for paired galaxies with the 50 kpc separation (red triangle) and isolated galaxies (blue dot). Error bars of the blue dots represent the standard deviation in each redshift bin. The color figure can be viewed online.

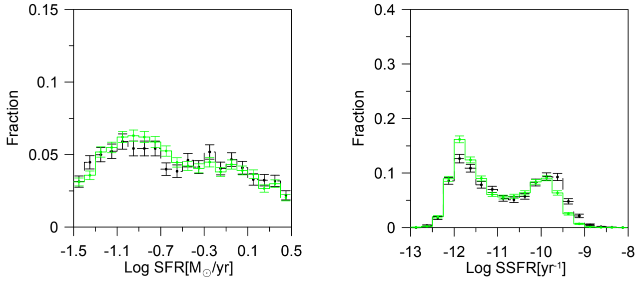

Fig. 5. SFR and SSFR distributions for Sample 0-100 and Sample 100-200: the black dashed line represents Sample 0-100, and the green solid line indicates Sample 100-200. The error bars are 1σ Poissonian errors. The color figure can be viewed online.

4. THE DEPENDENCE OF THE SFR AND SSFR ON THE THREE-DIMENSIONAL SEPARATION BETWEEN THE PAIR MEMBERS

Li et al. (2008a) showed that the enhancement of the average SFR in a galaxy depends strongly on the projected separation r_p between the galaxy and its companions. Other studies have also demonstrated that the degree of enhancement is a strong function of the projected separation between the two galaxies as well as of their difference in redshift (e.g., Lambas et al. 2003; Nikolic et al. 2004; Woods et al. 2006). In this study, we attempt to explore the dependence of the SFR and SSFR on the three-dimensional separation between the two members of pairs. From our pair sample, we construct two subsamples with three-dimensional separations of $s \leq 100$ kpc and $100\,\mathrm{kpc} < s \leq 200$ kpc; we refer to these subsamples as Sample 0-100 and Sample 100-200, respectively. Sample 0-100 includes 1052 pairs, and Sample 100-200 contains 2087 pairs. Figure 5 shows the SFR and SSFR distributions for Sample 0-100 and Sample 100-200. The K-S probability of the SFR is 0.0114, while that of the SSFR is 9.49×10^{-9}. There is almost no difference in the SFR and SSFR distributions between Sample 0-100 and Sample 100-200. It is difficult to conclude, then, that the degree of enhancement is a strong function of the three-dimensional separation. In Figure 6, we note that there are still small differences in the redshift distributions between Sample 0-100 and Sample 100-200. Thus, we further calculate the mean SFR and SSFR in each redshift bin for the two pair subsamples. Based on Figure 7, it is also difficult to conclude that the enhancement of the average SFR in a galaxy depends strongly on the three-dimensional separation.

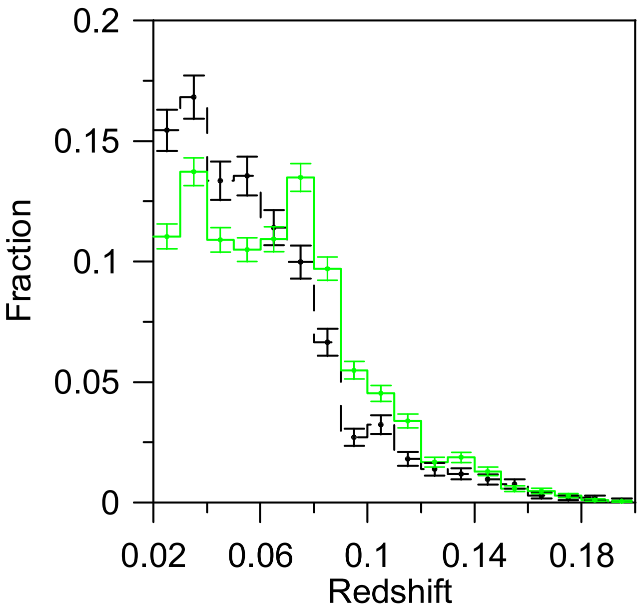

Fig. 6. Redshift distributions for Sample 0-100 and Sample 100-200: the black dashed line represents Sample 0-100, and the green solid line indicates Sample 100-200. The error bars are 1σ Poissonian errors. The color figure can be viewed online.

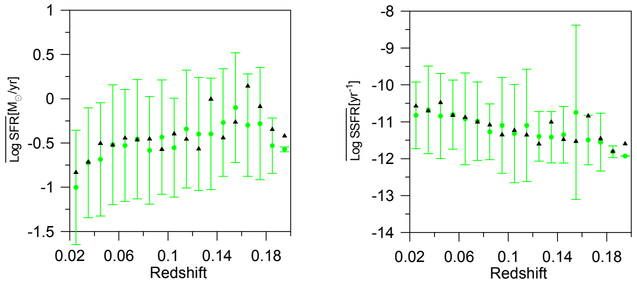

Fig. 7. Mean SFR and SSFR as a function of redshift z for Sample 0-100 (black triangles) and Sample 100-200 (green dots). Error bars of green dots represent the standard deviation in each redshift bin. The color figure can be viewed online.

5. SUMMARY

From the apparent magnitude-limited main galaxy sample of the SDSS DR7, we construct a paired galaxy sample and an isolated galaxy sample, and compare

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the star formation rate (SFR) and the specific star formation rate (SSFR) of paired galaxies with those of isolated galaxies to explore the influences of galaxy interactions on star formation. It is found that isolated galaxies have an enhanced SFR and SSFR, indicating that interactions between galaxies are not the trigger of enhanced star formation. N-body simulations demonstrate that interactions can bring gas from the disk to the central regions of the galaxy, leading to enhanced star formation. Therefore, our results preferentially support Bitsakis et al. (2010)'s guess: interactions have stripped significant amounts of gas out of galaxies, which leads to reduced star formation in paired galaxies.

We also investigate the dependence of the SFR and SSFR on the three-dimensional separation between the two members of pairs, but do not find evidence for the dependence of the SFR enhancement on the three-dimensional separation.

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