The Differences of Star Formation History Between Merging Galaxies and Field Galaxies in the EDR of the SDSS

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Abstract

Based on the catalog of merging galaxies in the Early Data Release (EDR) of the Sloan Digital Sky Survey (SDSS), the differences of star formation history between merging galaxies and field galaxies are studied statistically by means of three spectroscopic indicators the 4000-Å break strength, the Balmer absorption-line index, and the specific star formation rate. It is found that for early-type merging galaxies the interactions will not induce significant enhancement of the star-formation activity because of its stability and lack of cool gas. On the other hand, late-type merging galaxies always in general display more active star formation than field galaxies on different timescales within about 1Gyr. We also conclude that the mean stellar ages of late-type merging galaxies are younger than those of late-type field galaxies.

Key words: galaxies: interactions - galaxies: formation and evolution - galaxies: starburst - galaxies: statistics

1. Introduction

According to the current hierarchical galaxy formation theory, galaxy merging and interacting play crucial roles in determining their properties and interpreting certain unusual
phenomena in galaxies (e.g. the starbursts and the occurrence of activity galaxy nucleus). Observations also show that merging and interacting galaxies often have special morphologies, such as galactic bridges and tidal tails. Moreover, they generally display stronger emission in Hα, radio continuum and infrared than field galaxies (Kennicutt et al. 1987; Bushouse 1987; Hummel 1981; Condon et al. 1982; Lonsdale, Persson & Matthews 1984; Solomon & Sage 1988; Joseph et al. 1984), which implies that galaxy interaction can always trigger strong star formation activities.

Numerical simulations have been widely adopted to study how galaxy interaction and merging proceed star formation activity, and many useful results have been obtained (Toomre & Toomre 1972; Mihos & Hernquist 1996). On one hand it is hard to give the detailed descriptions theoretically about star formation history due to finite resolution in simulations and complicated physical processes of interstellar medium (ISM). From observational point of view, on the other hand, different samples of interacting galaxies have been studied statistically galaxy interaction on star formation since many years ago (Kennicutt et al. 1987; Larson & Tinsley 1978; Bushouse, Werner & Lamb 1988; Bergvall, Laurikainen & Aalto 2003), while their results cannot be in good consistence with each other: some studies showed that galaxy interactions have enhanced star formation activity greatly and some did not. Note that inconsistent results are also shown recently by Lambas et al. (2003) and Nikolic et al. (2004), respectively, according to their more reliable statistic results based on thousands of galaxy pairs. In fact, the connection between star formation and galaxy interaction has been suspected ever since the first large survey was available.

In this paper we investigate statistically this problem according to the catalog of merging galaxies in the Early Data Release (EDR) of the Sloan Digital Sky Survey (SDSS) (York et al. 2000; Stoughton et al. 2002; Hogget et al. 2001; Strauss et al. 2002) provided by Allam et al. (2004). This catalog is deeper in redshift and wider in the sky area than most of the other wide-area catalog up to date. Same as Kauffmann et al. (2004), three spectroscopic indicators, the 4000-Å break strength \( D_n(4000) \), the Balmer absorption-line index \( \text{H} \delta_A \) and the specific star formation rate (SFR) \( \text{SFR}/M_\star \) with \( M_\star \) the stellar masses in a galaxy, are adopted as diagnostics to study the star formation histories of galaxies. The reasons are as follows. Since \( \text{SFR}/M_\star \) of individual galaxies are estimated by the nebular emission lines (particularly the Hα line), it probes star formation activity on a timescale similar to the lifetime of a typical HII region, i.e., \( \sim 10^7 \) years. The index \( \text{H} \delta_A \) of the absorption line denotes the timescale of \( 3 \times 10^8 \) years because it peaks once hot O and B stars have terminated their evolution and the optical light is dominated by late-B to early F-stars, while the strength of the 4000-Å break \( D_n(4000) \) increases monotonically with time (but at stellar ages of more than \( \sim 1 \) Gyr, metallicity effects also become important) (Kauffmann et al. 2004; Kauffmann et al. 2003a,b; Goto 2005, 2004; Goto et al. 2003).
2. the Sample and data

The SDSS is a digital photometric and spectroscopic survey that covers one-quarter of the entire sky by using a dedicated 2.5-meter wide-field telescope at the Apache Point Observatory (York et al. 2000; Stoughton et al. 2002). The EDR of SDSS consists of 462 square degrees of imaging data in \( u, g, r, i \) and \( z \) bands together with medium-resolution spectra for approximately 40,000 galaxies and 4000 quasars. By the SDSS imaging reduction software (PHOTO) (Lupton et al. 2002), Allam et al. (2004) identified isolated merging galaxy pair candidates for galaxies in the magnitude range \( 16.0 \leq g^* \leq 21.0 \) within the EDR through their automated systematic search routine. In their routine, a merging pair is basically defined as one in which the centers of two galaxies has the separation less than the sum of the members’ Petrosian radii. Their selection algorithm implemented a variation on the original Karachentsev (1972)’s isolated pair criteria and proved to be very efficient and fast. Moreover, to remove spurious pairs due to poor image deblending, Allam et al. (2004) also inspected all the merging pairs by eyes. After all rejections and verifications the final number of candidates of merging pairs is 1479, most of which have only one member galaxy with known spectroscopic redshift. And Allam et al (2004) also estimated that the contamination by chance projections is less than 3.4%.

There are 744 galaxies with known spectroscopic redshifts among these 1479 merging galaxy pairs. Based on all available spectroscopic observations in the EDR of the SDSS, it is found that 581 of the above 744 merging galaxies have the spectroscopic indicators \( D_n(4000) \), H\( \delta_A \) and SFR/\( M_* \) measured by Kauffmann et al. (2004), who obtained these indicators according to a special-purpose code described in detail by Tremonti et al (2004). We take these 581 merging galaxies as our sample for further studies below.

Since numerical simulations of pre-prepared mergers showed that interactions between axis-symmetrical systems without bulges or with small ones might induce gas inflowing to the central region of the systems and triggering starburst episodes while the interactions would not trigger strong starburst for galaxies with dense bulges before they finally collide due to their deep potential wells, we divide these 581 selected galaxies into two sub-samples: the early-type galaxy sub-sample (hereafter EGS) and the late-type galaxy sub-sample (hereafter LGS) by adopting a galaxy morphological classification scheme of the concentration parameter \( c \) (defined as the ratio of Petrosian 90%- to 50%-light radii as measure in the r-band, i.e. \( c = R_{90}/R_{50} \)) among member galaxies. According to Shimasaku et al. (2001) and Strateva et al. (2001), \( c \sim 2.6 \) is adopted in the present paper as the selection criterion for early- and late-type galaxies and the resulted numbers of galaxies in the EGS and LGS are 336 and 245 respectively.

There are 21 merging galaxy pairs within these selected 581 galaxies. The numbers of pairs with two early-type galaxies and two late-type galaxies are 13 and 5 respectively.
Only 3 pairs show their members as one early-type galaxy and another late-type galaxy. So, the contamination of the above classification for the EGS or the LGS in studying the star formation history of merging pairs below is very small.

To investigate the effect of interaction on star formation histories in merging galaxies, we construct the corresponding samples of field galaxies for individual sub-samples of merging galaxies respectively by a Monte Carlo algorithm from the full EDR spectroscopic galaxy catalog, which is named as the control galaxy samples (hereafter CGSs). Each CGS has the same number of galaxies as the corresponding sub-samples of merging galaxies. Comparing the EGS and the LGS with their corresponding CGSs respectively, we can investigate the differences between them and unveil the effects of the interactions.

Since the star formation histories of galaxies are strongly correlated with their stellar mass, concentration parameter and redshift (Kauffman et al. 2003a,b), the influences of these factors must be eliminated when we compare the EGS and LGS with their corresponding CGSs, which is as follows. Galaxies in CGSs of individual corresponding merging galaxies with known spectroscopic redshifts and measured spectroscopic indicators $D_n(4000)$, $H\delta_A$ and SFR/$M_*$ are selected to have the similar redshifts, stellar masses and concentration parameter from the full EDR spectroscopic galaxy catalog. The distributions of redshifts, stellar masses and concentration parameters in CGSs mirror those of the EGS and LGS. It should be pointed out that the random constructing samples (CGSs) are approximate the samples of field galaxies, since only about 10% of all galaxies lie in rich clusters (Allam et al. 2004).

It is important to consider the effect of AGNs in star formation history analysis. Same as Kauffmann et al. (2003), AGNs were identified by their positions on the [NII]/H$\alpha$ vs [OIII]/H$\beta$ planes. It is found that less than 18% and less than 8% of galaxies in the EGS and LGS are identified as galaxies with AGN features respectively. This implies that the contaminations of AGNs in the present study do not significantly influence our statistical results.

3. The Differences of Star Formation History

By comparing the distributions of three spectroscopic indicators ($D_n(4000)$, $H\delta_A$ and SFR/$M_*$) of galaxies between EGS and its corresponding CGS, no significant differences have been found. It is because that the interaction will not induce significant enhancement of the star-formation activities for galaxies in EGS before they finally collide according to the previous numerical simulation (Mihos & Hernquist 1996), since dense bulges of early-type galaxies act to stabilize galaxies against the gas inflows and the early-type galaxies lack of cool gas intrinsically.

Galaxies in the LGS and its corresponding CGS display different properties of $D_n(4000)$, $H\delta_A$ and SFR/$M_*$ from those in EGS and its corresponding CGS. As an example, the distributions of the 4000-Å break strength $D_n(4000)$ for galaxies in the LGS and its corresponding CGS are plotted as the solid and dashed histograms respectively in Fig. 1 Error bars in the figure for merging galaxies are estimated by applying the bootstrap resampling technique (1000 random
samples) and those for CGS galaxies are taken as their standard Gaussian deviations. One can find significant differences from the figure that the median values of $D_n(4000)$ are about 1.3 and 1.5 respectively for galaxies in the LGS and the corresponding CGS. Since strength of the 4000-Å break increases monotonically with time and it is an excellent age indicator for young stellar population ($< 1$Gyr) as mentioned above, the smaller $D_n(4000)$ for merging galaxies implies that their average stellar ages are younger than the corresponding field galaxies, i.e., the merging galaxies in the LGS show stronger star formation activities recently.

The distributions of the Balmer absorption line index $H\delta_A$ for these two samples are plotted respectively in Fig. 2 with the same notations as Fig. 1. From this figure one can also see that the median values of $H\delta_A$ are about 4Å and 3Å for galaxies in the LGS and the corresponding CGS respectively, i.e., merging galaxies in the LGS tend to have larger $H\delta_A$. Because the strength of $H\delta_A$ absorption line peaks at about $3 \times 10^8$ years after an episode of star formation, the larger $H\delta_A$ indicates that the merging galaxies display more possibly a burst of star formation $0.1-1$Gyr ago.

Kauffmann et al. (2003) developed a method to distinguish recent star formation histories dominated by bursts from those that are more continuous. They pointed out that together with $D_n(4000)$ and $H\delta_A$ indices of a galaxy could allow one to constrain the fraction of its stellar mass formed in the recent burst and the mean age of the stellar population. Their results can be simply summarized as follows. There are four regions in the $D_n(4000)$-$H\delta_A$ plane. Two of them are the so-call “starburst region”. Galaxies located in “starburst region” with the onset of the burst occurred less than 0.1 Gyr ago always show $D_n(4000) \lesssim 1.1$; Galaxies
with the onset of the burst occurred more than 0.1 Gyr ago show the stronger $H\delta_A$ and have $1.5 \gtrsim D_n(4000) \gtrsim 1.1$. This region is called as the “post-starburst region”. The distributions of galaxies in the $D_n(4000)$-$H\delta_A$ plane for our LGS and its corresponding CGS are shown in Fig. 3. From the figure we can find that about 4% galaxies in the LGS locate in the ‘starburst region’, i.e., $D_n(4000) \lesssim 1.1$ while less than 1% galaxies in the corresponding CGS locate in this region. Moreover, it can be also found that about 10% galaxies in the LGS locate in the region with $1.5 \gtrsim D_n(4000) \gtrsim 1.1$ and $H\delta_A \gtrsim 6.0\text{Å}$ while in the CGS the fraction is about 7% which implies that more galaxies in the LGS display ‘post-starburst’ phase.

Furthermore, the relative distributions of spectroscopic indicator $SFR/M_*$ for galaxies of the LGS and its corresponding CGS are shown respectively in Fig. 4 with the same notation as those in Figs. 1 and 2. It is found that the distribution of galaxies in the LGS (solid line) shifts to the higher $SFR/M_*$ than that in the CGS (dashed line), which implies that the specific star formation rates of merging galaxies are generally larger than those of field galaxies. Since $SFR/M_*$ of a galaxy probes its star formation on a timescale about $\sim 10^7$ years, this result also indicates that merging galaxies have higher star formation activities at present or not a long time ago.
Fig. 3. The distribution of galaxies in the $D_n(4000)$-H$\delta_A$ plane. Solid triangles and open circles indicate the merging galaxies in the LGS and the field galaxies in the CGS. Vertical lines indicate $D_n(4000) = 1.1$ (left) and $D_n(4000) = 1.5$ (right).

Fig. 4. The distributions of spectroscopic indicators SFR/$M_*$ for galaxies in the LGS (solid line) and its corresponding CGS (dashed line), respectively.
4. Summary and Discussions

In the present paper, three spectroscopic indicators: the 4000-Å break strength $D_n(4000)$, the Balmer absorption-line index $H_\delta_A$ and the specific star formation rate $SFR/M_*$, are adopted to study the differences of star formation history between merging galaxies and field galaxies. Our results show that, for early-type merging galaxies, the interactions will not induce significant enhancement of the star-forming activities because of their stability and lack of cool gas. And for late-type merging galaxies, they generally display more active star forming activities than field galaxies on different timescales within about 1Gyr. According to numerical simulations (Toomre & Toomre 1972; Mihos & Hernquist 1996), the interaction between disk galaxies with comparable masses can initiate a strong inflow of gas and trigger intense but short-lived bursts of star formation. So the enhancement of star-formation in our LGC could be attributed to gravitational torques induced by galaxies interaction.

Since the strengths of the 4000-Å break and the $H_\delta_A$ absorption line index can constrain the ages of the stellar populations in galaxies and are able to distinguish recent star formation histories dominated by bursts from those that are more likely continuous (Kauffmann et al. 2003a), the smaller $D_n(4000)$ and larger $H_\delta_A$ in our merging sample imply that the mean stellar age of merging galaxies is younger than that of field galaxies and the fraction of stellar masses formed during bursts over the past few Gyr in merging galaxies is larger than field galaxies, which has been further confirmed by the distributions of $SFR/M_*$ for galaxies in the LGS and its corresponding CGS respectively.

Finally, it should be pointed out that (about 65% merging galaxies) in the LGC do not show the significant enhancement of the star-formation. It could be due to the complicated processes of star formation, especially for merging galaxies, such as the internal structure of the merging galaxies, merging orbital geometry and the rate of mass between merging pairs (i.e. major or minor merging) etc. In order to determine accurately how these factors work on the characters of merging galaxies, larger samples are needed for further investigations.

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