Recent Star-Forming Activity in Local Elliptical Galaxies

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ABSTRACT

The formation and evolution of elliptical galaxies (EGs) is still an open question. In particular, recent observations suggest that elliptical galaxies are not only simple spheroidal systems of old stars. In this paper we analyze a sample of elliptical galaxies selected from the Sloan Digital Sky Survey in order to study the star-forming activity in local elliptical galaxies. Among these 487 ellipticals we find that 13 EGs show unambiguous evidence of recent star-formation activity betrayed by conspicuous nebular emission lines. Using the evolutionary stellar population synthesis models and Lick absorption line indices we derive stellar ages, metallicities, and \( \alpha \)-element abundances, and thus reconstruct the star formation and chemical evolution history of the star-forming elliptical galaxies (SFEGs) in our sample.

We find that SFEGs have relative younger stellar population age, higher metallicity, and lower stellar mass, and that their star formation history can be well described by a recent minor and short starburst superimposed on old stellar component. We also detect 11 E+A galaxies whose stellar population properties are closer to those of quiescent (normal) ellipticals than to star-forming ones. However, from the analysis of their absorption line indices, we note that our E+A galaxies show a significant fraction of intermediate-age stellar populations, remarkably different from the quiescent galaxies. This might suggest an evolutionary link between E+As and star-forming ellipticals. Finally, we confirm the relations between age, metallicity, \( \alpha \) element abundance, and stellar mass for local elliptical galaxies.

Key words: galaxies: elliptical and lenticular, cD - galaxies: statistics - galaxies: stellar content

1 INTRODUCTION

The formation and evolution of elliptical galaxies (EGs) is very important for understanding galaxies formation and evolution, but several key issues are still open questions. Early studies regarded EGs as a family of galaxies that has very simple properties: smooth morphology; old stellar population; red optical color; free of cold gas and young star formation (Searle, Sargent & Bagnuolo 1973; Larson 1975). However, recent observations suggest that this viewpoint is really oversimple for EGs. Astronomers already detected cold gas and dust and even recent/residual star formation in EGs (Morganti et al. 2006; Yi et al. 2005; Kaviraj et al. 2007; see also the recent review by Sarzi et al. 2008). Fukugita et al. (2004) reported four star-forming EGs from Sloan Digital Sky Survey (SDSS) DR2, where the star formation rate can be comparable with normal spiral galaxies. With a much larger sample of 16,000 early-type galaxies, Schawinski et al. (2008) found that about 4% early type galaxies show ongoing star formation, this fraction is based on emission lines, but the fraction of these active elliptical or early-type galaxies is actually highly dependent on the data and the galaxy mass (see Schawinski et al. 2006, 2007b). For example, with NUV data from GALEX, this fraction could be as high as 30% (Kaviraj et al. 2007).

The detection of active star-forming EGs provides a severe challenge for galaxy formation and evolution model. There are two main competing formation scenarios for EGs: the monolithic collapse model and the hierarchical merger model. In the early monolithic collapse model, EGs formed from the violent starburst happened at very high redshift and evolved passively ever since then (Eggen, Lynden-Bell & Sandage 1962; Larson 1974; Arimoto & Yoshii 1987; Bressan, Chiosi & Fagotto 1994). On the other hand, the hierarchical merger model considers a more extended formation history. In this model, the EGs are formed from the major merger of disc galaxies of similar mass (Toomre 1977; White & Rees 1978; Kauffmann, White & Guiderdoni 1993). Both these models can explain some aspects of observed data and face some unavoidable problems at the same time: the monolithic collapse model is supported by the existence and the tightness of scaling relation like color-magnitude relation (CMR)(Sandage & Visvanathan 1978), fundamental plane (Djorgovski & Davis 1987) and Mg2-\( \sigma \) relation (Colless et al. 1999, Kuntschner et al. 2001) in EGs, but can not explain the active star-formation and remarkable cold gas found in EGs. For the hierarchical merger model, now
there are lots of observational evidence that demonstrates the importance of interaction and merger in the formation of early-type galaxies and it is expected by the most popular A-CDM cosmology. More and more recent observations indicate that some field EGs could be formed at relative low redshift and the stellar populations can spread widely, which also support the hierarchical merger model. But the observed "Down-Sizing" effect (Kodama et al. 2004; Cimatti, Daddi & Renzini 2006) is not consistent with the hierarchical merger model, which predicts that the most massive EGs should be formed most recently. Although from recent simulations, this "down-sizing" behaviour also could be obtained within the hierarchical model (De Lucia et al. 2006). These two models predict totally different star formation history (SFH) for EGs, and the recent star formation activity can be an important tracer of SFH in EGs. The time-scale and intensity of the recent star-formation, and the triggering mechanism contain important information on SFHs, which can be used to test EGs’ formation scenario.

The main purpose of this work is to obtain the stellar population properties of different types of EGs (e.g., star-forming and quiescent galaxies) and to shed light into the difference and connection in their SFHs. We thus select a sample of local EGs with reliable morphology classification from the Sloan Digital Sky Survey; then different methods of stellar population analysis are used to derive the properties of their stellar populations.

This paper is organized as following. Section 2 describes the sample selection and data reduction in this work. In Section 3, we describe the process of stellar population analysis and the method of emission line diagnostic, and Section 4 presents the main results, including the basic properties of the sample and the information about their stellar population. In Section 5, we discuss the implication of the results in the context of elliptical galaxies evolution, Section 6 is the conclusion.

Throughout this paper, we assume the ACDM cosmology consistent with the Wilkinson Microwave Anisotropy Probe (WMAP ) results with $\Omega_m = 0.3, \Omega_L = 0.7$ and $H_0 = 75h_0\text{km}^{-1}\text{s}^{-1}$ (Spergel et al. 2007) and magnitudes are given in the AB system.

2 THE SAMPLE

The sample is extracted from Fukugita et al. (2007; F07), which provided a catalog of morphologically classified galaxies in a region ($\sim 230\text{ deg}^2$) of the northern sky ($145^\circ < \alpha < 236^\circ, -1.26^\circ < \delta < 1.26^\circ$). In this area, there are 2658 photometric objects with r-band Petrosian magnitude brighter than 16 mag (e.g., $r_p < 16$ mag) in the Sloan Digital Sky Survey (SDSS) (Gunn et al. 1998; Blanton et al. 2003), among of which, 1866 have spectroscopic information. From the spectroscopic sample, 487 galaxies which are classified as E-E/S0 ($T = 0 - 0.5$) are selected to be the sample of this work. These 487 galaxies have both photometrical and spectroscopic informations in the SDSS database.

In order to examine the statistical completeness, Fukugita et al. (2007) compared the number of galaxies as a function of r-band magnitude with the N$^{-10^{0.0r}}$, which is expected for the Euclidean geometry, and found that the completeness for the sample is pretty good and does not miss too many galaxies even in the bright end of $10 - 10.5$ mag. For the spectroscopic sample, the completeness remains good for $r > 12.5$ mag, which means we might miss some bright galaxies. The number count of the sample EGs as a function of r-band Petrosian magnitude, r-band absolute magnitude and redshift are shown in Fig 1.

Among these 487 galaxies, 269 are classified as $T = 0$ and the others have $T = 0.5$, whose morphological type is E/S0. After examining the g-band images of all these 487 galaxies, it is very difficult to tell the difference between E and S0 galaxies by eye. However, we find that E/S0 ($T=0.5$) galaxies have somewhat smaller minor/major axis ratio than EGs ($T=0$) galaxies, some E/S0s have a very bright nucleus. But, in general, these two sub-samples are basically similar in the morphology, so all 487 galaxies are taken as the EG sample, although it may introduce contamination of S0 galaxies. The visual classification is really important for our work, because the correspondence between colour and morphology is complex (Lintott et.al. 2008) and only the visual classification of elliptical galaxies has no bias towards the ones with relative red color and without emission line.

The Petrosian magnitude, Petrosian radius (R50, R90) and other photometric informations of five bands (u,g,r,i,z) (Fukugita et al. 1996; Gunn et al. 1998) are extracted from the SDSS database. The SDSS spectrum is obtained with a 3-arcsec fiber, covers the spectral range of 3800 to 9200 Å with the spectral resolution of ∼1800. The typical signal-to-noise ratio (S/N) for our EGs is 40. The flux of emission lines, 25 Lick/IDS absorption line indices and corresponding errors are retrieved from the value-added catalog of SDSS provided by the MPA/JHU team.

Figure 1. The histograms of r-band Petrosian magnitude, r-band absolute magnitude and redshift of the sample

1 SDSS DR6: http://www.sdss.org
2 MPA/JHU VAGC: http://www.mpa-garching.mpg.de/SDSS/DR4/
indices are measured under the original SDSS resolution and corrected for contamination of sky emission lines.

3 DATA ANALYSES

3.1 Stellar Population Synthesis

In order to explore the SFH of EGs, we apply the stellar population synthesis code, STARLIGHT (Cid Fernandes et al. 2005, Mateu et al. 2006; Cid Fernandes et al. 2007; Asari et al. 2007), for EGs in our sample. The code is based on fitting an observed spectrum $O_j$ with a linear combination of simple theoretical stellar populations computed from evolutionary synthesis models (Cid Fernandes et al. 2004). The model spectrum is given by:

$$M_i = M_{0i} \left( \sum_{j=1}^{N_{j}} x_j b_{j,i}(\lambda_i) \right) \otimes G(v_*, \sigma_*)$$  \hspace{1cm} (1)

Where $M_i$ is the model spectrum, $M_{0i}$ is the synthesis flux at the normalization wavelength, $x_j$ is the so-called population vector, $b_{j,i} \lambda_i$ is the $j$th SSP spectrum at $\lambda$ and $r_i \equiv 10^{-0.4(A_\lambda-A_{\lambda_i})}$ represents the reddening term. At the end, the $G(v_*, \sigma_*)$ is the line-of-sight stellar motions that is modelled by a Gaussian distribution centered at velocity $v_*$ and with velocity dispersion $\sigma_*$. In this work, the model SSPs are from the BC03 evolutionary synthesis models (Bruzual & Charlot 2003) which have about the same spectral resolution of SDSS. The model base follows the work of SEAGal Group which is made up of $N_j = 150$ SSPs – 6 metallicities ($Z = 0.005, 0.02, 0.2, 0.4, 1$ and $2.5 Z_{\odot}$) and 25 ages (from 1Myr to 18 Gyr). The spectra were computed with Chabrier (2003) IMF, Padova 1994 models and the STELIB library (Le Borgne et al. 2003). The intrinsic reddening is modeled by the foreground dust model, using the extinction law of Cardelli, Clayton & Mathis (1989) with R = 3.1.

Before fitting, the spectra are shifted to the rest frame and corrected for the Galactic extinction according to the maps of Schlegel, Finkbeiner & Davis (1998) and Cardelli, Clayton & Mathis (1989) extinction law, then they are rebinned into 1 Å from 3600 to 8600 Å and the spectral regions of strong emission lines and bad pixels are masked. Fig. 2 and 3 show examples of spectral fits for two EGs in our sample. The top panel shows the observed spectrum (black) and the model (red). The bottom panel shows the residual spectrum and the masked regions are plotted with the pink line. These two examples demonstrate that the fitting method can reproduce spectrum of EGs to an excellent degree of accuracy.

STARLIGHT presents the fraction of each stellar component, the intrinsic extinction $A_*$, the velocity dispersion $\sigma_*$, and the current stellar mass $M_*$. Following Cid Fernandes et al. (2005), we could derive the flux- and mass-weighted average ages, which are defined as:

$$<\log t_*>_{T} = \sum_{j=1}^{N_j} x_j \log t_j$$  \hspace{1cm} (2)

where $x_j$ is the population vector (The fraction of flux contributed by each SSP) and

$$<\log t_*>_{M} = \sum_{j=1}^{N_j} \mu_j \log t_j$$  \hspace{1cm} (3)

The $\mu_j$ is the fraction of stellar mass contributed by each SSP. The flux- and mass-weighted average metallicities ($<Z_*>_{T}$ and $<Z_*>_{M}$) are derived in the same way.

3.2 Emission Line Classification

In the previous work, such as Fukugita et al. (2004); Zhao et al. (2006) and Schawinski et al. (2007, hereafter 507), several EGs have been detected with residual star-forming activities. In order to isolate weak AGNs, EGs are classified by emission lines according to their ionization states estimated from the flux ratios (Baldwin, Phillips & Terlevich 1981; Veilleux & Osterbrock 1987). The emission line ratios used are $[O\text{III}]$ at $\lambda 5007 / H\beta$, $[N\text{II}]$ at $\lambda 6583/H\alpha$, $[S\text{II}]$ at $\lambda 6716+6731/H\alpha$ and $[O\text{I}]$ at $\lambda 6300 / H\alpha$. Following the $S/N$ criterion of Kauffmann et al. (2003), we request $S/N > 3$ for all the four lines: $H\alpha$, $H\beta$, $[O\text{III}]$, $5007$ and $[N\text{II}]$, $6583$. For $[S\text{II}]$, $6716+6731$ and $[O\text{I}]$, $6300$, we did not set any criteria on their $S/N$ since they are basically very weak in EGs.

In the sample, 267 EGs with their $S/N$ of $H\alpha$ emission line greater than 3 (54.8% of the sample), 84 EGs with $S/N(H\beta)$ > 3 (17.4%), 238 EGs with $S/N([O\text{III}])$ > 3 (48.9%) and 284 EGs with $S/N([N\text{II}])$ > 3 (58.3%). The fraction of EGs with obvious emission lines, which are defined as EGs have $S/N > 3$ for all four lines in the first BPT diagram, is 15.0%. For comparison, such fraction is about 5% and 18% for Bernardi et al. (2003a,b) and K07, respectively. For 73 EGs with obvious emission lines, the diagnostic diagrams are (Fig. 4) used to classify them into different types according to the widely used criteria of Kewley et al. (2006), where we detect 14 star-forming EGs, 50 AGNs and 8 composite EGs. All the other EGs which are not satisfied our $S/N$ criteria are classified as the quiescent EGs, although, it should be noticed that the fraction of EGs have $S/N(H\alpha) > 3$ (54.8%) is much higher than
Balmer absorption lines reveal recent starburst which happened in about 1 Gyr (due to the lifetime of A-type stars). So the E+A galaxies are often considered as the post-starburst galaxies (Kavi-raj et al. 2007; Yang et al. 2008). In some work, such galaxies are also called as K+As (Franx 1993, Dressler et al. 1999) due to the presence of an old component in the galaxy spectra, resembling a K star spectrum. Although many K+As galaxies have disc-like morphology, Goto et al. (2003) found that E+A galaxies with higher completeness from SDSS DR5 generally have ETG-like morphology. The E+A galaxies with ETG- or EG morphology could possibly be the progenitors of normal EGs and can tell us some undiscovered information about the evolution of EGs.

According to the recent works of large sample of E+A galaxies like Goto et al. (2007a, 2007b, 2008) and Helmboldt et al. (2008, K+A), the selection criteria are: 1) the \((H\alpha)\) index has value > 2.5Å, 2) EW([OIII]λ3727)< 2.5Å, and 3) EW(H\(\alpha\))< 3.0Å. Generally speaking, these criteria are looser compared with the ones by Goto (2007), however since the EW(H\(\alpha\)) is included, there will be no contamination from Hz emission galaxies and the classification of E+A EGs in our sample is reliable.

3.3 Absorption Line Indices

The absorption line indices are also used here for the study of the stellar properties of EGs. The most widely used system is the Lick/IDS system (Worthey et al. 1994, Worthey and Ottaviani, 1997, Trager et al. 1998), which defines 25 indices including both atomic features (e.g H\(\beta\), Ca4227, Fe5270) and molecular bands (e.g Mg, CN, TiO).

The LICK/IDS indices and corresponding errors are retrieved from the MPA/JHU Garching DR4 VAGC as mentioned before. The measurements are performed under the original SDSS spectral resolution. Following the equations from Kuntschner (2004), we corrected the effect of velocity dispersion broadening. It’s worth noting that such measurement does not satisfy the requirement of Lick/IDS system as mentioned by Worthey et al. (1994). So the results here will not be compared with the previous works based on Lick/IDS system. However, by using LICK/IDS indices, we can explore relationships between the properties of different type of EGs and verify the validity of the results from STARLIGHT fitting.

3.4 E+A galaxies

E+A galaxies were first discovered by Dressler & Gunn (1983; 1992) during the research of distant galactic clusters, which show strong Balmer absorption lines (A-type stars) and no emission lines ([OIII]λ3727) just like the spectra of normal EGs. The strong absorption line indices are also used here for the study of different type of EGs. Generally speaking, these criteria are looser compared with the previous works based on Lick/IDS system as mentioned by Worthey et al. (1994). So the results here will not be compared with the previous works based on Lick/IDS system. However, by using LICK/IDS indices, we can explore relationships between the properties of different type of EGs and verify the validity of the results from STARLIGHT fitting.

Table 1. The Classification Result from Emission Line Diagnostic Diagrams

| Classification | Number | Fraction |
|----------------|--------|----------|
| Star-Forming   | 14     | 2.9%     |
| Quiescent      | 415    | 85.2%    |
| Composite      | 8      | 1.6%     |
| LINER          | 40     | 8.2%     |
| Seyfert        | 10     | 2.1%     |
| E+A            | 11     | 2.1%     |

4 RESULTS

4.1 Spectral Classification

By using the emission line ratios, we classify EGs with emission lines into AGNs and star-forming galaxies. The BPT diagnostic diagrams are shown in Fig.4 and the statistical results are summarized in Table 1. The effective classification is mostly according to the first and the second diagrams. The solid lines represent the criteria from Kewley et al. (2006), the red dot line in the first diagram is a more rigorous criterion from Stasinska et al. (2006). When we use this criterion, the number of SFEGs will drop to 5. The two purple dashed lines in the first diagrams are the criteria from Stasinska et al. (2006) which only use the [NII]/H\(\alpha\) ratio, from these criteria the number of SFEGs is also 5 for the sample. So, it is possible that among the 13 SFEGs, the contamination from AGN still exists for some EGs. But, in general, the classification is reliable, the active star formation must take place in these SFEGs at different level. Also there is a blue dotted line in the first diagram representing the empirical criterion from Kauffmann et al. (2003).

We have checked the optical images, historical literatures and multi-wavelength data from NED \(^5\) and Aladin \(^6\) for each SFEG and E+A galaxy. One galaxy in the SFEGs sample (SDSS J114013.23-002442.2 or Mrk 1303) is picked out because it is classified as a BCD (Blue Compact Dwarf) galaxy from previous observation.

\(^5\) NED: [http://nedwww.ipac.caltech.edu](http://nedwww.ipac.caltech.edu)

\(^6\) Aladin Java Applet: [http://aladin.u-strasbg.fr](http://aladin.u-strasbg.fr)
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4.2 Color - Magnitude Relations

Fig. 5 shows the color-color diagram of u-g vs g-r Petrosian color, the colors have already been corrected for extinction. There are several interesting features in this figure: 1) The distribution of quiescent EGs and LINERs concentrates in the same area, both of which have red optical colors as expected for normal EGs. 2) The distribution of SFEGs is quite scattered, 11/13 have relative blue colors, since they show active star-formation as found. The other two SFEGs have optical colors just as red as the quiescent EGs, one of which even locates among the reddest EGs. 3) For the E+A EGs, 8 E+A EGs have color distribution in the same area with quiescent EGs, while the other 3 are quite blue.

The color-magnitude relation (CMR) is a famous scaling relation for EGs (Bower, Kodama & Terlevich 1998), the tightness is considered as evidence for the monolithic collapse scenario. Fig. 6 is a plot of CMR, where the x-axis is the r-band absolute magnitude, and the y-axis is the g-r Petrosian color. Three dot-dashed lines are the simple linear fitting of the relation for the quiescent, E+A and SFEGs, respectively. The relation is basically tight for the whole sample, while the scatter is quite large at the low-luminosity end. The slopes of the CMR for SFEGs and quiescent EGs are similar but the zero point are different significantly, meaning that the SFEGs tend to have bluer colors than the quiescent EGs with the similar M_r. The SFEGs have much lower average M_r than the quiescent EGs, 5 of which are fainter than M_r = -21 mag. In Fig. 7, we plot r-band absolute magnitude versus the u-r Petrosian color, the trend is the same but the scatter is even larger than Fig. 6. The relations of SFEGs and quiescent

Figure 4. Emission line diagnostic diagrams from BPT. The solid lines in the diagrams are from the criteria of Kewley et al. (2006), the red dash line in the first diagram is a more rigorous criterion from Stasinska et al. (2006) and the purple dashed lines are the criteria from Stasinska et al. (2006) that only used the ratio of [NII]6583/Hα. In these figures, SFEGs are red circle, transition EGs are orange diamond, Seyferts are green triangle and LINERs are black cross.

Figure 5. u-g and g-r color-color diagram. SFEGs are red circle, and E+A galaxies are blue square. The transition region galaxies are orange diamond, Seyferts are green triangle and the quiescent EGs are black cross. These symbols are used in the same manner from this figure.

Figure 6. u-g vs g-r color-color diagram. SFEGs are red circle, transition EGs are orange diamond, Seyferts are green triangle and quiescent EGs are black cross.
galaxies are well separated. The CMR used to be interpreted as a sequence of increasing metallicity with luminosity. Now we already know, in addition to metallicity, the stellar age also plays an important role. Based on a very large sample of SDSS ETGs, Gallazzi et al. (2006) found unambiguous evidence for interpreting the CMR as a sequence of galaxy stellar mass.

For EGs, the central velocity dispersion is a wildly accepted indicator for galaxy mass. The STARLIGHT can provide us the velocity dispersion (Cid Fernandes et al. 2006). We do not set a lower limit for the velocity dispersion during the STARLIGHT fitting, while the SDSS spectra have intrinsic instrumental dispersion of 75 km/s (York et al. 2000). Some EGs show velocity dispersion lower than this value, this of course will lead a serious uncertainty. For these EGs, their velocity dispersions are still used. Since the velocity dispersion is treated as a Guassian with broad wings larger than the instrumental dispersion, thus the code can measure velocity dispersion slightly below 75 km/s (Schawinski, private communication). But we will keep this uncertainty in mind and just take these measurements as very rough estimation. And the velocity dispersion is corrected to the r-band half-light radius (R50) according to the equation in Cappellari et al. (2006).

Fig 8 show the relations between the velocity dispersion ($\sigma_*$) and several fundamental properties of the EGs: the r-band absolute magnitude, the u-r Petroson color, the r-band surface brightness and the r-band Petrosion R50. 16 EGs have $\sigma_* < 75$ km/s: 7 SFEGs, 2 E+A EGs. The vertical dash-dot line represents the intrinsic dispersion of SDSS spectrum (e.g. ~ 75 km/s). More than 50% SFEGs show $\sigma_*$ less than 75 km/s, which make further analysis more unreliable, though it might suggest that the SFEGs have smaller stellar mass in the local universe.

From these figures, we see tight relations of $\sigma_* - M_r$, $\sigma_* - (u-r)$, which could be explained as more massive EGs are more luminous and redder. The scatter of the $\sigma_* - M_r$ relation is larger below the 75km/s boundary. For the $\sigma_* - u - r$ relation, the scatter keeps about the same along the relation. The slopes of the correlations are almost same for all types of EGs, suggesting that these correlations may involve some of the most fundamental properties of the EGs and are barely influenced by their activity. Generally speaking, the SFEGs tend to be less massive, bluer and fainter than the normal quiescent EGs, which is consistent with S07. No correlation was found between the $\sigma_*$ and the surface brightness. It is physical reasonable for more massive EGs have bigger size, but the Petrosian R50 should be taken as the proxy of the effective radius of EGs, not exactly physical size. No clear correlation is found between the galaxy mass and their effective size, which could be explained by different brightness profile along the radius, which could be the evidence of different SFH for EGs have different mass.

The average properties and scatters of basic properties for different types of EGs are listed in Table 2, including the r-band Petrosian magnitude, r-band absolute magnitude, the u-r Petrosian color, the r-band surface brightness, concentration index and Petrosian R50. Except for the quiescent EGs, the sample size for other types of EGs is quite small, thus the statistical results are meaningless. On average, the SFEGs have the faintest $M_r$, the bluest $u-r$ color, the smallest Petrosian R50 and concentration index. From S07, the authors discussed the possibility of an evolutionary sequence from star-forming EGs to the quiescent EGs. Considered the "Down-Sizing" effect which means more massive EGs should evolve faster than their less massive counterparts, the trend is also seen here.

Now it is necessary to mention the problem of aperture effect of fixed SDSS 3-arcsec fiber, which means the physical information extracted could be only accounted for the central part of the EGs. Fig 9 shows a plot of the ratio of Petrosian R50 and SDSS fibre size as a function of the redshift. Although some EGs do suffer from aperture effect, in general, there is no strong aperture bias for the whole sample, especially for SFEGs. Most EGs have r-band Petrosian R50 1-3 times larger than the SDSS fibre radius, but it still
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Figure 8. The relation between the velocity dispersion and the galaxy absolute magnitude, $u$-$r$ color, r-band surface brightness and the r-band Petrosian R50. The lines are the linear fitting of these relation for the quiescent, star-forming and E+A galaxies. The black dash line is for the quiescent EGs, the red dash dot line is for the SFEGs and the blue dot line is for the E+A EGs. The vertical dash dot line represent the SDSS spectra dispersion (75 km/s).

Table 2. The average general properties for different types of elliptical galaxies. The values in parenthesis are the corresponding standard deviation.

| Properties/Classification | Quiescent | LINER | Seyfert | E+A | Star-Forming |
|---------------------------|-----------|-------|---------|-----|-------------|
| r (mag)                   | 15.01(0.58) | 15.29(0.60) | 15.49(0.54) | 15.42(0.48) | 15.58(0.35) |
| M (Mag)                   | -22.17(0.76) | -21.80(0.92) | -21.82(0.85) | -22.02(1.11) | -21.06(1.23) |
| u-r (Mag)                 | 2.75 (0.30) | 2.70 (0.25) | 2.43 (0.35) | 2.55 (0.34) | 2.10 (0.51) |
| SB (Mag/arcsec$^2$)       | 19.66(0.48) | 19.68(0.49) | 19.40(0.80) | 19.42(0.80) | 19.40(0.48) |
| CI                        | 3.17(0.22) | 3.21(0.19) | 3.00(0.32) | 3.14(0.29) | 2.89(0.33) |
| R50 (arc sec)             | 3.55(1.23) | 3.71(1.41) | 3.13(1.26) | 3.30(1.32) | 2.71(0.71) |

worth noting that the physical information about the stellar population obtained below should only account for the region within 1/3 to 1 effective radius of the EGs.

4.3 Star-Forming Elliptical Galaxies

1. SDSS J114031.65+005111.4 (PGC1177304)

The morphology of this galaxy is similar to a typical elliptical galaxy, the optical color is also close to the quiescent EGs (g-r= 0.79), but strong emission lines are detected in the SDSS spectrum. This galaxy is 305.6 ± 21.4 Mpc away, the r-band absolute magnitude $M_r = -21.40$. Based on Tago et al. (2008), it belongs to a small galaxy group (Group944) which has 4 members. This galaxy has 2MASS (Skrutskie et al. 2006) (J=14.826, H=14.112, K=13.596) and GALEX (Martin et al. 2005) (FUV=20.14) observation. The image and spectrum are shown in Fig.10.

2. SDSS J103534.47-002116.2 (PGC1130399)

It is also a typical elliptical galaxy in morphology, but has
very blue (g-r=0.50) optical color and a very bright nucleus. The spectrum is very similar to star-forming galaxies with flat continua and strong emission lines. This galaxy is classified as emission line galaxy (ELG) in NED. It is 181.2 ± 12.7 Mpc away and bright absolute magnitude (M_r = -23.05). This galaxy does not belong to any galaxy group or cluster. The 2MASS J, H and K magnitudes are 14.72, 14.11, and 13.56 mag, respectively. Its image and spectrum are given in Fig.11.

These two galaxies represent the SFEGs sample well and the detailed information for the other 11 SFEGs are listed in Table 3. Since this sample only belongs to a small sky region, it is not good for environmental research. We find that none SFEGs is cluster member, 3 SFEGs belong to small galaxy group, and 2 are even classified as isolated galaxies by Allam et al. (2005).

In Table 3, we summarized physical properties of 13 SFEGs. Besides the properties from SDSS data, the star-formation rate (SFR) and the nebular metallicity are also estimated. For calculating the SFR, the flux ratio of H_alpha and H_beta (F_Halpha/F_Hbeta) is used to estimate the nebular extinction A_{{nebular}} which is:

\[ A_{{nebular}} = 6.31 \times \log(F_{{H_\alpha}}/F_{{H_\beta}}) \]  

(4)

The mean nebular extinction is A_{{nebular}} = 0.70 (and the median is 1.02). After correcting extinction, H_alpha flux is used to calculate the H-beta luminosity. The SFR is estimated following the equation from Mateus et al. (2007), which considered the aperture correction for SDSS 3 arcsec fibre spectra:

\[ SFR(H_\alpha)(M_\odot/yr) = 5.22 \times 10^{-42} L(H_\alpha)10^{-0.4r/Petro} \]  

(5)

The r_petro is the r-band Petrosian magnitude and the r_fiber is the r-band fiber magnitude. The average SFR is 0.56 M_\odot/yr and the highest SFR is 1.62 M_\odot/yr, which are comparable with the normal star-forming galaxies. This is absolutely strange from the traditional view of EGs, though the SFR estimated here is quite cursory.

Following Denicolo et al. (2002), we estimate the nebular metallicity by using the so called ”N2 ratio calibrator” (log([NII]/6584Å/H_\alpha)), which is:

\[ 12 + \log(O/H) = 9.23(\pm0.02) + 0.79(\pm0.03) \times N2 \]  

(6)

The average nebular metallicity is log(O/H) + 12 = 9.05. Among 13 SFEGs, J100920.32-001854.1 shows the lowest SFR (only 0.014 M_\odot/yr) and nebular metallicity (log(O/H) + 12 = 8.68, even lower than Solar metallicity) and a negative nebular extinction (the only SFEG with negative extinction). This galaxy also has very red optical color and its spectrum is similar to a typical elliptical galaxy spectra, the emission lines are conspicuous in the observed spectrum, it belongs to a group with 18 members (Group 265 in Tago et al. 2008s).

4.4 SFH from STARLIGHT Fitting

By using STARLIGHT to fit the observed spectra of EGs, we can derive : 1) Velocity dispersion; 2) Extinction; 3) Average stellar population age; 4) Average stellar population metallicity and 5) the fraction of flux contribution for each SSP (the population vector). The average stellar population age and metallicity are estimated by both flux-weighted and mass-weighted. These properties can be used to draw a useful picture for SFH research. Of course, the situation here is not so optimistic, there are still several problems. Leaving the insufficiency of the models aside, the method of population synthesis used here has some drawbacks itself. Besides the velocity dispersion estimate which under the SDSS resolution, in the fitting process of STARLIGHT, the code uses a universal extinction law for all SSPs; Some of the EGs, especially for the quiescent EGs, have negative extinction. This is all due to the problems within STELIB, which makes the code believes the observed spectra are too ”blue”. So, the value of the extinction will not be taken seriously but its relation with other stellar population properties is still useful. The age-metallicity degeneracy will certainly influence the estimation of stellar population age and metallicity, it is not realistic to derive an accurate SFH, the reliable parameters include mean age and metallicity. During fitting, there is no detailed restriction for different SSPs, the flux contribution from each SSP is relatively arbitrary. The old-age high-metallicity SSPs could contribute a lot in the total flux, which is very suspicious from the chemical evolutionary theory. As stated above, these problems will make the results with larger uncertainties, however there are still lots of useful information which can be extracted from the fitting.

4.4.1 The Distribution of Mean Age and Metallicity

In the study of stellar population in EGs, the age-metallicity degeneracy is still an annoying problem that cannot be removed.

Figure 11. SDSS J150712.72-005735.2

Figure 12. The distribution of the average age and metallicity for different type of elliptical galaxies. The age and metallicy here are both flux-weighted. The horizontal and vertical dash lines represent the average age and metallicity for different types of elliptical galaxies.
are more reliable statistically. The two different di-only properties correlate with stellar mass (Thomas et al. 2005; Denicolo et al. 2005; Schawinski et al. 2007), which indicates that for EGs with different mass, their SFH and the chemical evolution history could be different. This is an important result for the theory of formation and evolution of EGs.

Many works on stellar populations in EGs show that many properties correlate with stellar mass (Thomas et al. 2005; Denicolo et al. 2005; Schawinski et al. 2007), which indicates that for EGs with different mass, their SFH and the chemical evolution history could be different. This is an important result for the theory of formation and evolution of EGs.

Table 3. The Properties of the 13 Star-Forming Elliptical Galaxies.

| Galaxy                | z       | m_r   | M_* | g-r   | S B_{R*,G} | R_{petro} | log(O/H) + 12 | A_{Vstellar} | SFR  |
|-----------------------|---------|-------|-----|-------|------------|-----------|----------------|--------------|------|
| SDSS J120823.51+000636.9 | 0.041   | 14.783 | -21.534 | 0.697   | 19.465    | 8.843     | 9.135         | 1.016        | 0.332 |
| SDSS J1103534.47-002116.2 | 0.029   | 15.568 | -20.007 | 0.464   | 19.493    | 6.529     | 9.016         | 0.575        | 0.295 |
| SDSS J152324.10-003823.0 | 0.037   | 15.089 | -21.042 | 0.628   | 18.856    | 6.226     | 9.180         | 1.142        | 0.321 |
| SDSS J123009.26+011446.1 | 0.026   | 15.862 | -19.416 | 0.503   | 19.236    | 4.614     | 9.033         | 0.317        | 0.218 |
| SDSS J113029.44+003556.0 | 0.079   | 15.645 | -22.224 | 0.685   | 19.660    | 6.572     | 9.160         | 1.021        | 0.299 |
| SDSS J114031.65+051111.4 | 0.075   | 15.497 | -22.234 | 0.792   | 20.229    | 9.875     | 9.148         | 1.348        | 0.239 |
| SDSS J140622.76-001325.1 | 0.105   | 15.720 | -22.835 | 0.701   | 19.721    | 8.340     | 9.027         | 1.250        | 0.678 |
| SDSS J112326.98-004248.8 | 0.041   | 15.467 | -20.856 | 0.519   | 19.506    | 6.434     | 9.064         | 1.055        | 0.550 |
| SDSS J112531.57+002619.1 | 0.026   | 15.971 | -19.329 | 0.437   | 19.941    | 6.066     | 8.946         | 0.918        | 0.286 |
| SDSS J100920.32-001854.1 | 0.070   | 15.749 | -21.808 | 0.791   | 19.697    | 6.550     | 8.685         | -3.280       | 0.014 |
| SDSS J110741.94+02608.3 | 0.066   | 15.958 | -21.470 | 0.594   | 19.152    | 4.193     | 9.104         | 1.772        | 1.624 |
| SDSS J150712.72-005735.2 | 0.044   | 15.777 | -20.717 | 0.500   | 18.985    | 4.933     | 9.076         | 1.066        | 0.957 |
| SDSS J101537.59+003131.0 | 0.071   | 15.189 | -22.416 | 0.652   | 18.289    | 4.183     | 9.062         | 0.891        | 1.478 |

In Fig.13, the overall distribution of EGs is much more concentrated. The distribution of SFEGs is much closer to quiescent EGs when using the mass-weighted properties. As mentioned above, the flux-weighted properties are more sensitive for young stellar population, which is always associated with recent star-forming activity. However, SFEGs show much older mean age when using mass-weighted population vector. Surprisingly, two E+A EGs with lower average age around 10^9 Gyrs in flux-weighted plot show the lowest average age in the mass-weighted plot, even much lower than the SFEGs. The detailed results of the synthesis indicate most of their stellar mass are formed around 10^9 Gyrs and almost no old stellar population, this is absolutely strange for EGs and we do not know for sure whether it is real or spurious.

4.4.2 Stellar Mass

Many works on stellar populations in EGs show that many properties correlate with stellar mass (Thomas et al. 2005; Denicolo et al. 2005; Schawinski et al. 2007), which indicates that for EGs with different mass, their SFH and the chemical evolution history could be different. This is an important result for the theory of formation and evolution of EGs. Here, we show the correlation of the stellar population properties of EGs with their mass.

Figure 13. The distribution of the average age and metallicity for different type of elliptical galaxies. The age and metallicity here are both mass-weighted. The horizontal and vertical dash lines represent the average age and metallicity for different types of elliptical galaxies.

From Fig.12, we find the distribution of EGs is quite scatter, which is mainly caused by the SFEGs. The distribution for other EGs are located in a much smaller region. The SFEGs have the youngest mean flux-weighted average age and the lowest mean flux-weighted average metallicity. In Fig.12 and 13, we plot the distribution of these average properties in the age-metallicity plane. The relations show the lowest average age in the mass-weighted plot, even much lower than the SFEGs. The detailed results of the synthesis indicate most of their stellar mass are formed around 10^9 Gyrs and almost no old stellar population, this is absolutely strange for EGs and we do not know for sure whether it is real or spurious.

The relation between the stellar velocity dispersion and the current stellar mass is shown in Fig.14. We find that the relation is very tight for the galaxies with σ_r larger than 75 km/s, but for EGs with σ_r less than 75 km/s, the scatter is much larger and several SFEGs are clearly away from the relation. This uncertainty has already been predicted before and, at the same time, we noticed that the stellar mass from STARLIGHT fitting have much larger values for these EGs. Besides the uncertainty from SSP fitting, there might be other factors. For example, from more detailed observations like the SAURON project (Bacon et al. 2001; de Zeeuw et al. 2002), there are accumulated evidence for the existence of stellar disk in the central region for some EGs, especially for the SFEGs (McDermid et al. 2006). This rotation-supported disc component could explain the uncertainty.
could lower the measurement of the velocity dispersion. This could be just the case for the SFEGs with very low velocity dispersion in our sample. Nevertheless, the velocity dispersion is still used as the proxy of galaxy mass throughout this paper.

We also find the correlation between dust extinction and the average age, both flux- and mass-weighted. In the first plot, a large fraction of EGs have negative $A_{\text{v, stellar}}$, especially for the quiescent EGs. However, most SFEGs (12/13) show positive $A_{\text{v, nebular}}$. We can see a tendency that more massive EGs may have lower dust extinction.

The correlation between stellar mass and the average stellar population age is obvious for both flux- and mass-weighted age. This relation indicates that the less massive EGs tend to have lower average age for their stellar population. The relation for mass-weighted average age is very tight except for two special E+A EGs. We note that the mass-age relation has been reported in a lot of works before, both in the field and the clusters (Caldwell, Rose & Concanon 2003; Denicolo et al. 2005; Kuntschner et al. 2002).

For metallicity, no relation is found for neither the flux- nor mass-weighted metallicity. Maybe there is very weak trend that less massive EGs also have lower metallicity, but the uncertainty is too large for conclusion. However, Kuntschner et al. (2000) reported a mass-metallicity relation for ETGs in cluster or high environmental density region (see also Trager, Faber & Dressler 2008).

### 4.4.3 The Approximate Star Formation History

STARLIGHT provides us the stellar population vector, e.g. the fraction of flux contributed by certain SSPs. Due to the drawbacks we discussed above, this vector does not stand for the accurate star-formation history. In fact, our SSPs are generally uniformly separated in the log-space of age, so the model’s resolution for stellar population analysis is limited in the end of old age. Even more SSPs are used, the age-metallicity degeneracy and the arbitrariness of the fitting will prevent us from deriving a unique answer.

In order to estimate the SFHs of EGs, we combine 150 SSPs into four ages, e.g., young-, middle- and old-age stellar population plus a population named burst-population. The young-age stellar population includes the SSPs with age less than 1 Gyr, the old-age population are SSPs with age larger than 10 Gyr, and the middle-age population is the SSPs between them. For the burst population, we defined its age less than 0.1 Gyr, which is extremely young for EGs and is always connected with the recent star formation activity. With the fractions of these four stellar populations, a very coarse SFH can be generated and the results are shown in Table 4.

Just as expected, we can see large diversity for different types of EGs. The quiescent and LINERs EGs are comprised by the old stellar population, only about 5% of their flux is from the young stellar population. We noticed the fraction of burst-population is not zero for neither of them (about 3% on average), this fraction is just similar as the resolution of the STARLIGHT code (∼ 5 %, Cid Fernandes et al. 2005), thus there is no significant evidence for presence of young stellar population in the center of the normal or LINERs EGs (30%-50% of the Petrosian R50), but see Graves et al. (2007), where they found the age of LINERs to be systematically younger than their quiescent counterparts, this could be the result from different method for deciding the average age or the different classification of LINERs. The most impressive result here is that SFEGs are significantly different from normal EGs, more than 50% flux are from the young stellar population, especially from the...
The average fraction of flux and mass contributed by stellar populations of different age. The values in parenthesis are the corresponding standard deviation.

| Properties | Classification | Quiescent | LINERs | Seyfert | E+A | Star-Forming |
|------------|----------------|-----------|--------|--------|-----|--------------|
| \( f_{\text{burst}} \) | 2.72(3.25) | 3.02(4.12) | 7.87(9.02) | 3.80(4.88) | 35.79(16.92) |
| \( f_{\text{young}} \) | 5.23(8.44) | 4.33(5.03) | 21.67(25.32) | 19.45(26.79) | 51.57(21.17) |
| \( f_{\text{middle}} \) | 23.70(14.02) | 20.90(13.07) | 28.31(18.02) | 22.07(12.97) | 18.85(8.31) |
| \( f_{\text{old}} \) | 71.00(15.80) | 74.71(12.90) | 49.89(31.59) | 58.38(36.15) | 29.45(18.51) |

| \( m_{\text{burst}} \) | 0.01(0.17) | 0.00(0.00) | 0.04(0.11) | 0.00(0.00) | 0.45(0.91) |
| \( m_{\text{young}} \) | 0.43(3.48) | 0.01(0.05) | 5.11(10.79) | 9.13(16.92) | 3.85(4.44) |
| \( m_{\text{middle}} \) | 5.87(8.05) | 3.79(3.46) | 18.26(20.02) | 16.12(24.11) | 14.54(12.29) |
| \( m_{\text{old}} \) | 93.62(10.28) | 96.13(3.49) | 76.38(26.27) | 74.66(39.05) | 81.10(14.23) |

We must emphasize these results are from the flux-weighted average population fraction, which is more sensitive to the young stellar population and star formation activity. Another important examination is for the mass of stellar population currently in the EGs or the so-called mass-weighted average population fraction. The same criteria of age bins are used and the results are also presented in the Table 4. From this part, the diversity seen from the flux-weighted SFH of all kinds of EGs are more complicated than what we see here and the star formation time scale in most EGs can extend to the middle age bin, but within this fitting, no further information could be obtained.

We summarize the stellar population properties for different types of EGs in Table 5. The mean values and the corresponding standard deviations of velocity dispersion, dust extinction, average age, metallicity and the current stellar mass are listed.

From this table, we could find SFEGs have the largest difference between the flux-weighted and mass-weighted average age, and this is the same for the average metallicity. This demonstrates that the ongoing star formation in SFEGs has great influence on the integral stellar properties. At the same time, their mass-weighted metallicities and ages are much closer to the quiescent EGs. These SFEGs are not different objects compared with the quiescent EGs. Essentially, they could have similar SFH that are only different in the intensity and time-scale of the star-forming activity. It is possible that these two types of EGs are in the same sequence of evolution which are only affected by the mass and the environment, we leave the detailed discussion at below.

4.4.4 Summary for the Sample

We summarize the stellar population properties for different types of EGs in Table 5. The mean values and the corresponding standard deviations of velocity dispersion, dust extinction, average age, metallicity and the current stellar mass are listed.

From this table, we could find SFEGs have the largest difference between the flux-weighted and mass-weighted average age, and this is the same for the average metallicity. This demonstrates that the ongoing star formation in SFEGs has great influence on the integral stellar properties. At the same time, their mass-weighted metallicities and ages are much closer to the quiescent EGs. These SFEGs are not different objects compared with the quiescent EGs. Essentially, they could have similar SFH that are only different in the intensity and time-scale of the star-forming activity. It is possible that these two types of EGs are in the same sequence of evolution which are only affected by the mass and the environment, we leave the detailed discussion at below.

4.5 Absorption Line Indices

In the study of EGs, the use of absorption lines can be traced back to more than 20 years ago (Burstein et al. 1984). Many important discoveries were made based on this method. For example: the famous \( M_{\text{Fe}} - \sigma \) relation (Kuntschner et al. 2000; Denicolò et al. 2005), where the value of \( M_{\text{Fe}} \) index increases for more massive EGs. The relation was considered as a mass-metallicity relation although the age and [\( \alpha/Fe \) also play roles (Thomas & Maraston 2003). The wildly used Lick/IDS system has 25 indices which can be separated into groups for different applications. For example, the Balmer indices are good indicators of the stellar age, especially the H\textsubscript{β} index, which is very sensitive to young star formation though it is often contaminated by nebular emission. For the metallicity, there are two groups of elements, the \( \alpha \)-elements which are mainly from the Type II supernovae and the Fe-peak elements that is associated with the Type Ia supernovae. The indices like Mg1, Mg2, Mg2 are good tracers of \( \alpha \)-elements and the Fe-peak elements are often represented by Fe5270, Fe5335 etc.. Using these indices, the stellar population properties could be obtained. Here we present a simple analysis using Lick absorption indices, which are taken from the MPA/JHU DR4 VAGC database.
Table 5. The Average Stellar Population Properties for Different Types of Elliptical Galaxies. The values in parenthesis are the corresponding standard deviation.

| Properties/Classification | Quiescent | LINERs | E+A | Seyfert | Star-Forming |
|---------------------------|-----------|--------|-----|---------|-------------|
| $\sigma_*$ (km/s)         | 213.13(54.25) | 208.12(54.73) | 210.45(86.87) | 171.20(71.16) | 99.84(52.60) |
| $A_V$                     | -0.12(0.12)  | -0.04(0.13)  | -0.16(0.13)  | 0.00(0.17)  | 0.19(0.17)  |
| $< t_*, >_{\text{phot}}$ (Log(Gyr)) | 9.84(0.18)  | 9.85(0.16)  | 9.64(0.46)  | 10.00(0.22) | 10.02(0.12) |
| $< t_*, >_{\text{mass}}$ (Log(Gyr)) | 10.14(0.10) | 10.16(0.04) | 9.94(0.42)  | 10.00(0.22) | 10.02(0.12) |
| $< Z_*, >_{\text{phot}}$ $(Z_\odot)$ | 1.32(0.24)  | 1.28(0.27)  | 1.33(0.33)  | 1.33(0.33)  | 0.79(0.25)  |
| $< Z_*, >_{\text{mass}}$ $(Z_\odot)$ | 1.30(0.21)  | 1.27(0.24)  | 1.34(0.26)  | 1.37(0.13)  | 1.27(0.24)  |
| $M_*, \text{current}$ (log($M_\odot$)) | 11.25(0.26) | 11.12(0.40) | 11.00(0.79) | 10.98(0.43) | 10.71(0.61) |

Figure 15. The first group of correlation between absorption line indices and the velocity dispersion. The indices here include $H_\beta$, $H_\delta A$, $H_\delta F$, $H_\gamma A$, $H_\gamma F$, $D_n 4000$.

4.5.1 Correlation With Galaxy Mass

Many authors mentioned different types of $\sigma$-index relations (mass-index relations) (Gonzalez 1993; Kuntschner et al. 2000; Nelan et al. 2005; Annibali et al. 2007; Trager, Faber & Dressler 2008). In Figs 15, 16 and 17, we plot the correlation of velocity dispersion against 18 different indices, which are separated into three groups and the linear fits of the relations for quiescent, E+A and star-forming EGs are also plotted as dashed lines.

The indices in Fig.15 are mostly Balmer indices, which could be used as the age indicator. The first five indices are $H_\beta$, $H_\delta A$, $H_\delta F$, $H_\gamma A$, $H_\gamma F$ and negative correlation with velocity dispersion is found for each of them. We find that the stellar age in EGs decreases as the mass increases, which is consistent with the mass-age relation from STARLIGHT fitting. For $H_\delta A$, $H_\delta F$, $H_\gamma A$ and $H_\gamma F$, except for the E+A EGs sample, two types of relations exit, the quiescent EGs and LINERs have a relative flat slope, while the slopes of SFEGs, Seyfert and transition region EGs are much steeper. These indices, especially the $H_\gamma A$, are thought to be more sensitive to the younger stellar population, so the difference may indicate that their general stellar properties are different. Besides that, a strange distribution of E+A EGs is found in these plots. For the properties mentioned before, the E+A EGs are usually closer to the quiescent EGs on average, but, from these age-sensitive indices, they become much closer to the SFEGs. This should not be unexpected if we consider the criteria used for the selection of E+A EGs sample and it can be explained by the character of post-starburst. In the last plot, we use the $D_n 4000$ index (Balogh et al. 1999) which is also a age indicator but more sensitive to the old stellar populations. The positive correlation of $D_n 4000$ actually has the same meaning.
These $\sigma_*$-index relations here confirm the results that the stellar population in E+A EGs have measurable difference with quiescent EGs.

In Fig.16, we concentrate on the indices that are associated with $\alpha$-elements. The clear positive correlations are presented for almost every index except for the Ca4227. The correlations for different types of EGs are almost the same except for the E+A EGs which show obvious separation from quiescent EGs again. If these indices are connected with the $\alpha$-elements abundance in EGs, these correlations can be seen as a mass-metallicity relation which means more massive EGs tend to have higher $\alpha$-elements abundance (Annibali et al. 2006; 2007), resulted from shorter time-scale of early star-formation and higher efficiency of chemical evolution process. From the average metallicity obtained by spectra fitting, no correlation between mass and metallicity is found. But it is obvious from the $\alpha$-elements sensitive indices, this difference may reflect that there are different kinds of elements influence the total metallicity. The famous Mg2-\$\sigma_*\$ relation for our sample is fitted as:

$$Mg_2 = -0.375(\pm0.29) + 0.264(\pm0.128) \log(\sigma_*)$$

We also check the correlation of mass and Fe-peak elements sensitive indices like Fe5270 and Fe5335. But we don’t find any significant correlation. This is very different situation when compared to the correlations for $\alpha$-elements. The formation of Fe-peak elements is associated with the Type Ia supernovae, the process is different from the $\alpha$-elements and may be not affected by the galaxy mass. Though the correlation for the entire sample is unconspicuous, there is still evidence which indicates the SFEGs are also poor in Fe-peak elements when comparing with the quiescent EGs. This could be seen as another proof that the SFEGs have different SFH from quiescent EGs. In the plots of age and $\alpha$-element sensitive indices, the E+A galaxies with high velocity dispersion show very clear separation with the quiescent EGs, but this difference is much less in the Fe-peak elements sensitive indices.

**Figure 16.** The second group of correlation between absorption line indices and the velocity dispersion. The indices here include Mg1, Mg2, Mg3, CN1, CN2, Ca4227.

**Figure 18.** The absorption diagnostic diagram of H$\beta$ and [MgFe] indices.
Figure 17. The third group of correlation between absorption line indices and the velocity dispersion. The indices here include Fe4383, Fe4531, Fe5015, Fe5270, Fe5335, Fe5406.

Figure 19. The absorption diagnostic diagram of Mg$_b$ and $<Fe>$_3 indices.

4.5.2 Absorption Line Diagnostic Diagram

When using the absorption line indices for stellar population study, the different indices diagrams are always effective method for breaking the age-metallicity degeneracy and estimating the age, metallicity and even the $\alpha$-element-to-iron abundance. There are several models based on the Lick/IDS system, for example, the most wide-used model by Thomas, Maraston & Bender (2003). But since the measurements of indices in our work are not well calibrated into Lick/IDS system, our results can not be compared with these models.

Instead, we use the synthetic spectral models for alpha-enhanced stellar populations from Coelho et al. (2007) which allows us to explore the influence of change of the [$\alpha$/Fe] on the high-resolution spectral properties of evolving stellar population. The model covers three different iron abundances ([Fe/H]=-0.5, 0.0, 0.2) and two [$\alpha$/Fe] (0.0, 0.4) for stellar populations between 3 and 14 Gyr. From these models, we can predict absorption indices used in our work under the resolution of SDSS spectra which are consistence with our measurements. This model is a powerful tool for extracting information about chemical properties of EGs.

A very useful diagnostic diagram is constituted by an age-sensitive plus a metallicity sensitive indices. The H$_{\beta}$ index is very good age indicator, especially for the young stellar population involving in the recent star formation activity (Tantalo et al. 2004). The situation for metallicity is somewhat more complicated, we already notice the different pattern for $\alpha$-elements and Fe-peak elements. So, we decide to use the so-called [MgFe] index which is almost free from the $\alpha$-enhanced effect, this element is defined as [MgFe] = $\sqrt{\text{Mgb} \times (0.72 \text{Fe5270} + 0.28 \text{Fe5335})}$ here (Thomas, Maraston & Bender 2003). The $H_{\beta}$-[MgFe] plot can be found at Fig.18 where we also plot the models grids we used on the figure, the red grid is for the models with [$\alpha$/Fe] = 0.0 and the blue grid is for [$\alpha$/Fe] = 0.4. From left to right, the age is decreasing from 14

\footnote{Go models: http://www2.iap.fr/users/pcoelho/alphamodels.html}
is because the age indicator we used here, the H index, giving much younger age estimate for most EGs in our sample, even a small fraction of EGs which are mainly from the SFEGs and E+A EGs sub-sample. These galaxies are left out from the models in the younger age and lower metallicity end, the trend is consistent with what we got from STARLIGHT fitting. Generally, the models will give much younger age estimate for most EGs in our sample, even younger than the estimate from flux-weighted average age. This is because the age indicator we used here, the H index, is very sensitive to the active star-formation and young stellar population formed in the recent star-formation. And this is also the reason why the E+A EGs can have much lower age-estimate even younger than SFEGs while their age-estimated from STARLIGHT are pretty close to the quiescent EGs.

The $\alpha$-enhanced effect is thought to be the key issue in the chemical evolution of EGs with different mass or other properties. This effect concern the star-formation time scale, the efficiency of chemical evolution and maybe indicate a different IMF. In our work, we do not give a direct estimate of the $[\alpha/Fe]$ effect, but still we can qualitatively check with the absorption line diagnostic diagram. In Fig.19, we plot another diagram for examining the $[\alpha]$-enhanced effect in our EGs sample, the two index we use are the $M_{\alpha}$ index which represent the abundance of $\alpha$-elements and the $<Fe3>$ index which defined as $<Fe3> = (Fe5015 + Fe5270 + Fe5335)/3$ for the abundance of Fe-peak elements (Kuntzchner 2000). Since both indices are metallicity sensitive, the models grids almost degrade into a model “line” in the figure. The models with different $[\alpha/Fe]$ are the same in different color.

The most important result from this figure is that we can see the $\alpha$-elements enhanced effect is really common for the EGs in our sample, though we do not have the detailed estimate of $[\alpha/Fe]$. In some works, there has been reported the $\alpha$-enhanced effect is increasing with the galaxy mass ( Worthey, Faber & Gonzalez 1992, Trager et al. 2000, Thomas et al. 2005, Nelan et al. 2005). For our sample, this is not very clear. More directly, we can use the ratio of $M_{\alpha}$ and $<Fe3>$ as a very rough proxy of the $[\alpha/Fe]$ ratio. We plot its correlation with galaxy mass estimate in Fig.20 and we find the relation maybe exists for the quiescent EGs though the trend is still unclear. For the entire sample, we find no significant correlation.

![Figure 20. The correlation of the $M_{\alpha}/<Fe3>$ ratio with the velocity dispersion estimate.](image)

At the end of this section, a statistical comparison of some useful indices of different types of EGs is shown in Table 6.

5 DISCUSSION

In this work, we show that SFEGs deviate from the normal or quiescent EGs, we try to explain it as a certain stage of evolution sequence of EGs that surmised from the similarity in their SFHs and some other aspects. Though this hypothesis and the two-component SFH is pretty consistent with our results, it is over simple for the theory of EGs evolution and many problems remain unsolved. Here, we present a brief discussion about several important ones, like the triggering mechanisms of the secondary starburst, the degree of confirmation for the evolution sequence and the EGs formation scenario.

5.1 Triggering Mechanisms

In this work, we find 13 EGs with ongoing star-forming activity and 11 post-starburst EGs, which show the generality of the secondary star formation activity in local EGs. This phenomenon has already been reported (Yi et al. 2005; Jeong et al. 2007). In fact, the optical band is not perfect for searching the evidence of residual star-formation in EGs, the result from GALEX already pointed out that there are much more EGs in the local universe than we thought have different level of residual or recent star-formation.

Since the secondary star formation activity is considered as a rejuvenation phenomena, the most possible origin might be the galaxy-galaxy merger or interaction. However, in our sample, we do not find any obvious evidence of morphological disturbance which often indicates the merger and interaction. This is partly because the spatial resolution and the depth of the image from SDSS is not enough for detecting the morphological perturbations. Also, merger events which are responsible for the star formation activity is relative minor, the morphological perturbations already disappear and the star formation activities are mostly shut down by the AGN feed back or the depletion of cold gas, but in the low-mass EGs, the star formation activity could continue much longer as we see in our sample.

5.2 Evolutionary Sequence?

To put all types of EGs into a uniform evolutionary sequence is a really tempting target and the evidence for the existence of such a sequence is already seen from our result.

From the properties we summarized before, we find that many properties show a sequence for different types of EGs. The number of Seyfert, LINER and composite EGs is quite small, so the average may suffer from larger uncertainties, but we can see their connections and relations in several observational or stellar population’s properties. For example, the optical color like u-r, the mass estimated by velocity dispersion and the average age of their stellar populations. All these information show us the possibility that there could be a sequence between these different types of EGs.

This sequence should be seen from two aspects, a time-related sequence and a mass-related sequence. The time-related sequence means there could be an evolutionary link between the star-forming and the quiescent EGs, may be like: Star-Forming EGs–Composite EGs–Seyfert Galaxies–LINER–Quiescent EGs. Actually, in S07, the author found a sequence in the same form from a much larger
early-type galaxies sample which is also selected from SDSS data, although their method for decoding the SFH is quite different from what we used here. This sequence is also supported by the concept of AGN feedback (Ciotti & Ostriker 1997; Silk & Rees 1998) who is responsible for shutting down of star-formation activity.

By the stellar population synthesis method we used here, the SFHs of different types of EGs are actually oversimplified and very coarse, we can not ascertain the accurate age and the intensity of the secondary starburst. So the evolutionary sequence we proposed above is generally a logical guess. Based on this hypothesis, we see clearly another sequence which is dominated by the mass of the galaxies which means the more massive of the EGs, the more rapid they evolve. The alpha-elements enhancement in the massive EGs suggest that the star formation activities were more efficient and rapid than their low-mass counterparts. The time scale of the secondary starburst estimated by the STARLIGHT supports the result too.

Besides the galaxy property like stellar mass, the influence from environment should be considered too. Although our sample is not suitable for the discussion of environment (relative small and only from a small area in the sky), we found among the 13 SFEGs, none of them is in the cluster, which at least show that the low-density environment may be more suitable for the residual star formation.

We already knew that galaxies in different stage of merger could show different level of activity and make up an evolutionary sequence. But, since we excluded the galaxies with obvious disturbed morphology, none of the EGs in our sample is in the process of strong interaction or major merger, which means that it is hard to determine the existence of such a merger-driven evolutionary sequence for our sample. If more accurate SFH could be derived from these EGs, we can compare them to the SFH of galaxies that are in the stage of on-going merger, then maybe the relations between different types of EGs with the mergers could be found.

Another interesting question is if the evolutionary sequence is really exist, where should the E+A EGs be placed. The stellar population properties show their similarity with quiescent and star-forming EGs in different way, we believe these galaxies are post-starburst galaxies, but their role in the evolution of EGs is still unclear. Also we should remember, if the star-formation activity is triggered by merger events, this sequence of evolution could happen more than once in the history of EGs, the real SFH could show evidence of impacts by several evolutionary sequences though the SFH we recovered didn’t have enough resolution. And for the E+A EGs in this sample, maybe it is not appropriate to put them about 1 Gyrs behind the SFEGs on the evolutionary sequence. From the mass fraction of young and intermediate age stellar population in E+A EGs and SFEGs, it seems like that the E+A EGs had more active star formation than the SFEGs. The SFH of E+A EGs is actually an interesting question to be answered.

### 6 CONCLUSIONS

We have studied the properties of EGs with recent star-forming activity in the local universe. Our main purpose is to establish the differences as well as the possible evolutionary connections among the different types of EGs, and thus to place star-forming EGs (SFEGs) in the correct sequence of EGs’ evolution.

The main results of this paper are the following:

(i) From a sample of 487 local ($z < 0.16$) EGs drawn from the SDSS DR3 we discover 13 galaxies with obvious active star-forming activity from emission line diagnostic diagrams, and 11 E+A post-starburst galaxies. Among the 13 SFEGs, 7 have unambiguous morphological classifications as EGs while the remaining 6 galaxies have been classified as $T = 0.5$. From a visual inspection of their images we found no obvious difference between the morphology of these 6 galaxies from those of typical EGs. The fraction of SFEGs is 2.7% (or 1.4% when consider only the 7 ones with $T = 0$) and the fraction for E+As is 2.3%.

(ii) SFEGs shows some obvious broad differences from quiescent EGs: smaller sizes, lower masses, and lower luminosities. Their optical colors are bluer than those of normal EGs. In particular, however, we actually found four SFEGs that have luminosities and masses typical of quiescent EGs. On the other hand, our E+As show a remarkable similarity in mass, luminosity, and color to the quiescent EGs.

(iii) From stellar population synthesis (STARLIGHT) fitting, we estimated the distribution of different stellar populations. We found for the local EGs in our sample, the star-formation history can be described by a minor “juvenile” stellar population formed during secondary star-forming activity around 1Gyr ago on the background of a dominant old stellar population formed a long time ago during a very intense period of star formation. This simple description is basically valid for all types of EGs including the quiescent EGs that show no evidence of recent star-formation at all. From this point of view we can say the secondary star-forming activity, the so-called “juvenile” effect, is quite common in local EGs.

(iv) We found a mass-age relation indicating that more massive EGs tend to have older average ages. A similar correlation between age and metallicity, however, was not found. From population synthesis we find that our SFEGs have younger ages (especially from the flux-weighted average age) and lower average metallicities. Also, due to the active star-formation these EGs have higher dust extinction. The discrepancy between mass estimates from stellar populations and from the velocity dispersion may be due to the presence of a central stellar disc or some other rotationally supported component associated with a recent star-formation event, and which can lower the velocity dispersion estimate.

(v) From our simple analysis of absorption line indices we find several interesting results. First, from our analysis of the $\alpha$-element sensitive indices, but no relation was found for Iron-peak sensitive indices. These results confirm the mass-age relation and sug-

| Properties | Classification | Quiescent | LINERs | Seyfert | E+A | Star-Forming |
|------------|----------------|-----------|--------|---------|-----|-------------|
| $H\beta$   |                | 1.88(0.79) | 1.85(0.26) | 2.31(0.77) | 3.26(1.77) | 3.12(0.64) |
| $Mg\alpha$ |                | 3.91(1.13) | 4.17(0.78) | 3.99(0.93) | 2.46(0.93) | 2.58(0.78) |
| $Fe3$      |                | 3.28(0.78) | 3.30(0.28) | 3.02(0.53) | 2.12(0.89) | 2.14(0.66) |
| $[MgFe]$   |                | 2.24(0.42) | 2.20(0.61) | 2.95(0.69) | 2.16(0.67) | 2.28(0.61) |
suggest that the $\alpha$-element abundances tend to be higher in more massive galaxies, but the Fe-peak elements abundance seem to show no correlation with galaxy mass. Second, we notice that E+As, which have masses (velocity dispersions) similar to those of quiescent EGs, show completely different distributions in most of the $\sigma$-$\alpha$ index diagrams, and specially in the relation between age and $\alpha$-element sensitive indices. In fact, line indices of E+As are much closer to those of SFEGs than to normal ellipticals. Third, we found that the $\alpha$-enhanced effect is very common among local EGs, but we do not find a correlation with galaxy mass.

(vi) From the different properties discussed above we consider that SFEGs are not a particularly special type of EGs: they are not "young" objects since the main stellar populations are as old as those of normal EGs while their star formation histories show considerable similarity with the quiescent ones. This seems to indicate that SFEGs are just passing through an evolutionary stage, which is more pronounced for low mass EGs, but is still part of a common evolutionary sequence for Elliptical galaxies that is determined by total mass and environment.

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Alpha-enhanced Model: TMB03

Fe3 Index (Angstrom)

Mgb Index (Angstrom)

[α/Fe]=0.0

[α/Fe]=0.5
