Abundance diagnosis of E+A (post-starburst) galaxies

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ABSTRACT
E+A galaxies are characterized as a galaxy with strong Balmer absorption lines but without any [OII] or Hα emission lines. The existence of strong Balmer absorption lines means that E+A galaxies have experienced a starburst within the last <1-1.5 gigayear. However, the lack of [OII] or Hα emission lines indicates that E+A galaxies do not have any on-going star formation. Therefore, E+A galaxies are interpreted as a post-starburst galaxy. Morphologically, E+A galaxies appear as early-type galaxies, implying E+A galaxies may be one of the progenitors of present-day elliptical galaxies. However, there remained other possibilities such as the dusty starburst scenario, where E+A galaxies have on-going star formation, but optical emission lines are invisible due to the heavy obscuration by dust. Therefore, an additional evidence of the post-starburst phenomena has been eagerly awaited.

Using one of the largest samples of 451 E+A galaxies carefully selected from the Sloan Digital Sky Survey Data Release 4, here we show the abundance diagnosis of E+A galaxies using Mg and Fe lines. Our findings are as follows: (i) E+A galaxies has enhanced α-element abundance ratio compared to the star-forming galaxies with similar Balmer absorption strength. Since the truncation of strong starburst is required to enhance the alpha element ratio, this is an additional evidence that E+A galaxies are in the post-starburst phase; (ii) the metallicity and α-element abundance of E+A galaxies are consistent with those of elliptical galaxies, suggesting that E+A galaxies could be one of the progenitors of present-day elliptical galaxies in terms of chemical abundances.

Key words: galaxies: evolution, galaxies: interactions, galaxies: starburst, galaxies: peculiar, galaxies: formation

1 INTRODUCTION

Dressler & Gunn (1983, 1992) found galaxies with mysterious spectra while investigating high redshift cluster galaxies. The galaxies had strong Balmer absorption lines with no emission in [OII]. These galaxies are called “E+A” galaxies since their spectra looked like a superposition of that of elliptical galaxies (Mg2537, Fe5270 and Ca3934,3968 absorption lines) and that of A-type stars (strong Balmer absorption lines). The existence of strong Balmer absorption lines shows that these galaxies have experienced starburst recently (within a gigayear; Goto 2004b). However, these galaxies do not show any sign of on-going star formation as non-detection in the [OII] emission line indicates. Therefore, E+A galaxies have been interpreted as a post-starburst galaxy, that is, a galaxy which truncated starburst suddenly (Dressler & Gunn 1983, 1992; Couch & Sharples 1987; MacLaren, Ellis, & Couch 1988; Newberry, Boroson, & Kirshner 1990; Fabricant, McClintock, & Bautz 1991; Abraham et al. 1996).

However, there remain other possibilities: E+A galaxies could also be explained as dusty-starburst galaxies. In this scenario, E+A galaxies are not post-starburst galaxies, but in reality star-forming galaxies whose emission lines are invisible in optical wavelengths due to the heavy obscuration by dust. Smail et al. (1999) performed a radio observation to investigate the star formation activity hidden by the dust, and detected 5 galaxies in radio (out of 8), which have strong Balmer absorption with no detection in [OII]. Owen et al. (1999) investigated the radio properties of galaxies in a rich cluster at z ∼0.25 (A2125) and found that optical line luminosities (e.g., Hα+[NII]) were often weaker than one would expect for the star formation rates (SFRs) implied by the radio emission. As a variant, Poggianti & Wu (2000) presented the selective dust extinction hypothesis, where dust extinction is dependent on stellar age since youngest stars inhabit very dusty star-forming HII regions while older stars have had time to migrate out of such dusty regions. If O, B-type stars in E+A galaxies are embedded in dusty regions and only A-type stars have long enough lifetimes (∼1 gigayear) to move out from such regions, this scenario can naturally explain the E+A phenomena. Buyle et al. (2006) detected large amount of neutral hydrogen (10^9 M_⊙) in four nearby E+A galaxies, suggesting that some E+A galaxies are observed in the inactive phase of their star formation duty cycle. Accordingly, an independent evidence of the post-starburst event in addition to the strong Balmer absorption has been awaited.
The abundance of α-element can carry crucial information about the star formation time-scales. α-elements such as Magnesium[1] are formed in the explosion of type II supernovae which occur rapidly after a burst of star formation (time scales of $10^5 - 10^7$ yr) whereas the iron peak elements originate in Type Ia supernovae which lag behind by at least 1 gigayear (Nomoto, Thielemann, & Yokoi 1984; Woosley & Weaver 1995).

Therefore, α-elements enhancement is determined by the duration of star formation, i.e., a super-solar α-element to Fe ratio indicates that stars formed in an initial burst tailing up the Type II supernova abundance pattern and then star formation ceased. If E+A galaxies are truly in the post-starburst phase as has been claimed before (e.g., Poggianti et al. 1999), E+A galaxies are expected to have an enhanced α-element ratio, where Type II SNe produced α-elements such as Mg, but the Type I SNe has not yet exploded to produce enough Fe. In environments where star formation can continue for a longer period of time (e.g., the disc of our own galaxy), one expects solar abundance ratio for the younger, more metal-rich stars, which indeed is the case (Peletier 1989; Worthey, Faber, & Gonzalez 1992; Edvardsson et al. 1993; McWilliam 1997; Vazdekis et al. 1997). Note that it is true that there will be some Type Ia SNe from the remaining star in E+A galaxies after they truncate the starburst to create some Fe. However, since the E+A galaxies have negligible amount of the remaining star formation activity, there is little chance for this newly created Fe to get into the stellar spectra.

In the meantime, there has been a claim that E+A galaxies could be a progenitor of present day elliptical galaxies (Quintero et al. 2004; Hogg et al. 2006). It has been found that E+A galaxies have early-type morphological appearance (Goto 2005a). Some of E+A galaxies have even dynamically disturbed appearance (Oegerle, Hill, & Hoessel 1991; Yamauchi & Goto 2005; Pracy et al. 2005; Hogg et al. 2006). Recently, Goto (2005a) has shown that E+A galaxies have more close companion galaxies than average galaxies, showing that the dynamical merger/interaction could be the physical origin of E+A galaxies. Since the dynamical computer simulations have shown that the dynamical merger can create an elliptical galaxy (White 1978; Barnes 1992; Bekki, Shioya, & Couch 2001; Shioya, Bekki, & Couch 2001), E+A galaxies are a perfect candidate of the progenitor of present-day elliptical galaxies, although two orders of magnitude of difference in the number density needs to be carefully considered. If E+A galaxies are one of the progenitors, they should have similar metallicity/abundance ratios to those of present-day elliptical galaxies.

One of the difficulties in investigating E+A galaxies has been their rarity: less than 1% galaxies are in the E+A phase in the present Universe (Goto et al. 2003a). In this work, we overcome this problem by creating a large sample of 451 E+A galaxies carefully selected from the fourth public data release of the Sloan Digital Sky Survey (SDSS, Adelman-McCarthy et al. 2006), and investigate metallicity, abundance ratios and α-element enhancement of E+A galaxies. The aim of this study is as follows: (i) By investigating the metallicity and α-element enhancement of 451 E+A galaxies, we seek an independent evidence that E+A galaxies are in truly the post-starburst phase; (ii) By comparing the abundance ratio and the α-element enhancement of E+A galaxies to those of luminous elliptical galaxies, we test if E+A galaxies can be a progenitor of present-day elliptical galaxies.

Unless otherwise stated, we adopt the best-fit WMAP cosmology: $(\Omega_m, \Omega_{\Lambda}) = (0.71, 0.27, 0.73)$ (Bennett et al. 2003).

## 2 SAMPLE

### 2.1 Data

We have created a new sample of 451 E+A galaxies using the fourth public data release of the SDSS (Adelman-McCarthy et al. 2006). This is the largest sample of spectroscopically selected E+A galaxies to date. The selection algorithm is essentially the same as that in Goto (2005a), which we briefly summarize below.

We only use those objects classified as galaxies (type=3, i.e., extended) with spectroscopically measured redshift of $z > 0.01$ and the spectroscopic signal-to-noise $> 10$ per pixel (in the continuum of the r-band wavelength range). For these galaxies, we have measured Hα, [OII] and H0 equivalent widths (EWs) and obtained their errors using the flux summing method described in Goto et al. (2003a). For the H5 line, we only used the wider window of 4082–4122Å to ease the comparison with models. Once the lines are measured, we have selected E+A galaxies as those with H6 EW $> 5.0$Å, and H5 EW $> -3.0$Å, and [OII] EW $> -2.5$Å. Although the criteria on emission lines allow small amount of emission in the E+A sample, they are relatively small amount in terms of the SFR. We also exclude galaxies at $0.35 < z < 0.37$ from our sample because of the sky feature at 5577Å. Our criteria are more strict than previous ones (e.g., H5 EW $> 4.0$Å and [OII] EW $> -2.5$Å), suppressing possible contaminations from other populations of galaxies (Goto 2004).

We stress the advantage in using the H0 line in selecting E+A galaxies. Previous samples of E+A galaxies were often selected based solely on [OII] emission and Balmer absorption lines either due to the high redshift of the samples or due to instrumental reasons. Goto et al. (2003a) showed that such selections of E+A galaxies without information on H0 line would suffer from 52% of contamination from H0 emitting galaxies, whose morphology and color are very different from that of E+A galaxies (Goto et al. 2003a; Blake et al. 2004) selected E+A galaxies from the 2dF using only Balmer and [OII] lines to find that some E+A galaxies in their sample have the H0 line in emission. Since Hβ and Hγ absorption features are subject to the emission filling, Blake et al. (2004) found that using three Balmer absorption lines (Hδ, Hγ and Hβ) can suppress the contamination from the galaxies with detectable H0 emission.

Among ~210,000 galaxies which satisfy the redshift and S/N criteria with measurable [OII], H6 and H0 lines, we have found 451 E+A galaxies, which is one of the largest sample of E+A galaxies to date. The 451 E+A galaxies span a redshift range of $0.027 < z < 0.394$, within which H0 line is securely covered by the SDSS spectrograph. Although this range covers about 2 gigayear of lookback time, majority of our E+A galaxies lie at $z \sim 0.1$. Therefore, we do not consider the evolutionary effect within the E+A sample in this paper. It is important to note that the SDSS fiber spectrograph only samples the inner 3" of the region in diameter. Therefore, for the lowest redshift E+As, the 3"-fiber only samples the inner bulge region. And thus, readers are cautioned that it is possible for these E+A galaxies to have some remaining star formation activity in the outside of the fiber. However, since these galaxies at least have a post-starburst phenomena at the centre of the galaxy, we still
consider these galaxies as E+A galaxies in this work. In addition, since majority of our sample lie at $z \sim 0.1$, there is little variation in terms of the sampling region within our E+A galaxies (see Goto et al. 2003a, for relevant description on the aperture effects).

For a comparison purpose, we also select two different populations of galaxies: we select emission line galaxies with comparable Balmer line strength of $H\alpha$ EW $> 5.0\,\AA$ together with both H$\alpha$ and [OII] in emission ($H\alpha$ EW $< 3.0\,\AA$ and [OII] EW $< 2.5\,\AA$). The same redshift and signal-to-noise ratio cuts are applied to these galaxies. AGNs are removed from the sample using the [SII]/$H\alpha$ vs [OIII]/$H\beta$ line ratios (see Goto 2005a, for more detail). Median star formation rate based on the extinction corrected H$\alpha$ flux is 9.3 $M_\odot$ yr$^{-1}$. For these galaxies, Balmer absorption lines suffer from significant amount of the emission filling, which we have corrected using the $H\alpha$/H$\beta$ ratio and the iteration procedure described in Goto et al. (2003a). There remained 15886 galaxies and we call these galaxies as star-forming galaxies hereafter.

Another comparison sample is selected with $H\alpha$ EW $> -3.0\,\AA$, and [OII] EW $> -2.5\,\AA$ (in addition to the same redshift and SN cuts), i.e., galaxies with no emission in H$\alpha$ nor [OII]. We call them as passive galaxies, and there are ~16500 such galaxies. Although we regard this as a representative of present-day elliptical galaxies, readers are cautioned that this passive galaxy sample includes lower mass systems than the so-called giant elliptical galaxies.

### 2.2 Lick indices

For these E+A, star-forming, and the rest of the galaxies, we measured Mgb, Fe5270, and Fe5330 Lick/Image dissection scanner (IDS) indices based on the definition of Worthey et al. (1994); Worthey & Ottaviani (1997). The Lick system involves measuring line fluxes in narrow wavelength ranges relative to a pseudo-continuum found by linearly interpolating between two spectral averages on either side of the lines. In order to compare measured indices with theoretical model predictions and the literature, the measurements have to be carefully calibrated to the Lick/IDS system, i.e., we have to account for (i) the difference in the spectral resolution between Lick/IDS system and the SDSS spectra; (ii) the internal velocity broadening of the observed galaxies. To achieve these, we convolved each spectrum with a wavelength-dependent Gaussian so that the broadened spectra together with the velocity broadening reproduce the Lick/IDS resolution presented in Fig.7 of Worthey & Ottaviani (1997). For galaxies without proper velocity dispersion measurement, we have assumed a median velocity dispersion of our sample (175 km s$^{-1}$). Strictly speaking, we further need to adjust the flux calibration to the Lick system using a defined set of Lick standard stars, which have not been observed with the SDSS telescope unfortunately. The difference in the flux calibration, however, brings much smaller effects than those of the resolution and the velocity broadening.

### 3 RESULTS

#### 3.1 Mgb and Fe5270

In Fig. 1 we plot equivalent width of Fe(5270Å) against the Mgb index. The dotted contours and the small dots show the distribution of passive galaxies in the SDSS spectroscopic sample (selected with $H\alpha$ EW $> -3.0\,\AA$, and [OII] EW $> -2.5\,\AA$, i.e., no H$\alpha$ nor [OII] in emission). We overplot models of Thomas, Maraston, & Bender (2003a), which provide simple stellar population models with variable element abundance ratios. These models are free from the intrinsic $\alpha$/Fe bias that was imposed by the Milky Way template stars, and thus, the models reflect well-defined $\alpha$/Fe ratios at all metallicities. This treatment of non-solar abundance ratios is one of the most crucial elements in determining absolute age/metallicity estimates. Although starburst galaxies generally have two distinct stellar populations, i.e., bursting population and the underlying old stellar population, according to the population synthesis models, if more than 5% of the galaxy mass experience the burst, the galaxy spectrum is dominated by the bursting population (see Yagi, Goto, & Hattori 2006; Yagi & Goto 2006, for the detail). The dash-dot lines are the models with $\alpha$/Fe = 0.3 and 0.0 (where $Z/H = 0.0$), where 1.2, 3, and 13 gigayears of ages are labeled. The contour levels are at 20, 40, 60 and 80 percentiles. E+A galaxies have slightly larger metallicity than the star-forming galaxies, and have similar $\alpha$-abundance with elliptical galaxies.

Since the late 1970s, evidence has been accumulating that the magnesium-to-iron ratio seems to be larger in luminous elliptical galaxies when compared to solar-neighborhood stars (O'Connell 1976; Peletier 1989; Worthey, Faber, & Gonzalez 1992; Davies, Sadler, & Peletier 1993; Henry & Worthey 1999; Jørgensen 1999). Compared to the $\alpha$/Fe = 0.0 model, the distribution of all the passive galaxies has significant $\alpha$-element enhancement and more consistent with the $\alpha$/Fe = 0.3 model. This is the well-known $\alpha$-element enhancement for luminous elliptical galaxies (O'Connell 1976; Peletier 1989; Davies, Sadler, & Peletier 1993; Worthey, Trager, & Faber 1995; Henry & Worthey 1999; Jørgensen 1999).

The solid contours and the dashed contours show the distribution of E+A and the star-forming galaxies with the $H\delta$ EW $> 5.0\,\AA$, Figure 1. Equivalent width of Fe(5270Å) is plotted against Mgb. The dotted contours and the small dots show the distribution of passive galaxies (with no emission lines). The solid contours and the dashed contours show the distribution of E+A and the star-forming galaxies, respectively. The dash-dot lines are the models of Thomas, Maraston, & Bender (2003a) with $\alpha$/Fe = 0.3 and 0.0 (where $Z/H = 0.0$), where 1, 2, 3, and 13 gigayears of ages are labeled. The contour levels are at 20, 40, 60 and 80 percentiles. E+A galaxies have slightly larger metallicity than the star-forming galaxies, and have similar $\alpha$-abundance with elliptical galaxies.
respectively. First, E+A galaxies are much younger than luminous elliptical galaxies, being consistent with the post-starburst interpretation of E+A galaxies. Interestingly, the peak of the E+A distribution is consistent with \( \alpha/Fe = 0.3 \), suggesting that E+A galaxies have similar amount of \( \alpha \)-element enhancement with luminous elliptical galaxies, although the distribution is well extended to \( \alpha/Fe = 0.0 \). Note that the \( M_{\text{Fe}} \) vs \( Fe(5270) \) plane is not suitable to investigate the total metallicity since it is degenerated with the galaxy age. Compared to the E+A galaxies, star-forming galaxies have younger age, and smaller \( \alpha/Fe \) ratio.

To clarify these points, we plot H\( \delta \) EW against \( M_{\text{Fe}} \) in Fig.2 and against \( Fe5270 \) in Fig.3. We use the H\( \delta \) line here because the line is isolated from other emission and absorption lines, as well as strong continuum features in the galaxy spectrum (e.g., D4000). Furthermore, the higher order Balmer lines (H\( \gamma \) and H\( \beta \)) suffer from significant emission–filling (Osterbrock 1989), while the lower order lines (He and H\( \zeta \)) are low signal–to–noise in the spectra. In both figures, E+A galaxies are better matched with the \( \alpha \)-enhanced model (\( \alpha/Fe = 0.3, Z/H=0.0 \), the dash-dotted line) with a similar \( \alpha \)-element enhancement with the passive galaxies in the dotted contours. In contrast, the star-forming galaxies are better described with the models with smaller metallicity and no \( \alpha \)-element enhancement (\( Z/H=0.33 \) and -1.35 in Figs.2 and 3).

### 3.2 \( \alpha \)-element enhancement

To clarify the \( \alpha \)-element enhancement in E+A galaxies, we plot \( Mg_{\text{b}}/Fe5270 \) ratio against H\( \delta \) EW in Fig.4. We notice that the \( Mg_{\text{b}}/Fe5270 \) distribution of star-forming galaxies are more extended to lower values than that of E+A galaxies. The trend is clearer in Fig.5 where we plot histograms of \( Mg_{\text{b}}/Fe5270 \) distributions of E+A galaxies (the hashed region) and star-forming galaxies (the dashed lines). The histogram of E+A galaxies is shifted toward higher values of \( Mg_{\text{b}}/Fe5270 \) (i.e., \( \alpha \)-enhanced). According to the Kolomogorov-Smirnov test, these two distributions are different with more than 99.999% significance.

### 3.3 Metallicity

In Fig 6 we plot H\( \beta \) EW against \([\text{MgFe}]'\) index, which is defined by Thomas, Maraston, & Bender (2003b) as \([\text{MgFe}] = \sqrt{Mg_{\text{b}}(0.72 \times Fe5270 + 0.28 \times Fe5335)} \). The \([\text{MgFe}]'\) index is independent of \( \alpha/Fe \), and hence, a better tracer of total metallicity than the original \([\text{MgFe}]\) index suggested by Gonzalez (1993). Indeed, two models only different in \( \alpha/Fe \) ratio (the dash-dot lines) are almost degenerate in Fig 6. An advantage in using H\( \beta \) line over H\( \gamma \) or H\( \delta \) is that H\( \beta \) shows little sensitivity to element ratio variations as well as total metallicity, because of the lack of strong metallic lines in the wavelength range of the index definition (Korn, Maraston, & Thomas 2005). In Fig 6 both E+A galaxies and the passive galaxies are more consistent with the \( (\alpha/Fe, Z/H)=(0.3,0.0) \) model, with E+A galaxies having younger age. It is suggested that E+A galaxies are as metal rich as present day elliptical galaxies. We note that \( Z/H=0.0 \) is the solar metallicity and is somewhat lower than that of giant metal rich elliptical galaxies. Part of the reason for this is that we include lower mass galaxies in the passive galaxy sample (the dotted lines), and also please note that galaxies are widely distributed around the model (see Tantalo, Chiosi, & Bressan 1998; Thomas, Maraston, & Bender 2003b, for a Z/H distribution of local galaxies). In any case, the comparisons within our samples are valid and they still show that E+A galaxies are as metal rich as present day elliptical galaxies.

Although H\( \beta \) is less sensitive to metallicity variation, it suffers from the emission filling if the nebular emission is present at the galaxy. One way to reduce emission contamination is to use higher order Balmer lines such as H\( \delta \) since they are less af-
Abundance diagnosis of E+A (post-starburst) galaxies

4 DISCUSSION

4.1 Age-Metallicity Degeneracy

In the section we have measured and interpreted several Lick line indices. Historically, one of the great obstacles in interpreting the galaxy spectra has been the age/metallicity degeneracy in old stellar populations. As pointed out by Worthey et al. (1994), the spectra of an old (>2 gigayear) stellar population looks almost identical when the age is doubled and total metallicity reduced by a factor of 3 at the same time. We partially broke this age-metallicity degeneracy by plotting age-sensitive indices such as Hδ and Hβ against metallicity-sensitive indices such as Mg and Fe lines. Usefulness of this approach has been demonstrated by many authors (Gonzalez 1993; Fisher, Franx, & Illingworth 1995; Kunth & Davies 1998; Mehlert 1998; Jorgensen 1998; Kuntschner 2000). Since E+A galaxies have such strong Balmer absorption lines (Hδ EW >5Å), it is rather obvious that E+A galaxies have much younger age (~1 gigayear) than the comparison sample of elliptical galaxies. It is, however, important to keep it in mind that the Hδ has dlog(age)/dlog(Z)=0.9 (the age change needed to balance a metallicity change so that the index remains constant) and that Hβ has dlog(age)/dlog(Z)=0.6 affected by nebular emission (Osterbrock 1989). In Fig. 7, we then plot Hδ EW against [MgFe]' index. Again both E+A galaxies in the solid contours and the passive galaxies in the dotted contours show good agreement with the (α/Fe, Z/H)=(0.3,0.0) model in the dash-dotted line. On the other hand, the star-forming galaxies in the dashed contours agree with the metal poorer model with (α/Fe, Z/H)=(0.0,-0.33).

4.2 α-element abundance

In Section 4 we found that E+A galaxies have high α-element abundance ratio, and interpreted that it is another evidence that E+A
elements can be obtained when the chemical enrichment is driven predominantly by the ejecta of SN II (producer of 
Although we focused on the metallicity and the \[\alpha/Fe, Z/H\] index, the galaxy truncate its starburst and is in the post-starburst phase; 

When the galaxy truncate its starburst and is in the post-starburst phase, it is more practical approach to use a model with variable truncation. In reality, the truncation of star formation. In reality, the truncation of star formation at the zero age, followed by post-starburst interpretation of E+A galaxies. 

Being consistent with our intension to select post-starburst galaxies, the age distribution of E+A galaxies is peaked at slightly younger than 1 gigayear, which is consistent with the previous picture of E+A galaxies (e.g., Possiante et al. 1999). However, it is important to note that this age estimation is based on the single stellar population model, which experienced the burst of star formation at the zero age, followed by the truncation of star formation. In reality, the truncation of star formation needs a short, but finite length of time scale, and therefore, it is more practical approach to use a model with variable truncation time scale of star formation (e.g., 0.25-1 gigayear). An initial attempt can be found in Goto (2004). 

Figure 7. H\(\alpha\) EW is plotted against [MgFe]+ index. E+A galaxies and the passive galaxies are in the solid and dotted lines, respectively. The models with the dash-dot lines are the models of Thomas, Maraston, & Bender (2003) with \((\alpha/Fe, Z/H) = (0.3,0.0), (0.0,0.0)\) and \((0.0,-0.33)\).

galaxies are in the post-starburst phase. However, it is important to keep in mind that this is under an assumption that the initial mass function (IMF) is universal. High abundance ratio of \(\alpha\) elements can be obtained when the chemical enrichment is driven predominantly by the ejecta of SN II (producer of \(\alpha\) elements), which could happen under the following two occasions: (i) when the galaxy truncate its starburst and is in the post-starburst phase; (ii) the fraction of high-mass stars is high, i.e., the top heavy initial mass function (Worthey, Faber, & Gonzalez 1992). For E+A galaxies, we not only have the information on the high \(\alpha\)-elements ratio, but also we know that E+A galaxies have extremely strong Balmer absorption lines (H\(\alpha\) EW >5Å). Therefore, the IMF has to be not just top heavy, but also need to be A-type star peaked. It is possible, but there is no strong reason that E+A galaxies have an A-star peaked IMF. Therefore, it is more straightforward to interpret that our findings of high \(\alpha\)-elements abundance ratio strengthened the post-starburst interpretation of E+A galaxies.

4.3 Age of E+A galaxies

Although we focused on the metallicity and the \(\alpha\)-element abundance ratio of E+A galaxies in Section 4 we have collected evidence that E+A galaxies have similar \(\alpha/Fe\) ratio and metallicity with luminous elliptical galaxies. Since the only difference in our plots between these populations of galaxies is the age, E+A galaxies will surely evolve into elliptical galaxies in a few gigayear. In addition, there has been accumulating evidence that the morphological appearance of E+A galaxies is either early-type or with dynamically disturbed signs (Goto 2005a; Yamauchi & Goto 2003; Yagi, Goto, & Hattori 2006; Yagi & Goto 2006). The surface brightness of E+A galaxies is also inbetween that of elliptical galaxies and star-forming galaxies (Quintero et al. 2004). These results suggest that E+A galaxies also look like one of the progenitors of elliptical galaxies in terms of morphology as well.

It has been reported, however, that there is a huge difference in the number density between E+A galaxies and elliptical galaxies; Goto (2005a) reported that E+A galaxies are only 0.2% of galaxies in a volume-limited sample. Assuming that the lifetime of the E+A phase is \(\sim 1\) gigayear based on the lifetime of A-type stars, only 2-3% of galaxies have been through the E+A phase in the Universe of 13.7 gigayears of age, if the fraction of the E+A galaxies has been constant at \(\sim 0.2\) %. This, however, is a too simple assumption. It has been known that cosmic star formation density was much higher at \(z > 1\) (Madau et al. 1996). According to Le Borgue et al. (2006), the fractions of the post-starburst galaxies was larger by a factor of 2 at \(z \sim 1\). If we loosen our criteria to select post-starburst galaxies to H\(\alpha\) EW >3Å, the fraction increase by a factor of \(\sim 3\) (Goto et al. 2003d). Therefore, an estimate on the high side yield \(\sim 15\)% of galaxies may have been through the E+A phase. However, this is still a small fraction of galaxies compared to the total number of galaxies and suggests that not all the elliptical galaxies have not been through the E+A phase. Therefore, it is likely that E+A galaxies are only one of the multiple progenitors of elliptical galaxies. If star-forming galaxies decrease their star formation rate more slowly, for example, exponentially with \(\tau \sim 1\) gigayear, the galaxies do not experience the E+A phase before they become passive galaxies (Goto 2003). It is important to investigate what special physical mechanism is needed for a galaxy to become an E+A galaxy.

Specifically on the high redshift cluster environments, there is a conflicting report on the fraction of E+A galaxies. Tran et al. (2003) found 7-13% of E+A galaxies in three high redshift clusters at \(z=0.33,0.58,\) and 0.83, claiming that \(> 30\)% of E+S0 members may have undergone the E+A phase if the effects of E+A downsizing and increasing E+A fraction as a function of redshift are considered. In their search for field E+A galaxies among 800 spectra, Tran et al. (2004) measured the E+A fraction at \(0.3 < z < 1\) to be \(2.7\% \pm 1.1\%\), a value lower than that in galaxy clusters at comparable redshifts. Based on 1823 galaxies in the 15 X-ray luminous clusters at \(0.18 < z < 0.55\), on the contrary, Balogh et al. (1999) found that the fraction of K+A galaxies is 1.5% \(\pm 0.8\%\) in the cluster and 1.2% \(\pm 0.8\%\) in the field, i.e., they found no difference.

Obviously these two papers are inconsistent to each other. Both of these work did not use H\(\alpha\) line in the selection criteria, and thus, could suffer from the up to 52% of the contamination (Goto et al. 2003a). More statistically significant analysis based on a larger sample is needed to shed light on the galaxy evolution in the high redshift cluster environment. In the low redshift cluster envi-
rnonment, Goto et al. 2003b) identified that passive spiral galaxies, i.e., galaxies with no star formation but with spiral morphology, preferentially reside in the cluster infalling regions. These passive spiral galaxies may be a more important smoking-gun in galaxy evolution in cluster environment.

5 CONCLUSIONS

We have constructed one of the largest sample of 451 E+A galaxies using the SDSS DR4. Using the sample we have investigated total metallicity and $\alpha$-element enhancement of E+A galaxies. Our findings are as follows:

(i) Compared to the star-forming galaxies with similar amount of Balmer absorption, E+A galaxies have larger amount of metallicity and $\alpha$-element enhancement. These results are consistent with the hypothesis that the star formation in E+A galaxies were truncated to enhance the age of $\alpha$-element abundance in E+A galaxies. This provides us with additional evidence that E+A galaxies selected to have no He emission are more likely to be truly in the post-starburst phase rather than dusty-starforming galaxies.

(ii) Compared to the present-day elliptical galaxies, E+A galaxies have similar amount of metallicity and $\alpha$-element enhancement. These results suggest that in terms of abundance diagnosis, E+A galaxies are consistent to be one of the progenitors of the present-day elliptical galaxies, although the difference in the spatial number density needs to be carefully considered.

(iii) Compared with the models of Thomas, Maraston, & Bender (2005a), which can handle the difference in the $\alpha/Fe$ ratio at all metallicities, E+A galaxies are well-explained with $(\alpha/Fe, Z/H) = (0.3, 0.0)$ and age of $\leq 1$ gigayear.

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REFERENCES

Abraham R. G., et al., 1996, ApJ, 471, 694

Adelman-McCarthy J. K., et al., 2006, ApJS, 162, 38

Balogh M. L., Morris S. L., Yee H. K. C., Carlberg R. G., Ellingson E., 1999, ApJ, 527, 54

Barnes J. E., 1992, ApJ, 393, 484

Bekki K., Shioya Y., Couch W. J., 2001, ApJ, 547, L17

Bennett C.L., et al., 2003, ApJS, 148, 1

Blake C., et al., 2004, MNRAS, 355, 713

Buyle P., Michielsen D., De Rijcke S., Pisano D. J., Dejonghe H., Freeman K., 2006, ApJ, 649, 163

Couch W. J., Sharples R. M., 1987, MNRAS, 229, 423

Davies R. L., Sadler E. M., Peletier R. F., 1993, MNRAS, 262, 650

de Jong R. S., Davies R. L., 1997, MNRAS, 285, L1

Dressler A., Gunn J. E., 1992, ApJS, 78, 1

Dressler A., Gunn J. E., 1983, ApJ, 270, 7

Edvardsson B., Andersen J., Gustafsson B., Lambert D. L., Nissen P. E., Tomkin J., 1993, A&A, 275, 101

Fabricant D. G., McClintock J. E., Bautz M. W., 1991, ApJ, 381, 33

Fisher D., Franx M., Illingworth G., 1995, ApJ, 448, 119

González J. J., 1993, PhD

Goto T., 2003, PASJ, 55, 757

Goto T., 2004, A&A, 427, 125

Goto T., et al., 2003a, PASJ, 55, 771

Goto T., et al., 2003b, PASJ, 55, 757

Goto T., et al., 2003a, PASJ, 55, 771

Goto T., et al., 2003b, PASJ, 55, 757

Goto T., Yamauchi C., Fujita Y., Okamura S., Sekiguchi M., Smail I., Bernardi M., Gomez P. L., 2003c, MNRAS, 346, 601

Goto T., 2003, PhD, the University of Tokyo

Henry R. B. C., Worthey G., 1999, PASP, 111, 919

Hogg D. W., Masjedi M., Berlind A. A., Blanton M. R., Quintero A. D., Brinkmann J., 2006, ApJ, 650, 763

Jørgensen I., 1999, MNRAS, 306, 607

Korn A. J., Maraston C., Thomas D., 2005, A&A, 438, 685

Kuntschner H., Davies R. L., 1998, MNRAS, 295, L29

Kuntschner H., 2000, MNRAS, 315, 184

Le Borgne D., et al., 2006, ApJ, 642, 48

Maclaren I., Ellis R. S., Couch W. J., 1988, MNRAS, 230, 249

Madau P., Ferguson H. C., Dickinson M. E., Giavalisco M., Steidel C. C., Fruchter A., 1996, MNRAS, 283, 1388

McWilliam A., 1997, ARA&A, 35, 503

Mehlert D., 1998, PhD

Newberry M. V., Boroson T. A., Kirshner R. P., 1990, ApJ, 350, 585

Nomoto K., Thielemann F.-K., Yokoi K., 1984, ApJ, 286, 644

OConnell R. W., 1976, ApJ, 206, 370

Oegerle W. R., Hill J. M., Hoessel J. G., 1991, ApJ, 381, L9

Osterbrock, D.E., 1989, Astrophysics of Gaseous Nebulae and Active Galactic Nuclei (University Science Books, Mill Valley CA)

Owen F. N., Ledlow M. J., Keel W. C., Morrison G. E., 1999, AJ, 118, 633

Peletier R. F., 1989, PhD

Poggianti B. M., Smail I., Dressler A., Couch W. J., Barger A. J., Butcher H., Ellis R. S., Oemler A. J., 1999, ApJ, 518, 576

Poggianti B. M., Wu H., 2000, ApJ, 529, 157

Pracy M. B., Couch W. J., Blake C., Bekki K., Harrison C., Colless M., Kuntschner H., de Propris R., 2005, MNRAS, 359, 1421

Quintero A. D., et al., 2004, ApJ, 602, 190

Shioya Y., Bekki K., Couch W. J., 2001, ApJ, 558, 42

Smail I., Morrison G., Gray M. E., Owen F. N., Ivison R. J., Kneib J.-P., Ellis R. S., 1999, ApJ, 525, 609
T. Goto

Tantalo R., Chiosi C., Bressan A., 1998, A&A, 333, 419
Thomas D., Maraston C., Bender R., 2003, MNRAS, 339, 897
Thomas D., Maraston C., Bender R., 2003, MNRAS, 343, 279
Tran K.-V. H., Franx M., Illingworth G. D., van Dokkum P., Kelson D. D., Magee D., 2004, ApJ, 609, 683
Tran K.-V. H., Franx M., Illingworth G., Kelson D. D., van Dokkum P., 2003, ApJ, 599, 865
Vazdekis A., Peletier R. F., Beckman J. E., Casuso E., 1997, ApJS, 111, 203
White S. D. M., 1978, MNRAS, 184, 185
Woosley S. E., Weaver T. A., 1995, ApJS, 101, 181
Worthey G., Faber S. M., Gonzalez J. J., 1992, ApJ, 398, 69
Worthey G., Faber S. M., Gonzalez J. J., Burstein D., 1994, ApJS, 94, 687
Worthey G., Trager S. C., Faber S. M., 1995, ASPC, 86, 203
Worthey G., Ottaviani D. L., 1997, ApJS, 111, 377
Yagi M., Goto T., Hattori T., 2006, ApJ, 642, 152
Yagi M., Goto T., 2006, AJ, 131, 2050
Yamauchi C., Goto T., 2005, MNRAS, 359, 1557