Integrated field spectroscopy of E+A (post-starburst) galaxies with the Kyoto tridimensional spectrograph II

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Received 2007 December 26; in original form 2007 October 16

ABSTRACT

We have performed two-dimensional spectroscopy of three nearby E+A (post-starburst) galaxies with the Kyoto tridimensional spectrograph II (Kyoto3DII) integral field spectrograph. In all the cases, Hα absorption is stronger at the centre of the galaxies, but significantly extended at the scale of a few kiloparsec. For one galaxy (J1656), we found a close companion galaxy at the same redshift. The galaxy turned out to be a star-forming galaxy with a strong emission in Hγ. For the other two galaxies, we have found that the central post-starburst regions possibly extend toward the direction of the tidal tails. Our results are consistent with the merger/interaction origin of E+A galaxies, where the infalling-gas possibly caused by galaxy–galaxy merging creates a central starburst, succeeded by a post-starburst (E+A) phase once the gas is depleted.

Key words: galaxies: evolution – galaxies: formation – galaxies: interactions – galaxies: peculiar – galaxies: starburst.

1 INTRODUCTION

Galaxies with strong Balmer absorption lines without any emission in [O II] or Hα are called E+A galaxies. The existence of strong Balmer absorption lines shows that E+A galaxies have experienced starburst recently (within a Gyr; Goto 2004). However, these galaxies do not show any sign of ongoing star formation, as non-detection in the [O II] emission line indicates. Therefore, E+A galaxies have been interpreted as post-starburst galaxies, that is, a galaxy that 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). A recent study has found that E+A galaxies have α-element excess (Goto 2007a), which also supports the post-starburst interpretation of E+A galaxies. However, the reason why they started starburst and why they abruptly stopped starburst remain one of the mysteries of galaxy evolution.

First, E+A galaxies are found in cluster regions, especially at higher redshift (Sharples et al. 1985; Lavery & Henry 1986; Couch & Sharples 1987; Broadhurst, Ellis & Shanks 1988; Fabricant et al. 1991; Belloni et al. 1995; Burger et al. 1996; Couch et al. 1998; Fisher et al. 1998; Morris et al. 1998; Dressler et al. 1999, 2004; Poggianti et al. 1999; Tran et al. 2003, 2004). Therefore, a cluster-specific phenomenon, such as ram-pressure stripping, was thought to be responsible for the violent star formation history of E+A galaxies (Spitzer & Baade 1951; Gunn & Gott 1972; Farouki & Shapiro 1980; Kent 1981; Dressler & Gunn 1983; Abadi, Moore & Bower 1999; Fujita et al. 1999; Quilis, Moore & Bower 2000; Fujita, Takizawa & Sarazin 2003; Bekki & Couch 2003; Fujita & Goto 2004).

However, Blake et al. (2004) found that low-redshift E+A galaxies are located predominantly in the field environment, suggesting that a physical mechanism that works in the field region is at least partly responsible for these E+A galaxies. Recently, Goto (2005) has shown that E+A galaxies have more close companion galaxies than average galaxies, which means that the dynamical merger/interaction could be the physical origin of field E+A galaxies. The dynamically disturbed morphologies of E+A galaxies also support this scenario (Liu et al. 2007; Yamauchi & Goto 2005). To reconcile the situation, independent evidence of the origin of E+A galaxies is needed.

The previous work mentioned above has focused on the investigation of the global/external properties of E+A galaxies, such as the environment of E+A galaxies (Goto 2005) and the integrated spectra of E+A galaxies (Dressler et al. 2004). However, if the physical origin of E+A galaxies is merger/interaction or gas-stripping, these mechanisms should leave traces of the spatial distribution of stellar populations in E+A galaxies. For example, a centrally concentrated post-starburst region is expected to be found in the case of a merger/interaction origin (e.g. Barnes & Hernquist 1992). In contrast, gas-stripping would create a more uniform, galaxy-wide
post-starburst region. Thus, the spatial distribution of the post-starburst region inside an E+ A galaxy contains important and independent clues about the physical origin of E+ A galaxies (e.g. Pracy et al. 2005; Swinbank et al. 2005). In this work, we try to obtain independent clues to the origin of E+ A galaxies by revealing the internal structure of E+ A galaxies using the Kyoto tridimensional spectrograph II (Kyoto3DII) integrated field spectrograph (IFS). We perform spatially resolved spectroscopy of three nearby E+ A galaxies with the Kyoto3DII IFS. By revealing the spatial distribution of H$\alpha$ absorption, we aim to obtain independent evidence to shed light on the physical origin of E+ A galaxies.

Unless otherwise stated, we adopt the Wilkinson Microwave Anisotropy Probe (WMAP) cosmology (Bennett et al. 2003): $(h, \Omega_\text{m}, \Omega_\Lambda) = (0.71, 0.27, 0.73)$.

2 SAMPLE SELECTION

We select our target E+ A galaxies from Goto (2005, 2007b), which contain a catalogue of 564 E+ A galaxies based on the $\sim$670,000 galaxy spectra of the Sloan Digital Sky Survey (SDSS; Adelman-McCarthy et al. 2006). Briefly, the 564 E+ A galaxies satisfy the following criteria:

(i) H$\alpha$ equivalent width (EW) $> 4$ Å;
(ii) [O II] EW $> -2.5$ Å;
(iii) H$\beta$ EW $> -3.0$ Å.

Note that the line measurement was performed on the spectra through the SDSS fibre spectrograph with a diameter of 3 arcsec. The use of the H$\alpha$ line is preferred over other hydrogen Balmer lines (e.g. H$\gamma$, H$\delta$, H$\epsilon$) as the line is isolated from other emission and absorption lines, and there are also strong continuum features in the galaxy spectrum (e.g. D4000). Furthermore, the lower-order Balmer lines (H$\gamma$ and H$\delta$) can suffer from significant emission filling, while the higher-order lines (H$\epsilon$ and H$\zeta$) have a low signal-to-noise in spectra. We stress that we select our E+ A galaxies where EW $> 4$ Å is very strong, compared with previous work. Thus, we can select strong post-starburst galaxies, which was not possible in previous work with a smaller population.

Out of the 564 E+ A galaxies, we have observed three, as described in Section 3.

3 OBSERVATION

Observations were carried out on the nights of 2005 July 20, 21 and 22 with the Kyoto3DII IFS (Sugai et al. 2004, 2006, 2007) attached to the University of Hawaii 88-in (2.2-m) telescope (UH88). Unfortunately, no useful data were taken on 2005 July 22 because of the heavy cloud. The Kyoto3DII is a multimode spectrograph with four observational modes: a Fabry–Perot imager, an IFS, filter-imaging modes and slit spectroscopy. When attached to the UH88, the IFS has a field of view of $\sim 14 \times 16$ arcsec$^2$ with a pixel scale of 0.43 arcsec pix$^{-1}$. We used the number 2 grism and the number 2 filter, which cover the wavelength range of 4200–5200 Å with a resolution of $R \sim 1200$.

Among the 564 E+ A galaxies described in Section 2, we observed three targets that had a bright magnitude, an appropriate redshift to measure H$\alpha$ line, and good visibility on the observing dates. We present the basic properties of the three targets in Table 1, where measured quantities such as positions, redshift, magnitudes in g and r and Petrosian radius are taken from the SDSS catalogue. Here, $R_{90}$ is the radius within which 90 per cent of the r-band Petrosian flux is contained. Magnitudes are dereddened (for the Galactic extinction) Petrosian AB magnitude in g and r bands. In Figs 1–4 (panels a), we show the g, r, i, composite images of the three targets. J1656 has a possible companion galaxy to the east. J2337 has a tidal tail from north-west to south-east.

The average seeing was $\sim 1.4$ arcsec on both nights, based on the point spread function (PSF) measured with standard stars. The seeing size corresponds to $\sim 3$ lenslets, which are smaller than the spatial scale we probe in Section 4. Exposure time was 2.5–5 h per target, depending on the target visibility. Data reduction was carried out using the MLA IRAF2 package for the Kyoto3DII (Kawai et al., in preparation),3 which takes care of the shift due to the atmospheric gradient because of moon shine) in the sky lenslets. Therefore, we used $\sim 100$ lenslets in the targets area (but well away from the target) for the sky subtraction.

4 RESULTS

4.1 SDSSJ210258.87+103300.6

We show the image of SDSSJ210258.87+103300.6 reconstructed from the whole light through the IFS (4200–5200 Å) in Fig. 1(b). Overplotted circles show radii of 1.5, 3, 4.5 and 6 lenslets.

In Fig. 1(c), we show the image constructed using only the light through the H$\alpha$ wavelength (4086–4110 Å to be exact). To see the difference, we take the ratio of H$\alpha$ to all the wavelengths in Fig. 1(d).

See Appendix A for details of estimating the ratio when both components have a large uncertainty. Because H$\alpha$ is an absorption line,

\begin{table}
\centering
\caption{Target properties.}
\begin{tabular}{|c|c|c|c|c|c|c|}
\hline
Object & Redshift & $R_{\text{AB}}$ & $g_{\text{AB}}$ & Petrosian radius (arcsec in r) & Exposure time (s) & Observing date (HST) & $M_r$ \\
\hline
SDSSJ210258.87+103300.6 & 0.093 & 16.14 & 15.37 & 5.15 & 3600 $\times$ 5 & 2005 July 20 & $-23.00$ \\
SDSSJ165648.64+114702.3 & 0.100 & 17.73 & 16.72 & 2.32 & 3600 $\times$ 2 $\div$ 1800 & 2005 July 21 & $-21.74$ \\
SDSSJ233712.76$-$105800.3 & 0.078 & 16.02 & 15.31 & 5.45 & 3600 $\times$ 3 & 2005 July 21 & $-22.47$ \\
\hline
\end{tabular}
\end{table}

1 Absorption lines have a positive sign throughout this paper.

2 IRAF is distributed by the National Optical Astronomy Observatories, which are operated by the Association of Universities for Research in Astronomy, Inc., under contract to the National Science Foundation.

3 See http://smoka.nao.ac.jp/about/subaru.jsp.

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IF spectroscopy of E+A galaxies with Kyoto3DII

Figure 1. J2102. (a) g, r, i-composite image taken from the SDSS website. The Kyoto3DII field of view is overlaid. (b) Observed IFS image using the light in all wavelengths (4200–5200 Å). Overplotted circles show radii of 1.5, 3, 4.5 and 6 lenslets. The orientation of the figure is indicated with an arrow. (c) IFS image using the light in the Hδ wavelength. The effective data area is larger than that in Fig. 1(b) because of the smaller wavelength range used. (d) The Hδ-to-continuum ratio. The scale and orientation are the same for Figs 1(b)–(d). (e) Spectra of the central 1.5 lenslet radius region, and the annuli of the 1.5–3, 3–4.5 and 4.5–6 lenslet regions of J2102 from the top to the bottom. The spectra are shifted to the rest frame and smoothed using a five-pixel box. (f) Hδ (diamonds) and Hγ (triangles) EWs are plotted against the distance to the galaxy centre.

it appears darker when stronger. We checked that this method returned a uniform image (ratio) for a standard star (see Appendix B for details). In Fig. 1(d), the centre of the galaxy is slightly darker with a small extension to the right, showing that Hδ absorption may be concentrated around the galaxy centre. Note that the pixel values are meaningless outside the galaxy, where no signal is present other than the noise. It is striking that the distribution of the post-starburst phenomena (with strong Hδ absorption) is mapped out in two
dimensions. The figure demonstrates the ability of the IFS observation to disentangle spatial and spectral information.

The trend becomes clearer in the spectrum. In Fig. 1(e), we show the spectra of the central 1.5 lenslet radius region, and annuli of the 1.5–3, 3–4.5 and 4.5–6 lenslet regions of J2102 from the top to the bottom. The spectra are shifted to the rest frame and smoothed using a five-pixel box. The spectrum from the outermost annulus (radius of 4.5–6 lenslets) is approaching zero and not reliable. In Fig. 1(e), it is noted that the Hδ and Hγ absorptions become deeper towards the centre of the galaxy. To quantify this, we have measured the Hδ and Hγ EWs in these spectra using the flux summing method described in Goto et al. (2003c). The results are shown in Fig. 1(f), where the Hδ and Hγ EWs are denoted by diamonds and triangles, respectively. The Hδ EW is the strongest at the centre, but remains strong as far as ~3 kpc away. Note that the seeing size is ~3 lenslets, and smaller than the extension of the strong Hδ absorption. The Hγ EWs are not as strong as Hδ, but show a similar trend.

4.2 SDSSJ165648.64+314702.3

In Fig. 2(b), we show the image of SDSSJ165648.64+314702.3 reconstructed using the light in all wavelengths (4200–5200 Å). This galaxy, J1656, has a possible nearby companion galaxy to the west, as shown in Fig. 2(a). The companion candidate is clearly detected in Fig. 2(b) using the IFS.

In Fig. 2(c), we show the image in the Hδ wavelength (4086–4114 Å). In Fig. 2(d), we show the ratio of Hδ (Fig. 2c) to the continuum (Fig. 2b). See Appendix A for details of estimating the ratio when both components have a large uncertainty. Interestingly, in the lower-right galaxy, the strong Hδ absorption (darker in the image) is concentrated around the centre of the galaxy. There is no obvious trend for Hδ for the upper-left galaxy.

In Fig. 2(e), we show the spectra of the central 1.5 lenslet radius region, and the annuli of the 1.5–3 and 3–4.5 lenslet regions of the upper-left galaxy from the top to the bottom. We did not use the radius of 4.5–6 lenslets because of the smaller galaxy size. The spectra are shifted to the rest frame and smoothed using a five-pixel box. Although the spectra are noisier, we recognize the same trend as for J2101 in Fig. 1 (i.e. both Hδ and Hγ absorptions become stronger with decreasing radius). This trend is confirmed in Fig. 2(f), where we show the Hδ and Hγ EWs as a function of radius (from the galaxy centre). The Hδ EW is as large as 8 Å at the centre, confirming our target selection of E+A galaxies. The Hγ EWs stay strong as far as ~3 kpc. Hγ EWs are also strong at 0–3 kpc annuli. Note that since the innermost spectrum is affected by strong noise at ~4300 Å, and we use a bluer wavelength range (4260–4280 Å) by hand to determine the continuum for the Hγ EW. These results suggest that the post-starburst region in E+A galaxies is extended to a few kpc of radius, and does not seem to be limited to the nucleus of the galaxy.

In Fig. 3(a), we show the image in the Hγ wavelength (4318–4354 Å). In contrast to Fig. 2(d), the upper-left galaxy is much brighter in the Hγ wavelength. In Fig. 3(b), we take the ratio of Hγ to all wavelengths (see Appendix A for the details of the procedure). The trend is clearer, suggesting that the upper-left galaxy might have Hγ in emission. In Fig. 3(c), we show the spectrum of the upper-left galaxy. As for previous spectra, the spectra show are from the central 1.5 lenslet radius region, and the annuli of the 1.5–3 and 3–4.5 lenslet regions centred on the upper-left galaxy. The redshift of this galaxy turned out to be the same as the E+A galaxy in the lower right (z = 0.100). Thus, we have confirmed that this galaxy is a physically associated companion galaxy, not a chance projection. Interestingly, this galaxy has an emission in Hγ (EW ~−18.0 Å), suggesting that this galaxy is a star-forming galaxy. The Hγ emission of EW = −18.0 Å is strong, and this galaxy may be called a starburst galaxy.

It has been suggested that galaxy mergers might create E+A galaxies (e.g. Goto 2005). Having a close companion at the same redshift, this E+A galaxy, J1656, is a real example produced by a galaxy–galaxy merger with an upper-left companion. At the same time, J1656 presents an interesting example where the companion galaxy is not necessarily an E+A galaxy, even though it involves the same galaxy merger. This example suggests that not only a merger but an additional condition is required to produce an E+A galaxy. So far, only a few spectroscopic companions of E+A galaxies are known. For example, a companion galaxy of an E+A galaxy in Yagi, Goto & Hattori (2006) was a passive galaxy. More spectroscopic follow-up of E+A companion galaxies is needed to reveal what type of galaxy merger can produce an E+A galaxy.

4.3 SDSSJ233712.76−105800.3

In Fig. 4(b), we show the images of J2337 using all the light (4200–5200 Å) through the IFS. Unfortunately, the tidal tail of J2337 is out of the 15-arcsec field of view of the Kyoto3DII, but the basic structures of the galaxies were recovered using the light through the IFS. In Figs. 4(c) and (d), we show the image using the Hδ wavelength (4087–4119 Å) and the ratio of Hδ to the continuum, as in Figs. 1 and 2. As noticed before, Hδ absorption is centrally concentrated, but spatially extended beyond the galaxy core. Although marginally significant, we note that in Fig. 4(d), the Hδ absorption may be shifted by a few lenslets toward the upper-right (or south) direction. We discuss a possible interpretation of this in Section 5.

In Fig. 4(e), we show the spectra of the central 1.5 lenslet radius region, and the annuli of the 1.5–3, 3–4.5 and 4.5–6 lenslet regions of J2337 from the top to the bottom. The spectra are shifted to the rest frame and smoothed using a five-pixel box. The spectrum from the outermost annulus (radius of 4.5–6 lenslets) is approaching zero and is not reliable. In Fig. 4(e), it is noted that the Hδ and Hγ absorptions become deeper with decreasing distance to the centre of the galaxy. Fig. 4(f) shows the Hδ (diamonds) and Hγ (triangles) EWs in these spectra. The Hδ EW is the strongest at the centre with ~10 Å, and remains strong as far as ~2 kpc away. The Hγ EWs are not as strong as Hδ, but show a similar trend. These results are similar to the previous two galaxies (i.e. strong Hδ and Hγ absorption is observed in the core of the galaxy, and both lines remain strong as far as a few kpc from the centre of the galaxy).

We would like to mention a possibly interesting different radial trend of Hδ and Hγ in Fig. 4(f). The Hδ EW is strongest at the innermost bin, and declines immediately at the second bin to remain flat at the third bin. However, the Hγ EW in the second bin is as large as in the first bin, and suddenly declines at the third bin. This behaviour can also be seen for J2102 in Fig. 1(f). We discuss a possible interpretation in Appendix C.

5 DISCUSSION

One of the main purposes of this paper is to shed light on the origin of E+A galaxies, based on the internal properties of E+A galaxies obtained with the Kyoto3DII IFS. Previous work on E+A galaxies was noticeably focused on their global/external properties, such as integrated spectra (Poggianti et al. 1999) and environment (Goto 2005). Thus, it is important to obtain independent evidence for their origin based on the internal structure.
We have observed three E+A galaxies with the Kyoto3DII IFS, and the main results are shared among these three galaxies. Balmer absorption, especially Hδ absorption, was strongest at the centre/core but significantly extended at a scale of a few kpc in all three galaxies. This suggests that the post-starburst phenomena are centred on the galaxy core, but are not limited to the core. These results have an important physical implication for the origin of E+A galaxies.
Figure 3. Upper-left galaxy of J1656. (a) Image using the light in the H\(\gamma\) wavelength. Overplotted circles show radii of 1.5, 3, 4.5 and 6 lenslets. (b) The H\(\gamma\)-to-continuum ratio. (c) Spectra of the central 1.5 lenslet radius region, and the annuli of the 1.5–3 and 3–4.5 lenslet regions of the upper-left galaxy from the top to the bottom. The spectra are shifted to the rest frame and smoothed using a five-pixel box. (f) H\(\delta\) (diamonds) and H\(\gamma\) (triangles) EWs are plotted against the distance to the centre of the upper-left galaxy.

Pracy et al. (2005) have run numerical simulations of the galaxy merger model and the truncation model (e.g. the tidal stripping or the ram-pressure stripping model) to predict radial profiles of the H\(\delta\) EW in the framework of Bekki & Shioya (1998), Bekki, Shioya & Couch (2001) and Bekki, Couch & Shioya (2002).

(i) In their galaxy–galaxy merger simulation, a centralized burst of star formation is produced. When the starburst ends, the galaxy is left with a central population of young stars, and hence a radial distribution of the H\(\delta\) EW, which is highest in the centre and decreases rapidly with galactocentric radius. After \(\sim\)1.5 Gyr, the radial H\(\delta\) profile evolves to be flat and uniformly low across the entire extent of the galaxy. This result is a natural consequence of recent major-merger computer simulations, in which during galaxy–galaxy collisions the gas readily loses angular momentum because of dynamical friction, decouples from the stars, and inflows rapidly toward the merger nuclei (Barnes 1992; Barnes & Hernquist 1992, 1996; Mihos & Hernquist 1994, 1996), creating a central starburst, which could evolve into an E+A phase if the truncation of the starburst is rapid enough (Goto 2004).

(ii) Their truncation model assumes a situation like a ram-pressure stripping model or a tidal stripping model, in which the star formation is simultaneously and uniformly truncated throughout the entire disc. Immediately after the truncation of star formation, the galaxy has a flat, uniformly high H\(\delta\) EW profile. As the system evolves, the contribution from the old stellar population becomes most prominent at the centre of the galaxy. This results in the H\(\delta\) EWs decreasing most rapidly in the central region of the galaxy.

A stark contrast between these two models makes the H\(\delta\) profile a powerful tool to investigate the physical origin of E+A galaxies. In Figs 1, 2 and 4 (panels d), we observed that a strong H\(\delta\) absorption is centred around the galaxy core in all three cases. Although the relative strength of the H\(\delta\) absorption depends on the strength of the starburst and the time since then, the observed trend is qualitatively consistent with the prediction from the galaxy–galaxy merger simulation. This result is unique in that it is obtained using only the internal structure of E+A galaxies.

Previous attempts also support our results. Caldwell et al. (1996) obtained long-slit spectra of E+A galaxies in the Coma cluster and showed that starburst signatures are prominent in the central core and are spatially extended. Similarly, Norton et al. (2001) found that the young stellar populations are more centrally concentrated than the older populations, but they are not confined to the galaxy core (radius <1 kpc). Recently, Yagi & Goto (2006) performed spatially resolved spectroscopy of three E+A galaxies using the Apache Point
Figure 4. J2337. (a) g, r, i-composite image of J2337 taken from the SDSS website. The Kyoto3DII field of view is overlaid. (b) Observed image of J2337 using the light in all wavelengths (4200–5200 Å). Overplotted circles show radii of 1.5, 3, 4.5 and 6 lenslets. The orientation of the figure is indicated with an arrow. (c) Image of J2337 using the light in the Hδ wavelength. The scale and orientation are the same in Figs 4(b)–(d). The effective data area is larger than that in Fig. 4(b) because of the smaller wavelength range used. (d) The Hδ-to-continuum ratio. (e) Spectra of the central 1.5 lenslet radius region, and the annuli of the 1.5–3, 3–4.5 and 4.5–6 lenslet regions from the top to the bottom. The spectra are shifted to the rest frame and smoothed using a five-pixel box. (f) Hδ (diamonds) and Hγ (triangles) EWs are plotted against the distance to the galaxy centre.

Observatory (APO) 3.5-m telescope. They found that the Hδ EWs were largest at the galaxy centre, although strong Hδ was significantly extended towards the outside of the galaxies (>4 kpc). Later, Yagi et al. (2006) observed a nearby E+A galaxy with a red companion galaxy at the same redshift (z = 0.033) with the Faint Object Camera and Spectrograph (FOCAS), a long-slit spectrograph, on the Subaru telescope. The spatially resolved spectra showed that the Hδ EWs were also strongest at the centre, but extended over ~5 kpc.
Swinbank et al. (2005) observed an H\(\alpha\)-strong galaxy with a weak [O\(\text{II}\)] emission from the Goto et al. (2003c) catalogue, and found that A stars are widely distributed across the system and are not centrally concentrated. Note, however, that this galaxy had a weak emission in [O\(\text{II}\)] (4.1 Å), and thus cannot be called an E+A galaxy in our definition. Yamauchi & Goto (2005) found that a significant number of E+A galaxies exhibit a positive slope of radial colour gradient (bluer gradient towards the centre), consistent with the hypothesis that E+A galaxies are caused by merger/interaction, having undergone a centralized violent starburst. All this work seems to be still affected by random noise possibly coming from sample selections, and possibly from errors in the measurements. However, the majority of works, including this work, seem to be advancing in a certain direction; that is, the post-starburst phenomenon is centrally concentrated in most cases, and significantly extended to a few kpc, consistent with the theoretical prediction for a merger/interaction remnant. These results are unique in not using information on the global/external properties of E+A galaxies but yet reaching similar conclusions about the origin of E+A galaxies. For example, Goto (2005) found an excess in the number of companion galaxies of E+A galaxies, concluding that it is evidence of merger/interaction. Many authors have reported disturbed morphologies of E+A galaxies, pointing to the merger/interaction origin (Oegerle, Hill & Hoessel 1991; Blake et al. 2004; Liu et al. 2007).

It has often been thought that E+A galaxies are altered by ram-pressure stripping in a galaxy cluster environment, as represented by the Butcher–Oemler effect (e.g. Butcher & Oemler 1978; Goto et al. 2003a; Goto 2003). However, our results suggest that ram-pressure stripping may not be the cause. Alternatively, passive spiral galaxies (Couch et al. 1998; Poggianti et al. 1999; Goto et al. 2003b; Yamauchi & Goto 2004) may be affected by ram-pressure stripping in galaxy cluster environments.

Regarding the work that found a flat, not centrally concentrated H\(\alpha\) radial profile (Pracy et al. 2005; Swinbank et al. 2005), this implies that there might be multiple physical mechanisms for creating E+A galaxies (e.g. ram-pressure stripping). In particular, E+A galaxies in Pracy et al. (2005) are in a high-redshift galaxy cluster, and thus there is a significant environmental difference from our sample of field E+A galaxies. Note, however, that these samples often lack information on [O\(\text{II}\)] or the H\(\alpha\) emission line, which emphasizes the importance of careful sample selection requiring no emission in either [O\(\text{II}\)] or H\(\alpha\). Another possible reason is the luminosity difference. In the last column of Table 1, we list the absolute magnitudes of our target galaxies in the \(r\) band. The \(k\)-correction is applied using Blanton et al. (2003a, v.3.2). The absolute magnitudes range from \(-21.7\) to \(-23.0\), which are brighter than the \(M_\bullet^\text{c} = (-21.2\) in our cosmology) of local galaxies (Blanton et al. 2003b). The reason why our target galaxies are luminous is partly because of our selection of apparently brighter galaxies and partly because of the flux-limited nature of the SDSS. However, it is also possible that nearby E+A galaxies may be intrinsically luminous. It is important to investigate the luminosity/mass distribution of local E+A galaxies, and such a study is in progress (Inami et al., in preparation). The galaxy in Swinbank et al. (2005) is taken from our sample (Goto et al. 2003c; Goto 2007b), and has an absolute magnitude of \(M_\text{r} = -22.32\). The galaxies in Pracy et al. (2005) have \(18.4 < R < 20.3\) at \(z = 0.32\). Therefore, the expected range of absolute magnitudes is \(-21.4 < M_\text{r} < -20.5\) (the colour conversion in Fukugita, Shimasaku & Ichikawa 1995 was used). Thus, they are significantly less luminous galaxies, which may be more vulnerable to gas stripping in the cluster environment because of their smaller gravitational potential. An IFS observation of less luminous nearby E+A galaxies would shed more light on the subject.

In Figs 1(d), 2(d) and 4(d), we have shown the ratio of H\(\alpha\)-to-continuum in two-dimensional images. Interestingly, Figs 1(d) and 4(d) show a possible shift of H\(\alpha\) absorption towards the south-west (although it is centrally concentrated when radially averaged). In Fig. 4(d), the darkest region inside a ring-like structure at the centre of the galaxy is slightly shifted towards the south-west direction. No shift is observed in Fig. 2(d) for J1656. Curiously, the directions of the shifts observed for J2102 and J2337 coincide with those of the tidal tails seen in Figs 1–4 (panels a). In Fig. 1(a), there is a possible tidal tail extending in the south-west direction. In Fig. 4(a), there is an obvious tidal tail from the north-east to the south-west. The coincidence of these post-starburst regions with the direction of the tidal tails suggests that the dynamical merger/interaction might have played an important role in forming the post-starburst regions in these galaxies. Although details of the coincidence need to be verified with numerical simulations, this demonstrates the power of the Kyoto3DII in investigating the two-dimensional structure of post-starburst regions.

We have to be careful of a possible selection effect. Our E+A selection is based on the SDSS fibre spectrograph, which has a diameter of 3 arcsec (i.e. by default, our E+A galaxies have strong H\(\alpha\) absorption at the centre of the galaxy). Therefore, in our sample, we do not find a galaxy with a post-starburst ring, or with a post-starburst region only at the edge of a spiral arm. This bias is especially strong for nearby galaxies at \(z < 0.05\). Fortunately in this work, because of the wavelength coverage of the instrument, the observed galaxies have larger redshifts of 0.078, 0.093 and 0.100, and thus are relatively immune from this aperture bias (see fig. 5 of Goto et al. 2003d; Goto 2007b). In addition, immediately after the truncation in the stripping model, the simulation predicts a flat H\(\alpha\) profile, which can be found very well in our sample. It is one of our important results that we did not find such E+A galaxies in our sample.

6 CONCLUSIONS

We have observed three nearby E+A galaxies with the Kyoto3DII IFS. The spatially resolved spectra show that the strong Balmer absorption characteristic of E+A galaxies is concentrated around the galaxy centre, but is spatially extended to a scale of a few kpc. These results support a scenario where the infalling gas caused by galaxy–galaxy merging may create the post-starburst phase in the centre of the galaxy. We have found that the extensions of the post-starburst regions coincide with the direction of the tidal tails for J2102 and J2337, possibly supporting the merger/interaction scenario. We have confirmed that an object near to J1656 was at the same redshift, and thus is physically associated. However, interestingly, this nearby companion is a star-forming galaxy, and not an E+A galaxy. This implies that the galaxy–galaxy merging may create E+A galaxies under certain conditions, but not all merging galaxies will evolve into E+A galaxies. We have found that the H\(\delta\) and H\(\gamma\) absorption lines show different radial trends, which are difficult to interpret with the age/metallicity mixture.

ACKNOWLEDGMENTS

We thank the anonymous referee for many insightful comments, which significantly improved the paper. We are grateful to Yoshiko Okita for valuable help in preparing the observations. We thank Chisato Yamauchi for useful discussions.
The use of the UH 2.2-m telescope for the observations is supported by the National Astronomical Observatory of Japan (NAOJ). The research was financially supported by the Sasakawa Scientific Research Grant from the Japan Science Society. This research was partially supported by the Japan Society for the Promotion of Science through Grant-in-Aid for Scientific Research 18B04047.

Funding for the creation and distribution of the SDSS Archive has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Aeronautics and Space Administration, the National Science Foundation, the United States Department of Energy, the Japanese Monbukagakusho, and the Max Planck Society. The SDSS website is http://www.sdss.org/.

The SDSS is managed by the Astrophysical Research Consortium (ARC) for the Participating Institutions. The Participating Institutions are the University of Chicago, Fermilab, the Institute for Advanced Study, the Japan Participation Group, Johns Hopkins University, Los Alamos National Laboratory, the Max-Planck-Institute for Astronomy (MPIA), the Max-Planck-Institute for Astrophysics (MPA), New Mexico State University, University of Pittsburgh, Princeton University, the United States Naval Observatory and the University of Washington.

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APPENDIX A: DIVISION OF TWO LOW SIGNAL-TO-NOISE RATIO IMAGES

In Figs 1–4 (panels c), we have shown the ratio of the Hα image to the continuum image. However, a straight division of two images does not return a correct ratio, as both images have a large uncertainty. In this section, we explain the details of the method we used to derive the ratio.

We estimate the Hα-continuum ratio in the low signal-to-noise region as follows. We call the Hα (or Hγ) image A, and the continuum image B, and we estimate A/B. The observed value of images A and B at a certain pixel (a and b, hereafter) follow some distribution whose typical values are $\delta_a$ and $\delta_b$. The problem is how to estimate $\delta_a/\delta_b$ from a, b and other information.

Formalizing the problem, we assume that a and b follow the normal distribution with variance $\sigma_a^2$ and $\sigma_b^2$. The variance of each distribution is estimated, assuming that the primary sources of the variation are the sky noise and readout noise.
The prior distributions of \( a_0 \) and \( b_0 \) are estimated as

\[
P(a_0)da_0 = \frac{1}{\sqrt{2\pi\sigma_a}} \exp\left[-\frac{(a_0-a)^2}{2\sigma_a^2}\right]da_0, \quad (A1)
\]

\[
P(b_0)db_0 = \frac{1}{\sqrt{2\pi\sigma_b}} \exp\left[-\frac{(b_0-b)^2}{2\sigma_b^2}\right]db_0. \quad (A2)
\]

The prior distribution of the ratio, \( r = a_0/b_0 \), is then calculated as

\[
P(r)dr = \frac{1}{2\pi\sqrt{\sigma_a\sigma_b}} \left\{ \int_0^\infty x \exp\left[\frac{(x-b)^2}{2\sigma_b^2}\right]dx \right\} \exp\left[\frac{(r-x-a)^2}{2\sigma_a^2}\right]dr.
\]

This distribution is not the normal distribution. We therefore adopted the median as the typical value of the distribution and took the upper and lower 15 per cent percentiles as the errors of the estimation.

An example of the distribution is shown in Fig. A1. When \( a = 0.5 \), \( b = 1.0 \) and \( \sigma_a = \sigma_b = 1 \), the estimated ratio is 0.75 ± 0.2. It should be noted that simple division, \( a/b = 0.5 \), is not the best estimation for \( a_0/b_0 \).

**APPENDIX B: A SYSTEMATIC TEST: AN EQUIVALENT WIDTH PROFILE OF A STANDARD STAR**

In Section 4, we showed that the H\(\delta\) and H\(\gamma\) EWs were larger at the centre of E+A galaxies, but extended to the scale of a few kpc. However, it is important to check that this result is not caused by any systematic effect. In this section, we perform the same analysis as in Section 4 on a standard star, BD+284211, which we observed just before the galaxy J2102. The observed position of the standard star is very close to that of J2101 (within a few lenslets), and therefore the star allows us to check any position-dependent systematic effect on the lenslet, if any exists.

In Fig. B1, we show the spectra of BD+284211 in the central 1.5 lenslet radius region, and in the annuli of the 1.5–3, 3–4.5 and 4.5–6 lenslet regions from the top to the bottom as in Figs 1, 2 and 4. The spectra are smoothed using a five-pixel box. H\(\beta\), H\(\gamma\) and He \(\Pi\) (4542 and 4686 Å) lines are marked.

In Fig. B2, we show the H\(\gamma\) EW of each spectrum as a function of radius (from the centre of the star). The H\(\delta\) line of the star is not covered with our grism/filter. The figure shows that the H\(\gamma\) EW does not depend on the position of the lenslet, and remains at \( \sim 3.3 \) Å. This test demonstrates that the radial trends we observed in Figs 1, 2 and 4 are not caused by any position-dependent systematic effect of the lenslet.

**APPENDIX C: POSSIBLE DIFFERENT RADIAL CHANGE OF H\(\delta\) AND H\(\gamma\) EQUIVALENT WIDTHS**

We would like to mention an interesting radial change of H\(\delta\) and H\(\gamma\) EWs. In Figs 1(d) and 4(d), the H\(\delta\) EW is highest at the first (innermost) bin, and then declines immediately at the second bin to remain flat towards the third bin (2–3 kpc). However, the H\(\gamma\) EW remains large at the first and second bins, and then suddenly declines at the third bin. Although we do not include J1656 in this discussion because of the larger errors, the feature is common to two galaxies (J2102 and J2337), and thus may originate from the nature of E+A galaxies. The H\(\delta\) and H\(\gamma\) EWs have been known to decrease at a
Figure C1. The Hγ EW is plotted against the Hδ EW for inner three data points of J2102 (filled circles), J1656 (squares) and J2337 (triangles). The solid (black) and dotted (blue) and dot-dashed (cyan) lines are SED models (Bruzual & Charlot 2003) with an instantaneous burst with Z = 0.2, 0.5 and 0.08, respectively. The long-dashed (green) and dashed (pink) lines show hybrid models where 5 or 50 per cent mass of instantaneous burst population is added on the 10-Gyr-old stellar population. Open circles on the models show ages of 250, 500 and 1000 Myr. The 5 per cent burst model shows little deviation from the other models because of the presence of the old stellar population. However, the deviation is only by 1 Å, which is not significant enough to explain the observed change of the Hδ/Hγ relation (by >2 Å).

In summary, the observed trend in the Hδ/Hγ relation is difficult to reproduce in the current framework of spectral energy distribution (SED) models, either by the metallicity change or by the mixture of stellar populations of different age. The only large change in Hδ/Hγ can be brought about by the age. However, the change is limited to a narrow locus along the models (Hγ = 1.2 × Hδ − 4.3), which does not agree with the observed data. To fully understand the observed radial change, both more sophisticated SED models and more IFS data with better signal-to-noise ratio are required.