Spatially resolved medium resolution spectroscopy of an interacting E+A (post-starburst) system with the Subaru Telescope

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ABSTRACT

We have performed spatially resolved medium resolution long-slit spectroscopy of a nearby E+A (post-starburst) galaxy system, SDSS J161330.18+510335.5, with the FOCAS spectrograph mounted on the Subaru Telescope. This E+A galaxy has an obvious companion galaxy 14 kpc in front with the velocity difference of 61.8 km s\(^{-1}\). Both galaxies have obviously disturbed morphology. Thus, this E+A system provides us with a perfect opportunity to investigate the relation between the post-starburst phenomena and galaxy–galaxy interaction. We have found that the H\(\delta\) equivalent width (EW) of the E+A galaxy is greater than 7 Å across a galaxy wide (8.5 kpc) with no significant spatial variation. The E+A galaxy has a weak [O\(\text{III}\)] emission (EW \(\sim\) 1 Å) offset by \(\sim\) 2.6 kpc from the peak of the Balmer absorption lines. We detected a rotational velocity in the companion galaxy of \(>\) 175 km s\(^{-1}\). The progenitor of the companion may have been a rotationally supported, but yet passive S0 galaxy. We did not detect significant rotation on the E+A galaxy. A metallicity estimate based on the r–H colour suggests \(Z = 0.008\) and 0.02, for the E+A and the companion galaxies, respectively. Assuming these metallicity estimates, the age of the E+A galaxy after quenching the star formation is estimated to be 100–500 Myr, with its centre having a slightly younger stellar population. The companion galaxy is estimated to have an older stellar population of \(>\) 2 Gyr of age with no significant spatial variation.

These findings are inconsistent with a simple picture where the dynamical interaction creates infall of the gas reservoir that causes the central starburst/post-starburst. Instead, our results present an important example where the galaxy–galaxy interaction can trigger a galaxy-wide post-starburst phenomenon.

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

1 INTRODUCTION

It has long been known that galaxies have varieties of morphology; Edwin Hubble was the first to classify galaxies into the so-called Hubble tuning fork, which mainly consists of elliptical, lenticular, spiral and barred spiral (Hubble 1926). Because of the similarity and gradual change of galaxy properties along the Hubble tuning fork, people speculated that this might be an evolutionary sequence, and extensively studied the galaxy evolutionary sequence since the dawn of extragalactic astronomy (e.g. Roberts & Haynes 1994). However, it is still not very well understood what physical mechanism drives the galaxy evolution, creating diverse galaxy properties such as in the Hubble tuning fork. As galaxies in a transition phase, one of the key populations in elucidating this galaxy evolution is so-called E+A galaxies.

Galaxies with strong Balmer absorption lines without any emission in [O\(\text{II}\)] or H\(\alpha\) 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 on-going star formation as non-detection in the [O\(\text{II}\)] emission line indicates. Therefore,
E+A galaxies have been interpreted as post-starburst galaxies, that is, galaxies which truncated the 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 found that E+A galaxies have an α-element excess (Goto 2007a), which also supported the post-starburst interpretation of E+A galaxies. However, the reason why they started the starburst, and why they abruptly stopped the starburst remains one of the mysteries in galaxy evolution. Since a post-starburst is an important stage of the overall galaxy evolution in the Universe, it is important to investigate the physical origin of E+A galaxies.

At first, E+A galaxies are found in cluster regions, especially at higher redshift (Sharples et al. 1985; Laverty & Henry 1986; Couch & Sharples 1987; Broadhurst, Ellis & Shanks 1988; Fabricant, McClintock & Bautz 1991; Belloni et al. 1995; Barger et al. 1996; Couch et al. 1998; Fisher et al. 1998; Morris et al. 1998; Dressler et al. 1999; Poggianti et al. 1999; Tran et al. 2003; Dressler et al. 2004; Tran et al. 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 & Nagashima 1999; Fujita et al. 1999; Quilis, Moore & Bower 2000; 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, providing statistical evidence that a dynamical merger/interaction could be the physical origin of field E+A galaxies. Dynamically disturbed morphologies of E+A galaxies also support this scenario (Yamauchi & Goto 2005; Liu et al. 2007).

To understand whether the origin of E+A is cluster-related or merger-driven (or both), independent evidence on the origin of E+A galaxies has been awaited. The previous work mentioned above has been 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 within each E+A galaxy. For example, a centrally concentrated post-starburst region is expected to be found in the case of the 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 the E+A galaxy contains important and independent clues on the physical origin of E+A galaxies (e.g. Pracy et al. 2005; Swinbank et al. 2005). In this series of papers (Yagi & Goto 2006; Yagi, Goto & Hattori 2006; Goto et al. 2008), we try to obtain such independent hints on the origin of E+A galaxies by revealing the internal structure of E+A galaxies. In this paper, we focus on spatially resolved long-slit scan spectroscopy of a nearby E+A system, J1613+5103. This E+A galaxy previously studied by Yagi et al. (2006) has an obvious companion galaxy in front (Fig. 1), and thus provides us with a perfect opportunity to reveal the relation between the post-starburst phenomena and galaxy–galaxy interaction. The colour gradient of the E+A galaxy was studied in detail by Yamauchi & Goto (2005). Compared to our own previous work (Yagi & Goto 2006; Yagi et al. 2006; Goto et al. 2008), this time we obtained E+A spectra with higher resolution and better signal-to-noise ratio (S/N) taking advantage of the Subaru Telescope.

Unless otherwise stated, we adopt the WMAP (Wilkinson Microwave Anisotropy Probe) cosmology: (h, Ω_m, Ω_Λ) = (0.7, 0.3, 0.7) (Komatsu et al. 2008).

### 2 Sample Selection

We selected our target E+A galaxy, SDSS J161330.18+510335.5, from Goto (2005, 2007b), who presented a catalogue of 564 E+A galaxies based on the ~670 000 galaxy spectra of the Sloan Digital Sky Survey (SDSS) (Adelman-McCarthy et al. 2006). The galaxy has extremely strong Balmer absorption lines with an Hδ EW of 7.37 Å, with significant emission in [O ii] or Hz within the 3 arcsec diameter of the SDSS fibre spectrograph. These are representative characteristics of an E+A galaxy and indicate that this galaxy is in the post-starburst phase.

The E+A galaxy has an apparent companion galaxy, SDSS J161332.23+510342.9, in front. Note that the companion galaxy is perhaps as massive as the E+A galaxy (see Section 4.3), even though we call it a ‘companion’. Previously, Yagi et al. (2006) confirmed that the companion galaxy is at the same redshift, i.e. these two galaxies are dynamically interacting. Along with the large apparent size of ~20 arcsec on the sky, this E+A system is a perfect target for spatially resolved spectroscopy.

We present the basic properties of the E+A and companion galaxies in Table 1, where measured quantities such as positions, redshift, magnitudes in g and r, and Petrosian radius are taken from the SDSS catalogue. Magnitudes are dereddened (for Galactic extinction) Petrosian AB magnitude in g and r band.

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1 Absorption lines have a positive sign throughout this paper.
Table 1. Target properties.

| Object | Redshift | $s_{AB}$ | $r_{AB}$ | Petro Rad in r(arcsec) | Exposure time (min) | Observing date (HST) | $M_r$ |
|--------|----------|----------|----------|-------------------------|---------------------|----------------------|-------|
| SDSS J161330.18+510335.5 (E+A) | 0.0341 ± 0.0009 | 15.86 | 15.38 | 19.6 | 50 (Core), 60 (North) | 2005 July 29 | −20.5 |
| SDSS J161332.23+510342.9 (Companion) | 0.0339 ± 0.001 | 15.89 | 15.09 | 4.6 | 50 (Core), 60 (North) | 2005 July 29 | −20.7 |

3 OBSERVATIONS

Observations were carried out on 2005 July 29, with the FOCAS spectrograph (the Faint Object Camera and Spectrograph; Kashikawa et al. 2002) on board the Subaru Telescope. We performed long-slit spectroscopy with the slitwidth of 1.0 arcsec on the positions A (core) and B (north) of Fig. 1. Both slits cover the E+A galaxy and the companion galaxy simultaneously. We used the VPH350 grism, which provides us with a wavelength coverage of 3800–5250 Å, with a resolution of $R \sim 1600$. We used 3 × 1 binning mode, giving a pixel size of 0.311 arcsec pixel$^{-1}$ in a spatial direction. The seeing was $\sim 1.6$ arcsec based on a bright star we simultaneously placed on the slit. The exposure time was 600 + 1200 × 2 s for slit A (centre), and 1200 × 3 s for slit B (north). We moved the target along the slit $\pm 2$ arcsec between the exposures to remove systematic effects.

The data reduction was performed with the standard procedure with IRAF; overscan subtraction, distortion correction, and flat fielding were performed. We used a Th–Ar lamp for the wavelength calibration. Then, frames were combined after the spatial shifts were accounted for. Background subtraction and the extraction of the spectra were carried out in a standard manner. A standard star HZ44 observed with the 2.0 arcsec slit was used for the flux calibration. In Fig. 2, we show spectra of the two galaxies obtained from each slit. It is immediately noticed that the E+A galaxy has strong Balmer absorption lines along with an A-star like continuum. The spectra of the companion galaxy are dominated by old stars with deep Ca H&K absorptions. Both galaxies have weak emissions in [O II] and possibly in [O III], which will be discussed later. Measured redshifts based on [O II], Ca H&K lines are 0.0341 ± 0.0009 and 0.0339 ± 0.001 for the E+A and companion, respectively. These values are consistent with the redshift measured by the SDSS (0.034 ± 0.00012) and by Yagi et al. (2006). The relative velocity is 61.8 km s$^{-1}$. 1 arcsec corresponds to 0.66 kpc at this redshift.

One of the main purposes of this observation was to carry out spatially resolved analysis. For this purpose, we have divided the 20.3–25.5 arcsec of aperture into nine equally spaced bins for each spectrum. And thus the size of each bin (2.3–2.8 arcsec) is larger than the point spread function size of 1.6 arcsec. In Fig. 3, we show the spectrum of each bin for both galaxies.

Using these spectra, we measured EWs of [O II], H$\delta$, H$\gamma$, H$\beta$ and [O III] lines using the flux summing technique in Goto et al. (2003). The wavelength ranges used are presented in Worthey & Ottaviani (1997) and Miller & Owen (2002). The strength of the 4000 Å break (D4000) was measured using the definition in Stoughton et al. (2002).
Figure 3. Spectra in each aperture. Right-hand panels are for the E+A galaxy. Left-hand panels are for the companion galaxy. Bottom panels are from the core. Top panels are shifted by 2 arcsec to the north. Each spectrum is spatially divided into nine equally spaced bins. In each panel, these nine spectra are normalized by the peak flux and aligned in the vertical direction (thus, the flux scale is arbitrary). The spectra are shifted to the rest-frame and smoothed using a 5-pixel box.

4 RESULTS

4.1 Line flux profile

In Fig. 4, we show normalized flux profiles of the measured lines. Profiles are normalized at a peak flux. Fluxes for absorption lines are measured by integrating the amount of absorption under the fitted-continuum, i.e. they are pseudo-flux measured in a similar way to emission line fluxes. The right two panels show the profile for the E+A galaxy. Absorption lines (Hδ, Hγ and Hβ) connected with the solid lines show a perfect agreement with each other. Interestingly, the [OIII] emission line peaks 4 arcsec away from the absorption peak on the bottom-right panel and −4 arcsec away on the top-right panel, possibly indicating that the current star formation is going on at a different location from the post-starburst region. [OII] emission is too noisy to locate the peak of the profile.

For a companion galaxy in the left-hand panels, only Hβ (magenta squares) and [OII] (green filled circles) have enough S/N to measure profiles. The peaks of these two profiles agree with each other. The [OII] emission shows a slightly extended profile.

4.2 EW profile

In Fig. 5, we present the EW distribution of three absorption lines (Hδ, Hγ and Hβ) and two emission lines ([O II] and [O III]) for the E+A/companion galaxies in the core/north spectra. The right-hand panels show EWs for the E+A galaxy. Absorption lines (Hδ, Hγ and Hβ) connected with the solid lines show a perfect agreement with each other. Interestingly, the [OII] emission line peaks 4 arcsec away from the absorption peak on the bottom-right panel and −4 arcsec away on the top-right panel, possibly indicating that the current star formation is going on at a different location from the post-starburst region. [OII] emission is too noisy to locate the peak of the profile.

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4.3 Rotation

With a resolution of $R \sim 1600$, we have a chance to measure the rotational velocity of galaxies. We fit a Gaussian to the Hδ (absorption) line, to measure the red/blueshifted central wavelength. On other occasions, emission lines such as [O II] or [O III] are preferred for this exercise. In our particular case, however, the Hδ (absorption) line is much stronger than the emission lines, providing us with a better measurement of the rotation curve. We visually inspected the
Figure 4. Normalized flux profiles. The right-hand panels show the normalized flux profiles for the E+A core (lower) and north (upper) spectra. The left-hand panels show the normalized flux profiles for the companion core (lower) and north (upper) spectra. The diamond (red), triangle (orange), and square (pink) symbols are for Hδ, Hγ, and Hβ, respectively. These absorption lines are connected with the solid lines. The cross (blue) and filled (green) circle are for [OIII] and [OII] emission lines, which have positive sign in this plot. The emission lines are connected with the dotted lines. The abscissa is shifted so that the Hδ flux peaks at $X = 0$. 1 arcsec corresponds to 0.66 kpc at this redshift.

Figure 5. EW profiles. The right-hand panels show the EW profiles for the E+A core (lower) and north (upper) spectra. The left-hand panels show the EW profiles for the companion core (lower) and north (upper) spectra. The diamond (red), triangle (orange) and square (magenta) symbols are for Hδ, Hγ, and Hβ, respectively. These absorption lines are connected with the solid lines. The cross (blue) and filled (green) circle are for [OIII] and [OII] emission lines, which have positive sign in this plot. The emission lines are connected with the dotted lines. 1 arcsec corresponds to 0.66 kpc at this redshift.
goodness of the Gaussian fit and only spectra where the line has sufficient S/N are used.

In Fig. 6, we show the recession velocity from the Hδ line. In the right-hand panel, the diamonds (blue) and triangles (green) are for the core/north E+A spectra. There may be a slight sign of the rotation of \( \sim 50 \text{ km s}^{-1} \) in the core spectra (blue diamonds). However, this is below the resolution of the spectra, and the trend cannot be recognized in the north spectra (green triangles). Therefore, we do not claim a rotation of the core/north E+A spectra.

The squares (magenta) and crosses (red) in the left-hand panel of Fig. 6 are for the companion galaxy in the core/north. A clear rotation curve is found from the position of \( X = -6 \) to \( X = +3 \) arcsec. The rotation observed for the companion galaxy is greater than \( 175 \text{ km s}^{-1} \).

It is interesting to find no significant rotation for a galaxy that has just experienced a starburst (E+A). This suggests the following possibilities: (i) the galaxy–galaxy dynamical interaction destroyed the rotation of the galaxy (however, the companion galaxy has rotation); (ii) the progenitor of the E+A galaxy was not a rotationally supported disc galaxy, although it possessed enough gas to create a starburst; or (iii) the rotation of the E+A galaxy is face-on although we do not see an obvious face-on disc in Fig. 1.

It is also puzzling that the companion galaxy whose spectra look like that of an elliptical galaxy has rotational velocity. One possibility is that the rotational velocity originates from the dynamical interaction, although no rotation was found for the E+A galaxy. Another possibility is that in Fig. 1, the core of the companion galaxy is slightly extended towards the north-east direction, implying a possible position-angle of the former disc component. Thus, the companion galaxy may have been a rotationally supported disc galaxy before the dynamical interaction started.

We also tried to measure the velocity dispersion for both the E+A and the companion galaxies. Our method is similar to that utilized by the SDSS spectroscopic pipeline: first we mask out possible emission lines, then the rest of the spectra are fitted with the combination of eigenspectra with varying velocity dispersion. The measured velocity dispersions are \( 279 \pm 49 \) and \( 224 \pm 31 \text{ km s}^{-1} \) for the E+A and companion galaxies, respectively. The results suggest that the galaxies have comparable mass, and thus the system is experiencing an equal-mass (major) merger with the mass ratio close to 1. The derived mass ratio is consistent with Bekki, Shioya & Couch (2001)’s prediction that requires a mass ratio of \( > 0.3 \) to create an E+A galaxy.

4.4 Metallicity estimate

Next, we would like to estimate the age and burst strength (stellar mass ratio of young population to old stellar population) of these two galaxies by comparing observational data with models. To do this, however, we first need to estimate the metallicity of these galaxies since there is a well-known fact that galaxy age and metallicity are degenerate in optical colour or spectra. This age–metallicity degeneracy can be lifted when you have near-infrared (NIR) photometry in hand; an optical–NIR colour such as \( V - K \) is a measure of the temperature of its red giant branch. The temperature is strongly dependent on metallicity but has little sensitivity to age (Puzia et al. 2002; Brodie & Strader 2006; Cantiello & Blakeslee 2007). In Fig. 7, we plot \( r - H \) colour against \( r - i \) colour. Optical colours are from the SDSS. The \( H \)-band image was taken with the SQUID NIR camera on board the Kitt Peak National Observatory telescope on the night of 2006 June 4. A complete analysis of these data will be presented elsewhere. The seeing sizes were similar.
among $r$, $i$ and $H$ bands. Fluxes are measured in a fixed aperture of 3 arcsec at the centre.

In Fig. 7, overplotted lines are the spectral energy distribution (SED) models; we constructed model SEDs with Bruzual & Charlot (2003, hereafter BC03), using the extinction law by Cardelli, Clayton & Mathis (1989), and a Salpeter initial mass function (IMF). Metallicities are changed in the range of $0.0004 \leq Z \leq 0.02$. The model galaxies evolve for 10 Gyr with an exponentially decreasing star formation rate ($\tau = 1$ Gyr), and then a secondary instantaneous burst occurs; the dots represent 100, 200, 300, 500 Myr and 1 Gyr of time after the instantaneous burst.

This $r - i$ versus $r - H$ diagram is advantageous in determining the metallicity of galaxies when a spectrum does not cover Fe or Mg lines. Three colours ($r$, $i$, $H$) are carefully chosen so that age, burst strength and dust extinction are degenerate in one (straight) direction perpendicular to the metallicity variation. The only possible alternative is $r - z - K_s$ colour among general broad-band optical–NIR filters. In other choices of colours, the models curve and overlap with each other. In fact in Fig. 7, age vectors (lower-left to upper-right in the figure) are almost perpendicular to the metallicity change. The models with different burst strengths (we checked $50, 30, 10, 5, 3$ and 1 per cent) almost overlap with each other, i.e. no degeneracy with the metallicity. Moreover, the dust-reddening vector (shown with an arrow in the figure) is almost parallel to the aging vector in this diagram. Therefore, the $r - i$ versus $r - H$ diagram provides us with a useful tool to measure metallicity of nearby post-starburst galaxies whose young population is 100 Myr–1 Gyr.

Measured colours of the E+A galaxy and the companion galaxy are shown with the black dots in Fig. 7. The E+A and companion galaxies are better described with a metallicity of $Z = 0.008$ (i.e. 0.4 x solar metallicity) and 0.02, respectively. We will assume $Z = 0.008$ in the next section to estimate the E+A galaxy age.

In this paper, these colour-based metallicity measurements are merely meant to aid the age determination in the following section. A more careful treatment such as high S/N spectroscopy covering Fe and Mg lines is needed if one wishes to obtain physical implications based on the metallicity measurements.

4.5 Age estimate

In Fig. 8, we plot H$\alpha$ EW against the strength of the 4000 Å break (D4000). This diagram has been used as a good tool to estimate age, stellar mass, and star formation history of galaxies (e.g. Goto 2003; Kauffmann et al. 2003; Yagi et al. 2006). Symbols for data points are the same as in Fig. 6. We overplot population synthesis models of BC03 with a Salpeter IMF and metallicity of $Z = 0.008$ (see Section 4.4). We have checked that a small change in metallicity $Z = 0.008$–0.02 does not affect the discussion below. Over the 10 Gyr old stellar population with an exponentially decaying star formation rate ($\tau = 1$ Gyr), we added 5, 10 and 50 per cent (in terms of stellar mass) of instantaneous starburst population. The 100 per cent burst in the figure is pureburst with no underlying old stellar population. In each model, we marked 0.1, 0.25, 0.5 and 2 Gyr of ages (after the instantaneous starburst) with filled circles. These are the same models as used in Yagi et al. (2006).

By comparing models with data, E+A galaxies are most consistent with the 30 per cent burst model with an age of 250 Myr although burst strengths of 5–30 per cent with an age of 100–500 Myr are allowed within the error. It seems that the core of the E+A galaxy has a slightly younger age (−100 Myr) than the outskirts (−500 Myr). This trend is more consistent with the age difference than the difference in burst fraction, suggesting that the galaxy core has experienced a starburst more recently. One end facing the companion seems to have a larger burst fraction (>30 per cent) than the other end (10 per cent). In any case, the comparison suggests that the E+A galaxy is in its young phase (−250 Myr) of the post-starburst. On the other hand, the companion galaxy is consistent with a much larger age of >2 Gyr. Although the companion galaxy has weak [O II] emission, this indicates that major star formation activity of the companion galaxy ceased well in advance of the current galaxy merger/interaction.

In Fig. 9, we compare [O II] EWs and H$\alpha$ EWs. Symbols are the same as in the previous figure. Overplotted models are from Bekki et al. (2003). Their dusty-starburst and dust-free merger models of equal mass are shown with filled circles and asterisks, respectively. We marked the ages (after the burst) of 40 Myr–1.5 Gyr. The E+A galaxy is consistent with ∼400 Myr of age of the dusty-starburst model after the starburst. The data points of the companion galaxies (magenta squares and red crosses) deviate from the models, and cannot be explained within the model assumption of an equal mass merger of gas-rich discs. Perhaps J1613+5103 is a wet–dry merger system, where the dry galaxy (companion) had a little remaining gas to induce star formation.

5 DISCUSSION

5.1 Comparison to previous work

In this subsection, we summarize previous work on spatially resolved spectroscopy of E+A galaxies, and compare it to 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 APO 3.5 m telescope. They found that the post-starburst region is as extended as the old population with no significant age gradient along the radius, concluding that the post-starburst in the E+A is a galaxy-wide phenomenon. Swinbank et al. (2005) observed an H\textsc{\alpha}-strong galaxy with weak [O\textsc{ii}] emission from the Goto et al. (2003) catalogue, and found that A-type stars are widely distributed across the system and are not centrally concentrated. Note, however, that this galaxy had weak emission in [O\textsc{ii}] (4.1 Å), and thus cannot be called an E+A galaxy in our definition.

It is important to keep in mind that these studies each had their own biases in sample selections, observations and analysis methods. In particular, earlier samples often lacked information on H\textsc{\alpha}, resulting in inviting contamination from H\textsc{\alpha} emitting galaxies up to 52 per cent (see Goto et al. 2003). The majority of the above work, however, concluded that the post-starburst phenomenon was centrally concentrated in most cases, and significantly extended to a few kpc, being consistent with a theoretical prediction for a merger/interaction remnant. These results were unique in that without using information on the global/external properties of E+A galaxies, they reached a similar conclusion on 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 the merger interaction. Many authors 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).

However, our results may create a stir in the interpretation of previous work; the E+A system J1613+5103 is clearly a dynamically interacting system. In Yagi et al. (2006), we confirmed the result with deeper and more extended observations, and found that the post-starburst feature is extended to 8.5 kpc, instead of the centrally concentrated post-starburst region which was expected based on the merger–interaction scenario of the E+A origin. We discuss possible implications of our results in the next subsection.

The colour gradient of this E+A galaxy was studied in detail by Yamauchi & Goto (2005), who found that the $g - r$ and $r - i$ colours are bluer in the central region within 1.9 kpc (see their fig. 3, galaxy no. 1). While we found a flat, uniform H\textsc{\alpha} distribution of 5 kpc. In this work, we confirmed the result with deeper and more extended observations, and found that the post-starburst feature is extended to 8.5 kpc, instead of the centrally concentrated post-starburst region which was expected based on the merger–interaction scenario of the E+A origin. We discuss possible implications of our results in the next subsection.

5.2 Physical interpretation

In this series of papers (Yagi et al. 2006, and this work), we have found the following. Our target E+A galaxy, J1613+5103, has a companion galaxy 14 kpc away with a velocity difference of 61.8 km s$^{-1}$. Both the E+A and companion galaxies have disturbed morphology with the core and a fan-shaped region extended away from each other. With this evidence, there is little doubt that the system contains dynamically interacting galaxies. Age estimates based

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**Figure 9.** H\textsc{\alpha} EW is plotted against [O\textsc{ii}] EW. The diamonds and triangles are for the E+A core/north spectra, respectively. The squares and crosses are for the companion galaxy’s core/north spectra. Only data points with positive [O\textsc{ii}] EW (i.e. in emission) are used. Grey lines are major-merger models from Bekki et al. (2001) with ages (after the burst) of 40 Myr–1.5 Gyr. Asterisks and filled circles are for dust-free and dusty-starburst models, respectively.

**Figure 10.** The radial profile of the 4000 Å break (D4000). The diamonds and triangles in the right-hand panel are for the E+A core/north spectra. Only data points with positive [O\textsc{ii}] EW (i.e. in emission) are used. Grey lines are major-merger models from Bekki et al. (2001) with ages (after the burst) of 40 Myr–1.5 Gyr. Asterisks and filled circles are for dust-free and dusty-starburst models, respectively.
on the Hδ–D4000 (Fig. 8) or Hδ–[O ii] (Fig. 9) diagrams suggest ~250 Myr after the burst, being consistent with the early stage of a dynamical interaction. In addition, the existence of such a system presents an important example that a dynamical galaxy–galaxy interaction can create an E+A galaxy as a matter of fact, and that the companion galaxy of the E+A system does not have to be an E+A galaxy.

In Section 4, we found that the Hδ EW of the E+A galaxy is very strong with >7 Å in the entire galaxy with no obvious spatial trend, despite the fact that the galaxies are dynamically interacting. The results are inconsistent with the previously believed simplified picture: during a galaxy–galaxy interaction, the gas readily loses angular momentum due to dynamical friction, decouples from the stars, and inflows rapidly towards the merger nuclei (Barnes 1992; Barnes & Hernquist 1992, 1996; Mihos & Hernquist 1994, 1996), creating a central starburst, which could evolve into the E+A phase if the truncation of the starburst is rapid enough (Goto 2004). In this scenario, the galaxy is left with a central population of young stars and hence a radial distribution of Hδ EW which is highest in the centre and decreases rapidly with galactocentric radius (Bekki et al. 2005; Pracy et al. 2005).

This scenario was the basis of the spatially resolved observational work in the literature; Yagi & Goto (2006) and Goto et al. (2008) found centrally concentrated post-starburst regions (but significantly extended) in E+A galaxies, concluding that it is evidence of the merger origin of the E+A galaxies. In contrast, if stripping is the cause of the E+A phenomenon, the star formation is simultaneously and uniformly truncated throughout the entire disc, creating a flat, uniformly high Hδ EW profile (Pracy et al. 2005).

However, our results present an example where dynamical interaction also can create a flat, uniform radial distribution of the post-starburst region. The discovery complicates the picture: investigating a spatial distribution of the post-starburst region may not be a good way to investigate the origin of the E+A phenomenon. In the case of J1613+5103, an obvious companion is present, and thus it is easy to be judged as an interaction. However, if the minor-merger can also create such a flat profile, there is no way to distinguish from the stripping scenario. Our example cautions us that it is important to combine multiple information together to investigate the physical origin of E+A galaxies.

We also found that this system is likely to be an equal-mass merger based on the velocity dispersion. The result is consistent with Bekki et al. (2005) who predicted that at least a mass ratio of 0.3 is required to create an E+A galaxy through a dynamical galaxy merger simulation. It is important to measure the mass of more E+A companion galaxies to constrain the mass ratio required to create an E+A galaxy. An attempt to spectroscopically follow-up E+A companions is on-going (Yamauchi, Yagi & Goto 2008).

It is interesting that we found rotational velocity only in the companion galaxy (Fig. 6), which did not experience a starburst. This velocity could be caused by the dynamical interaction of the two galaxies. However, considering that these two galaxies have similar mass, and the other (E+A) does not have rotational velocity, it is more plausible that the progenitor of the companion galaxy was a rotationally supported disc galaxy. There is a hint of disc plane in Fig. 1. Considering that the companion galaxy did not have major star formation at least for the recent 2 Gyr (Fig. 8), the progenitor of the companion galaxy may have been a passive, rotationally supported S0 galaxy. It also means that for at least 2 Gyr, the galaxy can sustain the rotational velocity without continuing star formation activity.

But then, why does the E+A galaxy not show rotational velocity even though it has experienced the starburst? We have to keep in mind that the E+A could be face-on although we do not see an obvious face-on disc in Fig. 1. Since the rotational velocity of the companion galaxy is not destroyed by the dynamical interaction, it is not likely that the E+A galaxy had an initial rotation. But at the same time, E+A galaxies had experienced a starburst, therefore, they must have had a significant amount of gas, and possibly some star formation activity even before the starburst. Taking all these together, one possibility, assuming not face-on, is that the progenitor of the E+A galaxy in the case of J1613+5103 may have been a pressure-supported, star-forming elliptical galaxy, which is quite rare in the present Universe.

We found weak emission in [O ii] and [O iii] for both the E+A and companion galaxies. The finding of the [O ii] emission line is apparently inconsistent with our selection criteria of E+A galaxies with no significant [O ii] or Hβ emission ([O ii] EW <2.5 Å and Hβ EW <3.0 Å). However, the detected emission is weak with EW~1 Å for both [O ii] and [O iii]. Using the prescription for the [O ii] line given in Hopkins et al. (2003), the star formation rate of this galaxy is 0.06 M⊙ yr⁻¹, which is small enough to be negligible compared with the post-starburst population. Our spectra have a higher resolution of R~1600 than those of the SDSS and Yagi et al. (2006). When we smooth the spectra to the resolution of the SDSS, the emission lines become almost invisible. This is perhaps why previous spectra did not detect the emission, and for the same reason, we still regard the galaxy as an E+A galaxy in the post-starburst phase.

The location of the emission lines in the E+A galaxy is puzzling. The [O ii] emission lines do not have enough S/N to probe the location. But the [O ii] emission at the core spectrum (the upper left-hand panel of Fig. 4) peaks at +4 arcsec away from the peak of the absorption line. The location is almost outside the core region, and around the border of the fan-shaped extended region in Fig. 1. However, in the north spectra (the upper right-hand panel of Fig. 4), the [O ii] emission is peaked at ~4 arcsec, right in front of the companion galaxy. These locations suggest that [O ii] emission may come from outside the post-starburst (strong Balmer absorption) core. However, the presence of only a single peak at both the core and north spectra in an opposite direction suggests that the [O ii] emission does not form a symmetric ring/sphere star-forming region, but instead it has a more complicated spatial distribution. In this context, it will be very interesting to perform integrated field unit (IFU) spectroscopy such as in Swinbank et al. (2005) and Goto et al. (2008) for this E+A system. In the literature, Swinbank et al. (2005) observed a Hδ strong galaxy SDSS J101435.39+011613.66 (Goto et al. 2003) with the Gemini IFU, and found a similar offset of the [O ii] emission line from the Balmer absorptions by ~2 kpc.

For the companion galaxy, only the [O i] emission has a good enough S/N to probe the spatial distribution (bottom panels of Fig. 4). The peak location of [O i] agrees with that of the Balmer absorption lines, but the emission is slightly more extended to ~5 arcsec on both sides, suggesting that the [O i] emission plausibly triggered by the interaction is widely distributed beyond the core region. The overall spectra of the companion galaxy are dominated by the old stellar population (Fig. 3), and thus it is not likely that the companion galaxy is experiencing a strong starburst of more than 5 per cent (Yagi & Goto 2006). Perhaps a small amount of gas remaining in the companion galaxy was disturbed by the interaction to create the weak [O i] emission observed here. Since the emission is spatially extended, the origin of the [O i] is not likely to be a
central active galactic nucleus (AGN). The weak [O iii] emission at the centre also supports the lack of an AGN.

6 CONCLUSIONS

We have performed spatially resolved long-slit spectroscopy of the nearby interacting E+A system J1613+5103 using the FOCAS/Subaru. The E+A galaxy with very strong Hδ EW of $>7$ Å (estimated age of 250 Myr) has an obvious companion at 14 kpc in front. Combined with a disturbed morphology, the system is a clear example that a dynamical interaction can actually create an E+A galaxy. The slit was aligned to include cores of both the E+A galaxy and the companion galaxy. Additional spectra were taken at 2 arcsec away in the north from the cores. Our findings based on these spectra are as follows.

(i) The strong Balmer absorption lines of the E+A galaxy are strong in the entire galaxy; in particular, the Hδ EW is $>7$ Å for the entire galaxy region ($>8.5$ kpc).

(ii) The peak of the weak (EW$<1$ Å) [O ii] emission of the E+A galaxy is slightly offset from that of the Balmer absorption lines, possibly suggesting that the remaining starburst is going on at a different location from the post-starburst region.

(iii) For the companion galaxy the emission line ([O ii]) profile is more extended than that of the Hδ, suggesting that on-going star formation happens in a more extended region than the central region of the old stellar population.

(iv) We found a rotational velocity of $>175$ km s$^{-1}$ for the companion galaxy (Fig. 6), implying that the companion was a disc galaxy without star formation activity before the dynamical interaction. No significant rotation was found for the E+A galaxy.

(v) Using the $r-H$ colour, we estimated that the metallicity of the E+A and the companion were $Z=0.008$ and 0.02, respectively (Fig. 7).

(vi) Based on the Hδ$-D4000$ and Hα$-[O ii]$ EW plots (Fig. 8), we estimate that the age of the E+A galaxy is around 250 Myr after the truncation of the burst. Possibly the centre of the E+A has a slightly younger age of $100$ Myr than its outskirts.

These results present an important example that a galaxy–galaxy interaction with equal mass can create a galaxy wide, uniformly distributed post-starburst region. In this example, it is obvious that the dynamical interaction is the physical origin of the E+A galaxy. At the same time, it warns us that simple classification of the E+A origin with the Hδ profile may not be adequate.

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