SPATIALLY RESOLVED SPECTROSCOPIC OBSERVATIONS OF A POSSIBLE E+A PROGENITOR: SDSS J160241.00+521426.9

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ABSTRACT
In order to investigate the evolution of E+A galaxies, we observed a galaxy, SDSS J160241.00+521426.9, a possible E+A progenitor which shows both emission and strong Balmer absorptions, and its neighbor galaxy. We used the integral field spectroscopic mode of the Kyoto Tridimensional Spectrograph (Kyoto3DII), mounted on the University of Hawaii 88 inch telescope located on Mauna Kea, and the slit-spectroscopic mode of the Faint Object Camera and Spectrograph on the Subaru Telescope. We found a strong Balmer absorption region at the center of the galaxy and an emission-line region located 2 kpc from the center, in the direction of its neighbor galaxy. The recession velocities of the galaxy and its neighbor galaxy differ only by 100 km s$^{-1}$, which suggests that they are a physical pair and would have been interacting. Comparing observed Lick indices of Balmer lines and color indices with those predicted from stellar population synthesis models, we find that a suddenly quenched star formation scenario is plausible for the star formation history of the central region. We consider that star formation started in the galaxy due to galaxy interactions and was quenched in the central region, whereas star formation in a region offset from the center still continues or has begun recently. This work is the first study of a possible E+A progenitor using spatially resolved spectroscopy.

Key words: galaxies: evolution – galaxies: individual (SDSS J160241.00+521426.9) – galaxies: interactions

Online-only material: color figures

1. INTRODUCTION

E+A galaxies are understood as post-starburst galaxies due to the presence of strong Balmer absorption lines (H$\beta$, H$\gamma$, and H$\delta$) and the lack of emission lines (Poggianti et al. 1999; Goto 2005). Examinations of galaxy morphologies (Yang et al. 2004, 2008) and statistics of companion galaxies (Goto 2005; Yamauchi et al. 2008) led to the conclusion that local field E+A galaxies are mainly driven by mergers and interactions. Integral field spectrograph (IFS) observations for E+A galaxies indicate disturbed morphologies and significant rotation, which supports the theory that they are produced by gas-rich galaxy mergers and interactions (Pracy et al. 2009). Recently, Rich et al. (2010) have reported that a starburst galaxy NGC 839 has both A-type stellar population and a galactic wind, and have discussed a link between lower mass starburst systems and E+A galaxies. An E+A galaxy is one phase in galaxy evolution, and thus, it is important to understand the evolution of E+A galaxies.

All these results, however, are based on information obtained from galaxies already in the post-starburst phase. In order to investigate the evolution of E+A galaxies, it is necessary to examine pre-E+A galaxies, or E+A progenitors, which would have both starburst and post-starburst regions, and this requires spatially resolved spectroscopic observations.

In this work, we observed a possible progenitor of an E+A galaxy, SDSS J160241.00+521426.9 (J1602), using the IFS mode of the Kyoto Tridimensional Spectrograph (Kyoto3DII; Sugai et al. 2010), mounted on the University of Hawaii 88 inch telescope on Mauna Kea. The galaxy has an apparent companion galaxy, seen in the Sloan Digital Sky Survey (SDSS) image. The $3''$-fiber spectra from the SDSS show an interesting combination of very strong Balmer absorption lines and emission lines. With the IFS observation on the UH 88 inch telescope as well as slit-spectroscopic observations using the Subaru Telescope Faint Object Camera and Spectrograph (FOCAS; Kashikawa et al. 2002), we investigated the spatial distributions of absorption and emission-line regions. Identifying the locations of starburst regions in E+A galaxies provides constraints on E+A galaxy formation theories. The presence of both post-starburst regions and current starburst regions in one galaxy may provide us with an unprecedented opportunity of examining the progenitor of an E+A galaxy. Through detailed analysis, we attempted to understand the underlying physical process that caused the simultaneous presence of post-starburst and current starburst regions in this galaxy.

2. OBSERVATIONS AND DATA REDUCTION

2.1. Target

We selected a target galaxy which has both strong post-starburst and starburst properties, based on its line ratios from an H$\delta$ strong galaxies catalog (Goto 2005) produced from the spectra of the SDSS Data Release 2 (SDSS DR2; Abazajian et al. 2004). The redshift of J1602 was measured as 0.0430 \pm 0.0001 (York et al. 2000), and the distance was estimated as 170 Mpc ($1''=0.82$ kpc) with $h = 0.73$, $\Omega_m = 0.24$, and $\Omega_{\Lambda} = 0.76$ (Spergel et al. 2007). A possible companion galaxy appeared in the same field of view (FOV); its redshift had not been measured by the SDSS. We retrieved a $K_s$-band fits image from Two Micron All Sky Survey (Skrutskie et al. 2006) and estimated the total $K_s$-band magnitudes of J1602 and the companion galaxy as 14.8 mag and 15.7 mag, respectively. Using the mass-to-luminosity ratio of 0.6 (Balogh et al. 2005), we calculated the stellar masses of J1602 and the companion galaxy as $3.4 \times 10^9 M_\odot$ and $1.5 \times 10^9 M_\odot$, respectively, assuming that the redshift of the companion galaxy is the same as that of J1602.
2.2. Kyoto3DII Data

We observed J1602 on 2005 May 25 (UT) using the IFS mode of the Kyoto3DII mounted on the University of Hawaii 88 inch (2.2 m) telescope at Mauna Kea. This mode uses a 37 × 37 lenslet array, allowing us to obtain simultaneous spectra of \( \sim 10^3 \) spatial elements. The Kyoto3DII has two separate FOVs: one for the target field and another, smaller FOV for the sky field. This is important for accurate sky subtraction. The FOV of the array for the target field is \( \sim 16'' \times 12'' \), with a spatial sampling of 0.43. We used the No. 2 grism and No. 2 filter, which cover the 4170–5260 Å wavelength range (Sugai et al. 2010), and obtained two 1 hr exposure frames. The wavelength resolution in a full-width half-maximum (FWHM) was \( \sim 4.8 \) Å, which corresponds to a velocity resolution of \( \sim 290 \) km s\(^{-1}\).

The IFS data of a spectroscopic standard star from IRAF’s irtscal database, HD161817, were used for flux calibration, and those of helium and halogen lamps were used for wavelength calibration and flat-fielding, respectively. The velocity accuracy was estimated to be 22 km s\(^{-1}\) (1σ) from the lines of the comparison lamp and sky absorption. The averaged sky spectrum was subtracted from the target spectra. Cosmic rays were removed. Atmospheric dispersion correction was performed for all object frames. The spatial resolution was \( \sim 1'' \) which was measured from the FWHM of a standard star. The background noise level was 1.0 × 10\(^{-18}\) erg cm\(^{-2}\) s\(^{-1}\) Å\(^{-1}\) (0.43 arcsec\(^{-2}\)) (1σ). We tried Voronoi binning (Cappellari & Copin 2003) for Kyoto3DII data, but the quick drop-off of continuum flux in the outer region led to very large bins, and thus we did not use Voronoi binning for the Kyoto3DII data.

2.3. FOCAS Data

We also observed J1602 and the neighbor galaxy on 2009 May 20 (UT) using FOCAS on the Subaru Telescope. We adopted a longslit of 0.8 width, and observed with the 300B grism without a filter. The wavelength coverage was about 3750–7100 Å and the spectral resolving power was \( \sim 700 \). The CCD was read out in 3 × 1 binning, and the image scale along the slit was 0.31 arcsec pix\(^{-1}\). We obtained three sets of 10 minutes exposures along the major axis of J1602, and another three sets of 5 minutes exposures along the major axis of the neighbor.

We used five dome-flat frames for flat-fielding. A spectrophotometric standard star from Oke (1990), BD+28D4211, was observed for flux calibration. The seeing size, estimated from the standard star, was 0.56. The wavelength of each exposure was calibrated using a ThAr lamp. The velocity accuracy for the standard star, was 0.02 Å. Errors of Lick indices were estimated using Figure 7 and Table 8 of Worthey & Ottaviani (1997). The Lick indices were calculated from Kyoto3DII and FOCAS spectra after their spectral resolution was matched to the Lick system using Figure 7 and Table 8 of Worthey & Ottaviani (1997). Lick offsets displayed in Table 6 of Bruzual & Charlot (2003), the internal extinction and the emission-line corrections were performed for the observed Lick indices. For the emission-line corrections, we used the value estimated from the H\(_\alpha\)/H\(_\beta\) flux ratio observed by FOCAS because the H\(_\gamma\) flux observed with Kyoto3DII was affected by absorption and a low signal-to-noise ratio (S/N). The H\(_\alpha\)/H\(_\beta\) flux ratio was calculated from the Galactic-extinction-corrected values. The extinction law of Calzetti et al. (2000) was used for extinction correction for J1602 and its companion galaxy. We used two reddening ratios between gas and stars: \( E_{\text{star}}(B - V) = E_{\text{gas}}(B - V) \), which corresponds to a situation where dust exist outside of a star-forming region, and \( E_{\text{star}}(B - V) = 0.44 E_{\text{gas}}(B - V) \) (Calzetti et al. 2000), which corresponds to a situation where dust coexist with stars and gas in a star-forming region. For the emission-line correction, the spectra observed with FOCAS were used. We calculated the fraction of the emission-line fluxes from measured equivalent widths, and corrected the magnitudes in each band. This correction was performed for emission lines within the FOCAS wavelength range of 3750–7100 Å only. Thus, the corrected \( u - g \) indices may be redder, and \( r - i \) may be bluer. As we cannot correct for the effect of emission lines in the \( z \) band, no emission-line correction for the \( i - z \) indices was attempted.

2.4. Stellar Population Synthesis Models

In order to predict the star formation history in several regions in the galaxies, we compared in Section 4.1 the observed Lick indices of the H\(_\gamma\)/A and H\(_\beta\)/A (Worthey & Ottaviani 1997) and the color indices in the rest frame with model values. We used stellar population synthesis models (GALAXEV; Bruzual & Charlot 2003). Each model provides the Lick indices and color indices as a function of starburst age, assuming a star formation history, the Salpeter initial mass function (IMF; Salpeter 1955), and no dust. We calculated three models as follows: (1) a simple stellar population (SSP) model, in which a starburst occurred only at year 0, (2) an exponential (exp) model, in which the star formation rate decreased exponentially (on a timescale \( \tau = 1 \) Gyr), and (3) a constant (const) model, in which starbursts continued constantly. Color indices are calculated from redshift-corrected model spectra. Model spectra do not include emission lines so that emission-line correction is needed for the observed color indices in starburst regions.

2.5. SDSS Data

In order to calculate color indices, we retrieved the SDSS DR7-corrected images (FITS files; Abazajian et al. 2009) and performed aperture photometry using a 1.7 diameter aperture at several regions in the galaxies. The FITS images were resampled using SWarp (Bertin et al. 2002) according to the World Coordinate System (WCS) information of each corrected image. SWarp also subtracted the background. The zero point for the photometry was calibrated with tsField.5 Galactic extinction was corrected according to Schlegel et al. (1998), adopting \( E(B - V) = 0.015 \) for J1602.

As we will compare the color indices with dust-free and emission-free models by Bruzual & Charlot (2003), the internal extinction and the emission-line corrections were performed for the observed Lick indices. For the emission-line corrections, we used the value estimated from the H\(_\alpha\)/H\(_\beta\) flux ratio observed by FOCAS because the H\(_\gamma\) flux observed with Kyoto3DII was affected by absorption and a low signal-to-noise ratio (S/N). The H\(_\alpha\)/H\(_\beta\) flux ratio was calculated from the Galactic-extinction-corrected values. The extinction law of Calzetti et al. (2000) was used for extinction correction for J1602 and its companion galaxy. We used two reddening ratios between gas and stars: \( E_{\text{star}}(B - V) = E_{\text{gas}}(B - V) \), which corresponds to a situation where dust exist outside of a star-forming region, and \( E_{\text{star}}(B - V) = 0.44 E_{\text{gas}}(B - V) \) (Calzetti et al. 2000), which corresponds to a situation where dust coexist with stars and gas in a star-forming region. For the emission-line correction, the spectra observed with FOCAS were used. We calculated the fraction of the emission-line fluxes from measured equivalent widths, and corrected the magnitudes in each band. This correction was performed for emission lines within the FOCAS wavelength range of 3750–7100 Å only. Thus, the corrected \( u - g \) indices may be redder, and \( r - i \) may be bluer. As we cannot correct for the effect of emission lines in the \( z \) band, no emission-line correction for the \( i - z \) indices was attempted.

2.6. Lick Indices

The Lick indices were calculated from Kyoto3DII and FOCAS spectra after their spectral resolution was matched to the Lick system using Figure 7 and Table 8 of Worthey & Ottaviani (1997). Lick offsets displayed in Table 6 of Bruzual & Charlot (2003; Table 1) were applied to the observed values, because only one and no Lick standard star was observed by Kyoto3DII and FOCAS, respectively, in our observing runs. The Lick offset of H\(_\gamma\)/A with Kyoto3DII was estimated from HD161817 data as \( -0.20 \pm 0.02 \) Å. Errors of Lick indices were estimated using equations of Cardiel et al. (1998).

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5 http://www.sdss.org/dr7/algorithms/fluxcal.html
Figure 1. (a) Continuum flux (4600–5000 Å in the observed frame), (b) Hγ flux, (c) Hβ flux, (d) [O iii]5007 flux, (e) [O iii]5007 velocity with respect to the systemic velocity (z = 0.043), and (f) HγA Lick index maps of SDSS J160241.00+521426.9 (J1602) and the companion galaxy observed with Kyoto3DII. The unit of flux density in the continuum image is $10^{-17}$ erg cm$^{-2}$ s$^{-1}$ Å$^{-1}$ (0.43 arcsec)$^{-2}$, and that of the flux in the Hγ, Hβ, and [O iii]λλ4959,5007 images is $10^{-17}$ erg cm$^{-2}$ s$^{-1}$ (0.43 arcsec)$^{-2}$. The unit of the [O iii]5007 velocity map is km s$^{-1}$, and that of the HγA Lick index map is Å. The two arrows in the upper left panel indicate the north and west directions. The bar at the lower right in each panel indicates a 1 kpc length. The two regions surrounded by the lines represent PS1 (left) and SB1 (right) in the Kyoto3DII definition.

(A color version of this figure is available in the online journal.)

Table 1
Lick Offsets Applied to the Kyoto3DII and FOCAS Data

| Index     | Offset (Å) |
|-----------|------------|
| Hβ        | 0.13       |
| Mg b      | 0.03       |
| Fe5270    | 0.17       |
| Fe5353    | 0.07       |
| Hα, A     | 0.83       |
| HγA       | −0.89      |

Note. These values were subtracted from the Lick indices calculated from our data.

3. RESULTS

3.1. Kyoto3DII Results

3.1.1. Region Definition

Figure 1(a) shows the continuum image in the 4600 Å–5000 Å wavelength range in the observed frame obtained from Kyoto3DII IFS data. Two galaxies fall within our FOV: a brighter northern galaxy and a fainter southern one. We designated the northern galaxy J1602 and the southern one, the possible companion galaxy of J1602. The positions of the galaxies in our continuum image are consistent with those in the image retrieved from the SDSS archive data (Figure 2). As described below in detail, absorption lines were found in some regions (e.g., the Hγ and Hβ maps; Figures 1(b) and (c), respectively), and emission lines were found in other regions in both galaxies (e.g., the [O iii]5007 map: Figure 1(d)). From the observed wavelengths of the Hβ, Hγ, and [O iii]λλ4959,5007 emission lines, the redshift of J1602 was measured as 0.0431 ± 0.0001 (1σ), consistent with the results from the SDSS spectroscopic data. We also calculated the redshift of the fainter galaxy from its [O iii]λλ4959,5007 emission lines as 0.0434 ± 0.0002. The redshift of the possible companion galaxy is almost the same as that of J1602, showing that these two galaxies are indeed physically close to each other and, most likely, form a dynamically interacting pair. As this companion galaxy was not spectroscopically observed with the SDSS, our spectroscopic results confirmed for the first time a physical connection between these galaxies.

We defined two regions in J1602 (Figure 1): the Balmer absorption region (post-starburst region; hereafter PS1) and the [O iii] emission region (starburst region; hereafter SB1). These regions were defined by visual inspection of the three-dimensional data. The location of PS1 lies at and around the center of J1602, whereas SB1 is located 2.5 arcsec southwest from PS1. The apparent sizes of PS1 and SB1 are 2.6 arcsec and 4.1 arcsec, respectively. The size of PS1 is comparable to the seeing size (2.5 arcsec), whereas that of SB1 is significantly larger than the point-spread function. Tables 2 and 3 provide detailed data for each absorption or emission line measured by Gaussian fitting in PS1 and SB1, respectively.

3.1.2. PS1

Figure 3(a) shows that the spectra of PS1. Hβ, Hγ, and Hδ lines are seen in absorption. No emission line was found. Strong
Figure 2. (a) Original SDSS image. North is up and east is left. The bar in the upper left panel indicates 5'' in length. (b) Continuum image observed with Kyoto3DII superposed on the SDSS image.

(A color version of this figure is available in the online journal.)

Table 2

| Line   | Wavelength (Å) | EW (Å) | FWHM (Å) |
|--------|----------------|--------|-----------|
| Hδ     | 4278.6         | 6.1    | 13.7      |
| Hγ     | 4526.8         | 7.1    | 16.9      |
| Hβ     | 5070.1         | 7.9    | 28.2      |

Table 3

| Line   | Wavelength (Å) | Flux (10⁻¹⁶ erg cm⁻² s⁻¹) | EW (Å) | FWHM (Å) |
|--------|----------------|---------------------------|--------|-----------|
| Hγ     | 4527.2         | 4.4                        | -6.4   | 3.6       |
| Hβ     | 5070.8         | 13.5                       | -20.1  | 4.4       |
| [O iii]λ4959 | 5173.1         | 19.1                       | -30.4  | 5.1       |
| [O iii]λ5007 | 5223.4         | 58.3                       | -97.3  | 4.7       |

Note. * This emission line was observed at a low S/N.

Balmer absorption lines (Lick(HγA) = 8.3 Å; Table 4) and no emission lines suggest that PS1 is a post-starburst region. We will discuss the age and star formation history of this region in Section 4.1. Figure 1(f) shows that the HγA Lick index outside PS1 is also larger than ~5 Å, which suggests that a post-starburst population is present there.

3.1.3. SB1

The spectrum of SB1 is quite different from that of PS1. Figure 3(b) shows the SB1 spectrum. The continuum emission in SB1 was fainter than that in PS1, and no absorption lines were detected. Instead, the [O iii]λλ4959,5007, Hβ, and Hγ emission lines were detected, which indicates that SB1 is a starburst region. The Hγ emission line was observed at a low S/N, probably affected by stellar Hγ absorption (see Section 3.2.3). Although the [O iii]λ5007/Hβ ratio in this region (~3) is similar to typical active galactic nucleus (AGN) values, we doubt that there is any AGN activity in this galaxy, because the [N ii]/Hα and [S ii]/Hα ratios from SDSS observation data are much smaller than theoretical “maximum starburst lines” defined by Kewley et al. (2001). Moreover, given that the observed Hα flux is reduced by stellar absorption, the intrinsic [N ii]/Hα and [S ii]/Hα ratios are probably even smaller.

![Figure 4](image_url)

Figure 4 shows the filterless image observed with FOCAS. The spatial resolution of this image (0.7′) is the best of our images. The southwest side of J1602 is brighter than the opposite side. The difference in stellar mass or mass/luminosity ratio due to differences in stellar ages may have produced this asymmetry. The shape of the companion galaxy is also asymmetric. The
The eastern side of this galaxy is 5 kpc longer than the western side, if we consider that the continuum flux peak marks the galactic center.

We defined three regions in J1602 in a manner similar to that used for the Kyoto3DII definitions: the Balmer absorption region (PS1), the emission-line region (SB1), and the region on the opposite side SB1 (PS2). The location of PS1 is at the center of J1602. The location of SB1 is 2°5 southwest from PS1, and that of PS2 is 2°5 northeast. We also defined the central region in the companion galaxy as SB2. To obtain one-dimensional spectra of these regions, we combined five pixels for the spatial direction, which corresponds to 1′6. Tables 5–8 provide detailed data for each absorption or emission line measured by Gaussian fitting in PS1, SB1, PS2, and SB2, respectively. Figure 5 shows the Lick index profiles of J1602 and the companion galaxy from FOCAS data after binning low S/N pixels.

### Table 5

| Line         | Wavelength (Å) | EW (Å) | FWHM (Å) |
|--------------|----------------|--------|----------|
| H13          | 3893.8         | 2.1    | 7.7      |
| H12          | 3909.6         | 2.6    | 7.8      |
| H11          | 3931.1         | 4.5    | 10.4     |
| H10          | 3959.7         | 6.4    | 13.5     |
| H9           | 3999.2         | 6.8    | 14.0     |
| H8           | 4055.2         | 8.0    | 16.7     |
| Ca ii K      | 4100.7         | 1.4    | 11.3     |
| Hε + Ca ii H | 4140.0         | 8.4    | 15.7     |
| Hδ           | 4277.6         | 6.6    | 14.5     |
| Hγ           | 4526.7         | 7.6    | 18.3     |
| Hβ           | 5069.3         | 7.8    | 22.8     |

### Table 6

| Line         | Wavelength (Å) | Flux (10^{-16} erg cm^{-2} s^{-1}) | EW (Å) | FWHM (Å) |
|--------------|----------------|------------------------------------|--------|----------|
| [O ii]λ3726,3729 | 3887.5         | 59.9                              | -87.0  | 8.2      |
| H8           | 4057.2         | 2.7                               | -4.1   | 7.1      |
| Hε           | 4140.9         | 2.0                               | -2.8   | 6.0      |
| Hδ           | 4279.6         | 4.2                               | -6.5   | 6.7      |
| Hγ           | 4528.5         | 10.0                              | -17.2  | 7.2      |
| [O i]λ4363    | 4553.6         | 11.1                              | -1.6   | 9.4      |
| Hβ           | 5071.4         | 24.5                              | -47.3  | 7.0      |
| [O ii]λ4959   | 5173.3         | 29.6                              | -51.8  | 6.9      |
| [O ii]λ5007   | 5223.2         | 88.7                              | -156.5 | 6.8      |
| He i λ5876   | 6129.6         | 3.6                               | -7.7   | 6.8      |
| [O i]λ6300    | 6572.6         | 1.7                               | -4.0   | 7.1      |
| [O i]λ6363    | 6639.1         | 0.6                               | -1.4   | 6.4      |
| [N ii]λ6548   | 6831.1         | 2.9                               | -7.2   | 6.8      |
| He i λ6678   | 6846.9         | 90.9                              | -247.9 | 6.8      |
| [N ii]λ6583   | 6867.8         | 7.6                               | -22.7  | 7.2      |
| He i λ6678   | 6967.4         | 0.9                               | -2.5   | 6.5      |
| [S ii]λ6716   | 7006.8         | 7.9                               | -22.5  | 7.4      |
| [S ii]λ6731   | 7021.9         | 5.7                               | -15.8  | 7.0      |

### 3.2.2. PS1, PS2, and Outer Regions of J1602

Figures 6(a) and (c) display the spectra of PS1 and PS2, respectively, observed with FOCAS. We detected many absorption lines in PS1 and PS2 and found no emission line. It is
Figure 5. Lick index profiles of (a) J1602 and (b) the companion galaxy observed with FOCAS. Filled and open circles represent Hβ and Hγ. Lick indices, respectively, with 1σ error bars. Open squares represent the continuum flux (4387–4453 Å in the observed frame) in the logarithmic scale, as shown on the right axis. The uncertainties for continuum flux are too small to be plotted in these figures. Horizontal bars represent binned regions. The abscissa indicates distance from each galactic center, i.e., PS1 for J1602 and SB2 for the companion galaxy, respectively. The locations of PS1, PS2, SB1, and SB2 are indicated on the top of the figure. The characters on the top represent the directions relative to each galactic center. (A color version of this figure is available in the online journal.)

Table 7

| Line  | Wavelength (Å) | EW (Å) | FWHM (Å) |
|-------|---------------|-------|----------|
| H10   | 3960.8        | 4.1   | 10.1     |
| H9    | 3999.6        | 4.6   | 9.7      |
| H8    | 4056.0        | 3.4   | 11.1     |
| He + Ca II H | 4139.6    | 6.5   | 14.3     |
| Hδ    | 4279.7        | 6.5   | 17.3     |
| Hγ    | 4527.5        | 7.2   | 19.2     |
| Hβ    | 5071.4        | 5.8   | 21.6     |

unclear whether the Hα line is an absorption or emission line. Table 4 shows the Hδ, Hγ, and Hβ indices of PS1 and PS2. The Lick indices of Hγ and Hδ are larger than 6 Å in both regions. This suggests that not only PS1, but also PS2 is a post-starburst region. We will discuss the star formation history of PS1 and PS2 in detail in Section 4.1.

At outer regions of J1602, more than 5 kpc from the center, Lick indices of Hγ and Hδ are larger than 5 Å (Figure 5(a)). These indices are similar to PS1 and PS2 values, and significantly larger than those of old population with the age of ~10 Gyr (see Section 4.1). Thus, a post-starburst population may be the main component on the continuum flux around the Hγ wavelength at the whole J1602, including outer regions. There are some examples which have post-starburst regions at whole galaxies, such as SDSS J161330.18+510335.5 (Yagi et al. 2006).

3.2.3. SB1

Figure 6(b) shows the SB1 spectrum observed with FOCAS. Many emission lines, such as Balmer lines, [O ii]λλ3726,3729, [O iii]λλ4959,5007, [N ii]λλ6548,6583, and [S ii]λλ 6716,6731, were detected. A closer inspection revealed that broad absorptions appear around the Balmer emission lines, especially the Hβ. Since the [N ii]λ6583/Hβ flux ratio was smaller than 0.1 (Table 6), we concluded that no AGN activity was present in SB1.

The extinction value was estimated from the Hα/Hβ flux ratio, although the Hγ/Hβ ratio was used in Section 3.1.3, This was done because the broad absorption around Hγ affects the Hγ emission-line flux measurement. We estimated the extinction as 0.82 mag in B band from the Hα/Hβ ratio using the intrinsic Hα/Hβ ratio of 2.87 (Osterbrock & Ferland 2006) and the Calzetti et al. (2000) extinction law. Using the Hβ flux from the Kyoto3DII result and the extinction value from the FOCUS result, the star formation rate in SB1 was found to be 0.25 M⊙ yr⁻¹. Meanwhile, if we assume the same condition as that in Section 3.1.3, we can estimate the extinction as ~0 mag and the star formation rate as 0.11 M⊙ yr⁻¹.

Then, we estimated the metallicity in this region from the [N ii]λ6583/Hα flux ratio, which was 0.077. Using the relationship between the [N ii]/Hα ratio and the metallicity (Nagao et al. 2006), the metallicity (12 + log(O/H)) was found to be 8.29 ± 0.09 (1σ). This value is smaller than the solar value (8.73; Lodders et al. 2009), and the metallicity Z was equal to 0.005. This small metallicity may be explained by the fact that present stars have not yet captured metals previous generation stars produced. It might be the case that few stars, i.e., few metals have been produced.
3.2.4. Companion Galaxy

Figure 6(d) shows the SB2 spectrum observed with FOCAS, which is similar to that of the SB1. Many emission lines, and the broad absorption around Hβ, were detected. Because the [N ii]/Hα ratio was smaller than 0.1 (Table 8), we concluded that no AGN activity was present in this galaxy. Using the method outlined in Section 3.2.3, we calculated the extinction value of SB2 as 1.8 mag in the V band from the Hα/Hβ flux ratio, and the metallicity (12 + log(O/H)) was calculated as 8.11 ± 0.14 (1σ). In the entire region of the companion galaxy, the Lick indices of HγA and HδA are ~4 Å, which are larger than the old population (Figure 5(b)). Thus, a post-starburst population may be present in some regions in the companion galaxy. Some additional emission-line regions were found in this galaxy. We conclude that these also indicate starburst regions because their line ratios are similar to those of the SB2.

4. DISCUSSION

4.1. Comparison of Models and Observed Values

We compared the Lick indices of HγA and HδA and the color indices in the rest-frame with predictions taken from star formation models. We used a metallicity of Z = 0.004 or 0.008, which is similar to the estimated value from [N ii]/λ6583/Hα ratio (Section 3.2.3). The Lick indices of HγA and HδA are a good indicator of the fraction of A-type stars. Le Borgne et al. (2006) display that only the models with r < 100 Myr pass through the region with EW(Hδ) > 6 Å and EW([O ii]λλ3726, 3729) > −5 Å (their Figure 12). The u − g, g − r, r − i, and i − z color indices generally increase with increasing age. The u − g color index is useful for determining the star formation history in each region because it has a strong dependence on the star formation history, especially for ages of more than 30 Myr.

Figure 7 shows the predicted Lick indices of HγA and HδA as a function of starburst age. The observed Lick indices in each region are summarized in Table 4 and are plotted in Figure 7. The large HγA index in PS1 suggests that the SSP model at 200–700 Myr is plausible; the const and exp models cannot produce these large values. The HδA index of 6.8 Å matches the SSP model at 0.1 or 1 Gyr, or the const or exp models at 1 Gyr. Figure 8 shows the predicted u − g, g − r, r − i, and i − z color indices as a function of starburst age. The observed color indices in each region are summarized in Table 9 and are plotted in Figure 8. The observed u − g color in PS1, 1.06, corresponds to an age of 200 Myr in the SSP model, to 2 Gyr in the exp model, and to longer than 10 Gyr in the const model. The other indices correspond to ages of ~200 Myr in the SSP model or 700 Myr in the exp or const model. Although an age of 7 Myr for Z = 0.004 or 30 Myr for Z = 0.008 in the SSP model may fit the g − r, r − i, and i − z color indices, they completely disagree with the red u − g color.

We carried out a least-squares fit for the two Lick indices and the four color indices in PS1. The best-fit model was 200 Myr in the SSP model for Z = 0.004 and 0.008. The lowest χ^2 values for the SSP model are one order of magnitude lower than those of the other star formation histories (Table 10). Yamauchi & Goto (2005) showed that the burst model, which has a constant starburst with a duration of 1 Gyr at the beginning and no star formation thereafter, is a plausible star formation history of E+A galaxies (their Figure 13). We also compared the observed values with the values predicted by this burst model. Figure 9 shows the HγA Lick index and u − g color index predicted by SSP, exp, and burst models. The burst model can produce a larger HγA index than the exp model. The u − g color of the burst model at the age of the peak HγA index, ~1.2 Gyr, is comparable to the observed u − g color. However, even at that age, the burst model cannot explain the large observed HγA index at ~3σ.
Lick index is plotted against the [MgFe] served Lick indices of the absorption lines. In Figure 10, the effectiveness of the SSP or burst. Sudden quenching, whether the best-fit star formation history PS1 is a post-starburst region and the star formation in PS1 was after the burst begins, and this burst model at 100 Myr. Predicted values of the short burst stellar population, we changed the star formation duration of level, due to the older stellar population born before the end of star formation. Then, to reduce the contribution of the older stellar population, we changed the star formation duration of the burst model to 100 Myr. Predicted values of the short burst model become almost the same as those of SSP around 200 Myr. However, the burst model to 100 Myr. Predicted values of the short burst model become almost the same as those of SSP around 200 Myr. Predicted values of the short burst model.

We roughly estimated the metallicity in PS1 from the observed Lick indices of the absorption lines. In Figure 10, the Hβ Lick index is plotted against the [MgFe] index, which is defined as $\sqrt{Mg} \times (0.72 \times Fe5270 + 0.28 \times Fe5335)$ (Thomas et al. 2003). These are good metallicity indicators, as the Hβ index has little sensitivity to element ratio variations or total metallicity, and the [MgFe] index is independent of $\alpha$/Fe (Goto 2007). In this figure, we emphasize on FOCAS data rather than on SDSS data because the SDSS spectrum contains a component of SB1 as well as PS1 due to its wide aperture (3″). The star formation history used for the model is SSP. Metallicity $Z = 0.004$, 0.008, or 0.02, which is comparable to the value estimated from the [NII]γ 6583/Hα flux ratio at SB1, can explain observed index values.

4.1.2. PS2

The Lick indices and color indices of PS2 are close to those of PS1 except for the $u - g$ color, which indicates that PS2 is also

![Figure 7. Hβ (top) and Hγ (bottom) Lick indices predicted by three star formation models (Bruzual & Charlot 2003) as a function of starburst age, with the indices obtained in PS1. The metallicities used in the models are (a) $Z = 0.004$ and (b) $Z = 0.008$, respectively. Solid, long-dashed, and dotted lines mark the Lick indices of the SSP, exp, and const models, respectively (see the text for detail). The faint horizontal lines mark the observed Lick indices in PS1 observed with FOCAS. The shaded regions represent the values that fall within $\sigma$ for FOCUS data.](image-url)

(A color version of this figure is available in the online journal.)
Figure 8. Color indices predicted by three star formation models (Bruzual & Charlot 2003) as a function of starburst age, with the indices obtained in PS1, PS2, SB1, and SB2. The metallicities used in the models are (a) $Z = 0.004$ and (b) $Z = 0.008$, respectively. Solid, long-dashed, and dotted lines represent the color of the SSP, exp, and const models, respectively (see the text for details). Faint horizontal lines represent the observed and corrected indices. Labels on these lines indicate the regions, e.g., the line marked “SB1” represents the observed color index at SB1, while the one marked “SB1c” represents the corrected value at SB1. Bars on the SB1c and SB2c lines represent uncertainties due to the assumption of gas-to-star reddening ratio.

(A color version of this figure is available in the online journal.)

a post-starburst region. Because of the bluer $u-g$ color, the exp and const models at $\sim 1$ Gyr can also reproduce the observed Lick indices and color indices of PS2. However, these models conflict with the fact that no emission line was found in PS2.

4.1.3. Two Population Model

It is unlikely that J1602 only has a recently formed population only, because it would be necessary to maintain the large star formation rate, e.g., more than $30 M_{\odot}$ yr$^{-1}$ for 100 Myr, to produce observed stellar mass of J1602, $3.4 \times 10^9 M_{\odot}$. Even a larger star formation rate would be required for the shorter star formation duration. We roughly estimated the fraction of the stellar mass of the post-starburst population to the total stellar mass of J1602 using the Lick index of H$\gamma_A$. The observed index is almost the maximum value possible in the models; thus, it will put a severe constraint. We assumed a combination of two stellar populations for J1602: a post-starburst population (burst model) and an old population (exp 10 Gyr). The continuum
Figure 9. HγA Lick index (top) and u – g color index (bottom) predicted by four star formation models (Bruzual & Charlot 2003) as a function of starburst age, with the indices obtained in PS1. The metallicities used in the models are (a) Z = 0.004 and (b) Z = 0.008, respectively. Bold solid, long-dashed, dotted, and faint solid lines represent the index of the SSP, exp, burst (star formation duration: 1 Gyr), and burst (star formation duration: 100 Myr) models, respectively (see the text for detail). The faint horizontal lines mark the HγA Lick index observed by FOCAS and the u – g color in PS1. The shaded regions in the HγA index panels represent the values that fall within 3σ for FOCAS data.

Figure 10. Hβ Lick indices plotted against the [MgFe]′ indices. Open and filled squares represent the indices obtained for the central region of J1602: by SDSS for the central 3″ and by FOCAS for PS1, respectively, with 1σ error bars. Lines represent the models (Bruzual & Charlot 2003). One line represents the evolutionary track for varying age at constant metallicity. The model metallicities are 0.0001 (bold solid), 0.0004 (bold dotted), 0.004 (bold long-dashed), 0.008 (faint solid), 0.02 (faint dotted), and 0.05 (faint long-dashed), respectively. Filled circles represent the ages at 10 Myr, 100 Myr, 300 Myr, 1 Gyr, 3 Gyr, and 10 Gyr.

(A color version of this figure is available in the online journal.)

flux was normalized with g-band magnitude, and metallicities Z = 0.004 and 0.008 were used. To produce more than 6 Å of HγA index, more than ~20% of post-starburst population is needed, whether the star formation duration of the burst model was 100 Myr or 300 Myr. In order to produce this post-starburst population, the star formation rate of 11 M⊙ yr⁻¹ or 4 M⊙ yr⁻¹ is required when masses of already dead early-type stars are also taken into consideration. Although even 4 M⊙ yr⁻¹ may be too large for J1602, whose stellar mass is only 3.4 × 10⁹ M⊙, a 300 Myr burst would be more plausible. Even a larger HγA index of 7.5 Å is required at PS1, and more than 40%–70% of the post-starburst population is needed.

4.1.4. SB1 and SB2

Many observed color indices in SB1 and SB2 are redder than those in PS1 and PS2. This is consistent with the SDSS image (Figure 2(a)): the western side of the companion galaxy is redder than the eastern side. We consider that dust formed by starbursts is reddening the western side. The extinction and emission-line-corrected indices in SB1 correspond to the exp or const model at 100 Myr–1 Gyr (Figure 8). These indices also correspond to the SSP model at 6–100 Myr. Taking further into consideration the observed Hα and Hβ equivalent widths (Table 6) and a starburst model (Starburst99, Leitherer et al. 1999), the const model at 300–400 Myr or the SSP model at ~6 Myr is most likely. The SB2 age is about the same as or slightly older than SB1 because of similar color indices and smaller Hα and Hβ equivalent widths (Table 8).

SB1 probably has a post-starburst population as well as a young population. If the post-starburst population greatly affects the observed color indices, the conclusion with respect to SB1 star formation history is invalid. To estimate the effect of the post-starburst population, assuming that the magnitudes of the post-starburst population in SB1 are the same as those in PS2, which is at the opposite side of SB1, we calculated that the fraction of flux from the post-starburst population is only ~30% and color indices are affected by only ~0.07 mag. Therefore, the conclusion of the SB1 star formation history derived from the SB1 color is valid.

4.2. Evolutionary History of J1602

From our results, we suggest a history of J1602. (A) Before galaxy interaction, both J1602 and its companion galaxy were probably in only a moderate star formation phase. (B) They
came close to each other and starbursts occurred within the central 2 kpc of J1602, including PS1, PS2, and maybe SB1. (C) Starbursts within the central 2 kpc were suddenly quenched about 200 Myr ago, whereas starburst in SB1 may have continued. (D) In the present state, PS1 and PS2 have become post-starburst regions, whereas SB1 is still or has become a starburst region. (E) In the future, starburst at SB1 would eventually stop, and all of J1602 would become post-starburst regions. If a gas mass of $10^8 M_\odot$, for example, is continuously converted into stars in the present star formation rate in SB1 ($0.25 M_\odot$ yr$^{-1}$, Section 3.2.3), the starburst will continue further for about 400 Myr and J1602 will become a pure E+A galaxy after about 600 Myr from now (i.e., about 200 Myr after the starburst stops).

We suggest two possible scenarios of starbursts in the second phase (B). (B1) There was enough gas in all of J1602, and galaxy interaction triggered starbursts within its central 2 kpc; or (B2) the gas was transported from the companion galaxy to J1602, and galaxy interaction triggered starbursts within the central 2 kpc. This scenario, however, needs a large amount of gas transfer. Assuming that half of the stars in PS1 were produced in phase (B) (Section 4.1.3), we calculated the produced stellar mass as $1.5 \times 10^9 M_\odot$, by using the observed SSF mass in PS1 and GALAXEV (Bruzual & Charlot 2003). Even if the amount of gas in the companion galaxy is one-tenth of its stellar mass, $1.5 \times 10^8 M_\odot$ (Section 2.1), the gas mass will be equal to the required amount. It would be difficult to transfer almost all gas in the companion galaxy since the galaxy mass ratio of J1602 to the companion is only $\sim$2. Therefore, we consider that the (B1) scenario is more plausible.

We suggest three possible causes for starbursts to cease in the third phase (C). (C1) All gas within the central 2 kpc was completely consumed, whereas gas in SB1 may still have remained. In this scenario, however, star formation would not fall sharply. Thus, this scenario may not produce large Lick indices of $\delta A$ and $\delta B$. (C2) Gas transport from the companion galaxy to J1602 ceased, and there was no gas in J1602, whereas gas in SB1 may still have remained. As mentioned above, however, gas transport from the companion galaxy is not likely. (C3) Galactic winds occurred and expelled gas from the central 2 kpc. Galactic winds can quench a starburst suddenly and produce large Lick indices. Although no signature of galactic winds was found in J1602 through our observations, it would not be a serious problem because the time since the galactic wind occurred in J1602 is much longer than the typical dynamical timescales of galactic winds, which are shorter than 10 Myr (e.g., Veilleux et al. 2005; Matsubayashi et al. 2009). Therefore, we consider that the (C3) scenario is plausible.

### 4.3. Further Details

We should mention the timescales of galaxy rotation and galaxy movement because these are comparable to the timescale between phases (C) and (D), about 200 Myr. Assuming that the dynamical mass of J1602 within the central 2 kpc is equal to its stellar mass, $3.4 \times 10^9 M_\odot$, we calculate that stars at PS2 make one rotation around J1602’s center in 150 Myr. Thus, the post-starburst population in PS2 was not necessarily born at the apparent present place. Taking into account the rotation of J1602, we suggest two possible scenarios of the place where its starburst occurred in phase (B). One scenario is that the starburst occurred in the entire central 2 kpc of J1602. This includes the case of an axisymmetric starburst distribution. The other scenario is that the starburst occurred only at PS1 and at the near side to the companion galaxy (e.g., NGC 6090; Sugai et al. 2004). Stars which had been born at the near side moved to the apparent present position by galaxy rotation and are now observed as a post-starburst population there. We also roughly estimated the timescale of the galaxy motion, although the relative tangential velocity and the relative radial distance are uncertain. It takes 30 Myr for galaxies to move the apparent distance between J1602 and the companion galaxy, 4 kpc, with the observed relative radial velocity, 100 km s$^{-1}$. This means that J1602 and the companion in phase (C) were at a different orbital positions compared to phase (D). Therefore, there is a possibility that the first pericenter triggered a starburst in phase (B) and the second one triggered a starburst in phase (D).

J1602 and the companion galaxy are not severely disturbed in terms of morphology (Figure 4), unlike NGC 4038/9 (e.g., Whitmore & Schweizer 1995) or NGC 4676 (e.g., Hibbard & van Gorkom 1996). It may be because they did not experience a head-on collision and/or they are at the beginning of a collision. To guess whether the collision between these galaxies is prograde or retrograde, we calculated the velocity in each region. From Balmer absorption lines, the stellar velocity of SB2 relative to PS1 (i.e., the center of J1602) was calculated as $+100$ km s$^{-1}$. Thus, J1602 rotates in a clockwise direction as viewed from the northwest side if we assume a simple galaxy rotation. Since the velocity of SB2 (i.e., the center of the companion galaxy) relative to PS1 was calculated as $+200$ km s$^{-1}$, we suggest that this collision is retrograde.

Many galaxy-merger simulations (e.g., Barnes & Hernquist 1996) indicate that gas falls into the center faster than stars. Thus, it may be strange that in phase (D) SB1 is a starburst region but PS1 (the galactic center) is not. Barnes (2004) indicates that shock-induced star formation provides a better match to the observation of NGC 4676, an interacting galaxy system, than the density-dependent model (e.g., Mihos & Hernquist 1994). In the shock-induced models, more star formation occurs outside the center compared with the density-dependent model. There are some examples of off-center starbursts in interacting galaxy systems, such as SDSS J101345.39+011613.66 (Swinbank et al. 2005), SDSS J161330.18+510335.5 (Goto et al. 2008), and NGC 6090 (Sugai et al. 2004).

Our observational data enable us to investigate the spatial distributions of absorption and emission-line regions, and to suggest a history of an interesting galaxy, J1602. However, we cannot completely understand J1602’s history, e.g., the causes of starbursts in phase (B) and their quenching in phase (C). H$i$ or CO map observations of J1602 will be helpful. Neutral/molecular gas emission will be detected mainly in SB1, not in PS1, if scenarios (B1) and (C1) are true. If a large amount of neutral/molecular gas emission is detected between J1602 and its companion galaxy, scenarios (B2) and (C2) would be plausible. Follow-up observation of this interesting J1602 system, such as molecular gas mapping, is important for examining the evolution of E+A galaxies.

### 5. CONCLUSION

In order to investigate the evolution of E+A galaxies, we observed SDSS J1602 and its neighbor galaxy with Kyoto3DII and FOCAS. These are the first spatially resolved spectroscopic observations of E+A progenitors.

We found a post-starburst region at the center of J1602 (PS1) and a starburst region located 2 kpc from the center (SB1), in the direction of the neighbor galaxy. The fact that this galaxy has both starburst and post-starburst regions indicates that it is in

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a critical phase of evolution. The recession velocities of J1602 and its neighbor galaxy differ only by ~100 km s^{-1}. Thus, they are a physical pair and are considered to have been interacting, probably in a retrograde encounter. A local velocity field of 80 km s^{-1} is detected in SB1.

Comparing the observed Lick indices of the HγA and HδA and color indices to those predicted from stellar population synthesis models, we find that a suddenly quenched star formation scenario is plausible for the star formation history of PS1. From our results, we suggest a history for J1602. Starbursts occurred within 2 kpc from the center of J1602 probably due to galaxy interaction, then about 200 Myr ago starbursts were suddenly quenched, whereas the starburst in SB1 may have continued or may have occurred recently. The SB1 starburst will eventually stop, and all of J1602 will become post-starburst. Follow-up observation, for example, molecular gas mapping of this system, will further elucidate the evolution process of E+A galaxies.

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