AKARI NEAR-INFRARED SPECTROSCOPY OF SDSS-SELECTED BLUE EARLY-TYPE GALAXIES

Joon Hyeop Lee1, Ho Seong Hwang2, Myung Gyoon Lee3, Jong Chul Lee3, and Hideo Matsuura4

1 Korea Astronomy and Space Science Institute, Daejeon 305-348, Republic of Korea; jhlee@astro.snu.ac.kr
2 CEA Saclay/Service d’Astrophysique, F-91191 Gif-sur-Yvette, France; hoseong.hwang@cea.fr
3 Astronomy Program, Department of Physics and Astronomy, Seoul National University, Seoul 151-742, Republic of Korea; mglee@astro.snu.ac.kr, jclee@astro.snu.ac.kr
4 Institute for Space and Astronautical Science, Japan Aerospace and Exploration Agency, Sagamihara, Japan; maruma@ir.isas.jaxa.jp

Received 2010 March 7; accepted 2010 June 29; published 2010 August 4

ABSTRACT

A near-infrared (NIR; 2.5–4.5 μm) spectroscopic survey of Sloan Digital Sky Survey (SDSS)-selected blue early-type galaxies (BEGs) has been conducted using the AKARI. The NIR spectra of 36 BEGs are secured, which are well balanced in their star formation (SF)/Seyfert/LINER-type composition. For high signal-to-noise ratio, we stack the BEG spectra in its entirety and in bins of several properties: color, specific star formation rate, and optically determined spectral type. We estimate the NIR continuum slope and the equivalent width of 3.29 μm polycyclic aromatic hydrocarbon (PAH) emission. In the comparison between the estimated NIR spectral features of the BEGs and those of model galaxies, the BEGs seem to be old-SSP(simple stellar population)-dominated metal-rich galaxies with moderate dust attenuation. The dust attenuation in the BEGs may originate from recent SF or active galactic nucleus (AGN) activity and the BEGs have a clear feature of PAH emission, evidence of current SF. BEGs show NIR features different from those of ULIRGs from which we do not find any clear relationship between BEGs and ULIRGs. We find that Seyfert BEGs have more active SF than LINER BEGs, in spite of the fact that Seyferts show stronger AGN activity than LINERs. One possible scenario satisfying both our results and the AGN feedback is that SF, Seyfert, and LINER BEGs form an evolutionary sequence: SF → Seyfert → LINER.

Key words: galaxies: active – galaxies: elliptical and lenticular, cD – galaxies: evolution – galaxies: formation

Online-only material: color figures

1. INTRODUCTION

Early-type galaxies are often regarded as the objects at the final stage of galaxy evolution. Throughout many observations, it has been revealed that most nearby early-type galaxies have red colors and very poor contents of cold gas (e.g., Faber & Gallagher 1976; Trager et al. 2000; Treu et al. 2006). Such observational evidence indicates that early-type galaxies are composed of old stars and they probably will not have additional star formation (SF) in the future. That is, most early-type galaxies seem to evolve passively, unlike late-type galaxies with active SF.

However, since Abraham et al. (1999) and Menanteau et al. (1999) found a considerable fraction of early-type galaxies with blue colors and evidence of current SF in the Hubble Deep Field (Williams et al. 1996), the existence of blue early-type galaxies (BEGs) has become a new important factor to be considered in the formation scenario of early-type galaxies. BEGs are known to have positive color gradients (i.e., center bluer than outskirts) on average and consist of both old and young stars (Menanteau et al. 2001a; Elmegreen et al. 2005; Ferreras et al. 2005; Lee et al. 2006, 2008, 2010a). It has also been revealed that the internal color distributions of BEGs are neither homologous nor symmetric (Menanteau et al. 2004; Lee et al. 2006), and that some BEGs are suspected to host active galactic nuclei (AGNs; Menanteau et al. 2005; Lee et al. 2006, 2008). Unlike typical red early-type galaxies (REGs) preferring high-density environments, BEGs tend to reside in intermediate- or low-density environments (Kannappan et al. 2009; Lee et al. 2010b). The origin and future of BEGs are still controversial. Observational evidence indicates that some BEGs may originate from recent galaxy interactions or mergers (Lee et al. 2006), but the gas infall is also a possible mechanism for building BEGs (Menanteau et al. 2001b). After some time passes, BEGs may evolve into typical REGs (Lee et al. 2006, 2007, 2008), but it is also possible that they evolve into bulges of late-type galaxies (Hammer et al. 2005; Kannappan et al. 2009). In any case, BEGs are probably in the forming/growing phase of early-type galaxies or bulges.

To better understand the formation and evolution of BEGs, we need to inspect what happens in the inside of BEGs. Since more than half of BEGs have evidence of their merger/interaction origin (Lee et al. 2006), the interaction-induced SF is expected to make BEGs blue. On the other hand, galaxy merger/interaction sometimes also causes AGN activity (Kewley & Dopita 2003; Sánchez et al. 2005; Comerford et al. 2009), and the power-law continua of AGNs may affect the color of BEGs. Lee et al. (2008) reported that non-passive BEGs in the Sloan Digital Sky Survey (SDSS; York et al. 2000) include both SF galaxies and AGN host galaxies, the number ratio of which is about 3.5: for −22.9 < Mr < −20.1, 5 < −20.7. However, optical spectra are easily obscured by dust, causing the missing of a significant fraction of AGNs in optical surveys (Best et al. 2005). Moreover, ground-based spectroscopy (e.g., the SDSS spectroscopy) of bright galaxies in the optical band often suffers the dilution of low-contrast emission lines due to strong emission lines (Ho et al. 1997), which also causes inaccuracy in estimating AGN activity.

One of the most powerful tools to probe the SF/AGN activity is the spectroscopy in the infrared (IR) band. Polycyclic aromatic hydrocarbons (PAHs; Sellgren 1984; Leger & Puget 1984) have

5 Absolute Petrosian magnitude in the r band with K-correction as if the object were at z = 0.1 (Lee et al. 2008). All magnitudes in this paper are in the AB system.
have been detected in various objects, such as H II regions, protostellar clouds, planetary nebulae, and SF galaxies (Peeters et al. 2002; Hony 2002). It is known that UV photons excite the vibrational and stretching modes of PAH molecules, from the relaxation of which broad IR emission lines (such as 3.3, 6.2, 7.7, 8.6, and 11.2 μm lines) are produced (Cherchneff & Barker 1989; Shan et al. 1991). Such PAH emission features are good indicators of SF activity. On the other hand, Voit (1992) argued that PAHs in the central region of an AGN could be destructed by the strong X-ray emission from the AGN. Furthermore, AGN activity is known to suppress SF itself (AGN feedback; Antonuccio-Delogu & Silk 2008; Rafferty et al. 2008). Thus, those properties of PAH emission are believed to provide a reasonably clean diagnostic between SF and AGN. In addition, the shape of the IR continuum is another indicator of SF/AGN, because SF galaxies and AGNs have different spectral energy distributions (e.g., Imanishi et al. 2008; Risaliti et al. 2006, 2010). However, no systematic IR spectroscopic surveys of BEGs are seen in the literature.

In this paper, we report the result of the first BEG spectroscopic survey in the near-IR (NIR) band, using the AKARI (Murakami et al. 2007) Infrared Camera (IRC; Onaka et al. 2007). The outline of this paper is as follows. Section 2 describes the target selection and the AKARI spectroscopic observation. Section 3 explains the reduction and analysis of the AKARI data. The extracted NIR spectra of BEGs and their features are shown in Section 4. The results are discussed in Section 5, and the main results and their implication are summarized in Section 6. Throughout this paper, we adopt the cosmological parameters: $h = 0.7$, $\Omega_{\Lambda} = 0.7$, and $\Omega_{M} = 0.3$.

2. OBSERVATION

2.1. Target Selection

We selected 59 non-passive (i.e., currently star-forming or hosting an AGN) BEG targets based on the scheme of Lee et al. (2008) using the spectroscopic sample of galaxies in the SDSS Data Release 4 (DR4; Adelman-McCarthy et al. 2006). We adopted the physical parameters of the galaxies from several value-added galaxy catalogs (VAGCs) drawn from the SDSS: photometric parameters from the SDSS pipeline (Stoughton et al. 2002), structural parameters estimated by Park & Choi (2005) and Choi et al. (2007), and spectroscopic parameters from Max-Planck-Institute for Astrophysics (MPA)/Johns Hopkins University (JHU) VAGC (Kauffmann et al. 2003; Tremonti et al. 2004; Gallazzi et al. 2006). First, we selected the early-type galaxies from the SDSS galaxies using their distribution in the color, color gradient, and light-concentration parameter space (Park & Choi 2005). Next, we divided the selected early-type galaxies into REGs and BEGs, using the method of Lee et al. (2006), which is based on the color distribution of bright early-type galaxies as a function of redshift. The BEGs were classified using their flux ratios of PAH emission are believed to provide a reasonably clean diagnostic between SF and AGN. In addition, the shape of the IR continuum is another indicator of SF/AGN, because SF galaxies and AGNs have different spectral energy distributions (e.g., Imanishi et al. 2008; Risaliti et al. 2006, 2010). However, no systematic IR spectroscopic surveys of BEGs are seen in the literature.

In this paper, we report the result of the first BEG spectroscopic survey in the near-IR (NIR) band, using the AKARI (Murakami et al. 2007) Infrared Camera (IRC; Onaka et al. 2007). The outline of this paper is as follows. Section 2 describes the target selection and the AKARI spectroscopic observation. Section 3 explains the reduction and analysis of the AKARI data. The extracted NIR spectra of BEGs and their features are shown in Section 4. The results are discussed in Section 5, and the main results and their implication are summarized in Section 6. Throughout this paper, we adopt the cosmological parameters: $h = 0.7$, $\Omega_{\Lambda} = 0.7$, and $\Omega_{M} = 0.3$.

2.2. AKARI Spectroscopy

The AKARI is a Japanese infrared astronomy satellite from the Institute of Space and Astronautical Science (ISAS) of the Japanese Aerospace Exploration Agency (JAXA). It was launched on 2006 February 21 and ran out of its onboard coolant (helium) supply on 2007 August 26 after its successful operation. The observation of our BEG targets was conducted during the AKARI open-time operation, the post-helium phase of the AKARI observation, in which NIR (1.8–5.5 μm) imaging and spectroscopic observations are available.

http://www.ipac.caltech.edu/2mass/

There is various unpredictability in the space telescope operation, which makes it difficult to carry out the observations exactly as planned. Because of such unpredictability, the perfect success of proposed observations is not guaranteed.

http://www.ir.isas.jaxa.jp/ASTRO-F/Outreach/index_e.html
Figure 2. Distribution of SDSS early-type galaxies (small dots) and the BEGs (filled circle) in the line flux ratio diagram. (a) The line is the boundary dividing SF galaxies (lower left) and AGNs (upper right) given by Kauffmann et al. (2003). (b) The line is the boundary dividing Seyferts (upper left) and LINERs (lower right) given by Kewley et al. (2006). The number of filled circles is smaller than the BEG sample size because the BEGs with each line S/N > 3 are not plotted here. SF BEGs are not plotted in panel (b).

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

The observation was conducted from 2008 November to 2009 August. The target BEGs were observed using the IRCZ4 Astronomical Observing Template (AOT), which is the spectroscopic AOT of the IRC. Between the grism and prism, we selected the nominal Observing Template (AOT), which is the spectroscopic positioning option, we used the point-source aperture (Np), because the typical effective radius of target BEGs is only several arcseconds. Among the successfully observed 36 targets, 29 objects were observed twice, while 7 targets were observed only once. The net exposure time for a single pointing observation is about 6 minutes (Onaka et al. 2007; Imanishi et al. 2008).

3. DATA REDUCTION AND ANALYSIS

3.1. Basic Data Reduction and Median Stacking

Unlike our expectation, two pointings per object were not enough to secure a sufficient signal-to-noise ratio (S/N) for most targets (half of the spectra have 3.5–3.9 \(\mu\)m continua with S/N < 6), although the spectra of a few objects are relatively good. Thus, we applied the median stacking analysis technique for high S/N. The steps of the stacking analysis are as follows.

1. We used the IRC Spectroscopy Toolkit for Phase 3 Data Version 20090221 provided by the AKARI team, for the basic processes such as dark subtraction, image flat fielding, spectral flat fielding, image combining, source detection and extraction, sky subtraction, wavelength calibration, and flux calibration.

2. Using the SDSS spectroscopic redshift, we converted the observer-frame wavelength into the rest-frame wavelength for each object. Since the rest-frame wavelength ranges are different between objects, we trimmed each spectrum with the rest-frame wavelength range of 2.5–4.5 \(\mu\)m.

3. All trimmed spectra were normalized for the median flux density at 3.5 \(\mu\)m < \(\lambda\) < 3.9 \(\mu\)m to be identical.

4. We stacked the normalized spectra by taking a median. We also produced several median-stacked spectra in bins of several properties such as optical spectral type, optical color, and [Oii]-based specific star formation rate (SSFR).

We selected the median stacking instead of mean stacking because it removes unreal data points (hot or bad pixels) more effectively, whereas it also improves data quality similarly to that which is done by the mean stacking. Not only the total stacking (i.e., stacking all spectra into a single spectrum) but also the subsample stacking was carried out to compare the NIR spectral features between subsamples with different optical properties. We simply estimated the uncertainty of the stacked spectra by supposing that the spectral noise follows the Poisson error and that the S/N is accumulated during the stacking process. That is,

\[
(S/N)_b = \sqrt{\sum (S/N)^2},
\]

where (S/N)_b is the S/N of the stacked spectrum and (S/N)_i is the S/N of the individual spectra.

3.2. Spectral Fitting

We used the power-law continuum +3.29 \(\mu\)m PAH emission (Gaussian) formula (Risaliti et al. 2006) to fit the stacked spectra:

\[
F_\lambda = A\lambda^\Gamma + Be^{-\left(\frac{\lambda - 3.29\mu m}{0.5}\right)^2},
\]

where \(F_\lambda\) is the flux density, \(\lambda\) is the wavelength in units of \(\mu\)m, \(\Gamma\) is the continuum slope, \(\sigma\) is the Gaussian spread in units of \(\mu\)m, and \(A\) and \(B\) are amplitudes. The fitting was conducted in the wavelength range of 2.5–3.9 \(\mu\)m, because the Br\(\alpha\) emission and CO absorption lines may affect the NIR spectra significantly at \(\lambda > 4\ \mu m\) (Imanishi et al. 2008; Risaliti et al. 2010).

4. RESULTS

Figure 4 displays the stacked spectrum of all BEGs in our sample. In this spectrum a clear PAH emission line is found, the central wavelength of which is 3.29 \(\mu\)m. The continuum is overall well fit to the function in the fitting range (2.5–3.9 \(\mu\)m).

The ice-cored dust absorption (\(\lambda \sim 2.8–3.2\ \mu m\)) feature is marginally found, but the bare carbonaceous dust absorption (\(\lambda \sim 3.4\ \mu m\)) feature is hardly seen in Figure 4. Around \(\lambda \sim 3.4\ \mu m\), instead of absorption features, a marginal excess is seen, which we do not currently understand. It is noted that the long-ward of 3.9 \(\mu\)m of the stacked spectrum shows values totally lower than the fit. The known line features at \(\lambda > 4\ \mu m\) are Br\(\alpha\) emission (\(\lambda = 4.05\ \mu m\)) and CO2 absorption (\(\lambda \sim 4.26\ \mu m\)), but those features are not clearly identified in Figure 4. The apparent “dip” at \(\lambda > 4\ \mu m\) may be simply because the spectral fitting was carried out in the wavelength range of 2.5–3.9 \(\mu m\).

Figures 5–7 show the stacked spectra of the BEGs in bins of several properties: [Oii]-based specific star formation rate (SSFR[Oii]), \(0.1(u-r)\) color, and optical spectral type. In the estimation of SSFR, the star formation rate (SFR) was estimated using the [Oii] emission line that is known to be hardly

\[
\text{SSFR}_{[\text{O} ii]} = \frac{L_{[\text{O} ii]}}{10^{10} M_{\odot} \text{yr}^{-1}},
\]

where \(L_{[\text{O} ii]}\) is the luminosity of the [Oii] emission line, which is the sum of the [Oii] line flux in the 6548 and 6583 Å bands.
contaminated by AGN emission (Ho 2005; Kim et al. 2006), and the stellar mass was derived using the Two Micron All Sky Survey (2MASS) $K_s$ magnitude (see Lee et al. 2010a). When considering the objects with a sufficient [O\textsc{ii}] emission signal ($S/N_{[\text{O\textsc{ii}}]} \gtrsim 3$; Figures 5(b) and (c)), PAH emission is hardly found for low SSFR$_{[\text{O\textsc{ii}}]}$ BEGs, whereas the stacked spectrum of the high SSFR$_{[\text{O\textsc{ii}}]}$ BEGs shows a clear PAH emission feature. This confirms the fact that PAH emission reflects current SF. It is noted that 14 BEGs have low $S/N_{[\text{O\textsc{ii}}]}$, which may be mainly due to the difficulty in measuring the [O\textsc{ii}](3727 Å) line using the SDSS spectroscopy (3800–9200 Å) at low redshift.

Figure 6 shows that the bluer BEGs have the stronger PAH emission feature, which indicates that the blue colors of BEGs reflect their SF activity. This trend is also confirmed in Figure 7: the PAH equivalent width (EW$_{3.29}$) of SF BEGs (25.2 nm) is larger than those of Seyfert and LINER BEGs (17.2 nm and 13.4 nm, respectively). In Figure 7, it is noted that the EW$_{3.29}$ of Seyfert BEGs (17.2 ± 0.8 nm) is larger than that of LINER BEGs (13.4 ± 1.4 nm) by more than 2σ. Seyferts show stronger AGN activity than LINERs (e.g., Groves et al. 2006) and the current consensus on the relationship between AGN activity and PAH/SF is that the AGN activity destroys PAH particles and suppresses SF (Voit 1992; Antonuccio-Delogu & Silk 2008; Rafferty et al. 2008). Apparently, however, our results seem to be contradictory to such previous understanding (i.e., Seyfert BEGs are more active than LINER BEGs in both AGN and SF activity).
star formation history, and dust attenuation, using the models

1950 LEE ET AL. Vol. 719

Figure 8 shows the variation of it is not easy to check this previous knowledge independently,

Due to this degeneracy, it is difficult to tell the dominant factor

exponentially decreasing, and constant SFR models. In Figure 8, it is found that

Ferreras et al. 2005; Lee et al. 2010a). In our results, however,

a considerable amount of old stars (Menanteau et al. 2001a;

Notes. a The r-band absolute magnitude with K-correction (Petrosian magnitude).

b The Kγ -band apparent magnitude (20 mag arcsec−2 isophotal Kγ fiducial ellipse aperture magnitude).

c The specific star formation rate in units of 10−12 yr−1 (that is, the newly forming stellar mass per unit stellar mass per year). For the objects with S/N[OIII] < 3, their SSFRs were not estimated (…).

5. DISCUSSION

5.1. The Identity of BEGs from the AKARI View

BEGs are known to have not only very young stars but also a considerable amount of old stars (Menanteau et al. 2001a; Ferreras et al. 2005; Lee et al. 2010a). In our results, however, it is not easy to check this previous knowledge independently, because the NIR continuum slope (Γ) depends on both stellar and dust contents (dust either in host galaxies or in AGN tori). Figure 8 shows the variation of Γ as a function of age, metallicity, star formation history, and dust attenuation, using the models of Bruzual & Charlot (2003): simple stellar population (SSP), exponentially decreasing, and constant SFR models. In Figure 8, it is found that Γ becomes less negative as SF ended earlier, as age increases, as metallicity increases, and as dust increases. Due to this degeneracy, it is difficult to tell the dominant factor in determining Γ of BEGs. Even if we suppose that the NIR continuum of the BEGs is old-SSP-dominated from previous knowledge (the age of most stars in BEGs is about 10 Gyr; e.g., Ferreras et al. 2005; Lee et al. 2010a), the Γ of the BEGs can be reproduced using either the metal-rich SSP model without dust or the significantly dust-attenuated SSP model with solar metallicity.

The effect of internal dust extinction is independently checked using the information extracted from the SDSS data; that is, using the Balmer decrement. Based on the formula of Calzetti et al. (1994), we derived the internal reddening E(B − V) (median value for each subsample) and compared them with the Γ and EW3 of the stacked BEGs in Figure 9. It is found that the NIR spectral parameters have correlations with E(B − V), in the sense that the Γ and EW3 increase with increasing E(B − V). The E(B − V) values of the BEGs are not small, but seem to be not large enough to explain the Γ of the BEGs in Figure 8 (the τγ corresponding to E(B − V) = 0.4 is 1.14; De Ruyter et al. 2005). Thus, if we suppose moderate (not too strong) dust attenuation in the BEGs, Figure 8 indicates that the BEGs may
Figure 4. Stacked spectrum (noisy thick solid line) using all BEGs in our sample. The noisy thin solid lines show the S/N-accumulated noise and the smooth solid line is the continuum + PAH emission fit using Equation (2). The estimated PAH equivalent width (EW) and the continuum slope (Γ) are denoted on the upper right corner. The dashed vertical line shows the PAH central wavelength (3.29 μm) and the dotted vertical line shows the upper limit of the wavelength range for fitting (3.9 μm).

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

Figure 5. Stacked spectra of BEGs in three subsamples with different [O ii]-based SSFRs: (a) S/N[O ii] < 3 (that is, SSFR[O ii] is not available), and among the BEGs with S/N[O ii] ⩾ 3; (b) SSFR[O ii] ⩽ 6.3; and (c) SSFR[O ii] > 6.3, in units of 10^{-12} yr^{-1}.

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

Figure 6. Stacked spectra of BEGs in three subsamples with different optical colors: (a) 0.1(u-r) ⩽ 2.2, (b) 2.2 < 0.1(u-r) ⩽ 2.5, and (c) 0.1(u-r) > 2.5.

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

Figure 7. Stacked spectra of BEGs in three subsamples with different optical spectral types: (a) SF BEGs, (b) Seyfert BEGs, and (c) LINER BEGs.

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

have stellar populations with slightly high metallicity, although this estimation is strongly model-dependent.

Meanwhile, BEGs are often thought to be the intermediate objects transforming from interacting galaxies or mergers to red elliptical galaxies or bulges of late-type galaxies (Lee et al. 2006, 2008; Kannappan et al. 2009). Known to have similar origins
Figure 8. Comparison of the NIR continuum slope ($\Gamma$) between population synthesis models and the stacked spectra of BEGs: (a) the SSP models with solar metallicity ($Z = 0.02$) and various dust attenuation values (solid, long-dashed, short-dashed, and dotted lines for $\tau_V = 0, 1, 5, 10$, respectively, where $\tau_V$ is the dust optical depth in the $V$ band); (b) the SSP models with $\tau_V = 0$ and various metallicity (short-dashed, solid, and long-dashed lines for $Z = 0.008, 0.02, 0.05$, respectively); and (c) the exponentially decreasing SFR model with the exponential timescale of 1 Gyr (EXP; long-dashed and dotted lines for $\tau_V = 0$ and 10, respectively), and the model with constant SFR of $1 M_{\odot}$ yr$^{-1}$ (CONST; short-dashed, solid, and long-dashed lines for $\tau_V = 0$ and 10, respectively), with $Z = 0.02$. The shaded area shows the $\Gamma$ range of the BEG stacked spectra and the horizontal solid line shows the $\Gamma$ value of the all-BEGs-stacked spectrum. Dust attenuation was estimated using the simple model of Charlot & Fall (2000).

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

Figure 9. Internal extinction $E(B - V)$ vs. $\Gamma$ and $EW_{3.29}$ of the BEGs. Filled circles are the values from the subsample-stacked spectra and crosses are the values from the all-BEGs-stacked spectrum. The horizontal error bars indicate the sample inter-quartile range for the median $E(B - V)$ value in each subsample.

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

AGN activity (Veilleux et al. 1995, 1999a), and are thought to be formed by strong interaction or merger of two disk galaxies (Sanders et al. 1988). Risaliti et al. (2006, 2010) estimated the $\Gamma$ and $EW_{3.29}$ of some ULIRGs showing an interesting division between AGN-host ULIRGs and starburst ULIRGs.

Figure 10 shows the loci of our BEGs on the $\Gamma$–$EW_{3.29}$ plane, compared with the objects presented in Risaliti et al. (2010). In this figure, it is found that our BEGs have $\Gamma$ and $EW_{3.29}$ values distinct from those of the ULIRGs, in the sense that the BEGs have largely negative $\Gamma$ values ($\sim -2.5$), while those of the ULIRGs are mostly larger than $-2$ (up to 6). The $EW_{3.29}$ of the BEGs is smaller than that of the ULIRGs on average, showing that the SF in the BEGs is not as active as that in the ULIRGs. The $\Gamma$ value is expected to be largely positive when the NIR continuum is dominated by dust emission. In our BEG sample, however, even the stacked spectra using optical AGN or optical SF BEGs have largely negative $\Gamma$. This indicates that the dust amount in those BEGs may not be as large as that in ULIRGs, as shown already using the internal dust reddening derived from the Balmer decrement (the mean $E(B - V)$ value of ULIRGs is larger than 1.0; Veilleux et al. 1999a, 1999b).

In short, the $\Gamma$ and $EW_{3.29}$ features of the BEGs are not easy to interpret, because they are affected by the combined effects of age, metallicity, star formation history, and dust attenuation. However, based on some previous knowledge, Balmer line information, and a few assumptions, the BEGs are thought to be old-SSP-dominated metal-rich galaxies with moderate dust attenuation. The dust attenuation in the BEGs may originate from recent SF or AGN activity. This interpretation is consistent with the previous understanding of stellar populations in BEGs (that is, mostly old stars + partially young stars; Ferreras et al. 2005; Lee et al. 2010a). There is a possibility that ULIRGs are the progenitors of BEGs in the merging/interacting phase (Veilleux et al. 2002), but any clear evidence of the close relationship between BEGs and ULIRGs is not yet found in our results based on the NIR spectroscopy.

are Ultra-Luminous Infrared Galaxies (ULIRGs). ULIRGs are very luminous in the IR band due to vigorous starburst and/or
5.2. NIR Features and AGN Activity in BEGs

As introduced in Section 1, NIR spectroscopy provides interesting clues to the internal evolutionary process of the BEGs, related to their SF or AGN activity. Those clues become more useful when combined with the optical properties of the BEGs. Figure 11 compares the stacked spectra in bins of several properties on the $\Gamma$–$EW_{3.29}$ plane, giving a summary of the key results in Figures 4–7. The $EW_{3.29}$ reflects the current SF of the BEGs well (Figure 11(c)), but it is noted that the Seyfert BEGs have $EW_{3.29}$ larger than that of the LINER BEGs. As mentioned at the end of Section 4, this result is not well explained simply by the current consensus that AGN activity destroys PAH particles.

In addition to $EW_{3.29}$, another key parameter is $\Gamma$. As shown in Figure 8, $\Gamma$ is commonly affected by age, metallicity, and dust. However, the bluest BEGs with the largest (least negative) $\Gamma$ in Figure 11(b) are not easily understood by the age or metallicity effects, because blue galaxies tend to be young or metal-poor, which will make $\Gamma$ more negative, unlike the bluest BEGs. Thus, the $\Gamma$ difference between the bluest BEGs and the other BEGs seems to be mainly due to the difference in their dust contents. It is also noted that the optical SF BEGs have small (largely negative) $\Gamma$ in Figure 11(d), which shows good consistency with the SF history dependence of $\Gamma$, indicating that those SF BEGs are not very dusty. That is, several AGNs with dusty tori in the bluest BEG subsample seem to mainly contribute to the largest (least negative) $\Gamma$.

In Figure 11(c), the BEGs with large SSFR$_{[O_3]}$ have $\Gamma$ intermediate between those of the bluest BEGs and optical SF BEGs. These are because the optical color, SSFR, and optical spectral type of the BEGs do not tightly correlate: some non-SF BEGs have large SSFR$_{[O_3]}$ or blue 0.61$(u-r)$ color. These results lead us again to the conclusion that the SF and the AGN activity in BEGs are not necessarily contradictory to each other. The coexistence of SF and AGN is not an entirely new discovery (e.g., Tzanavaris & Georgantopoulos 2007; Treister et al. 2009), but currently it is widely believed that the AGN activity tends to destroy PAH particles and truncate SF (Voit 1992; Weinmann et al. 2006; Schawinski et al. 2007; Tortora et al. 2009). In our result, however, Seyfert BEGs have larger $EW_{3.29}$ than LINER BEGs, in spite of the fact that Seyferts show stronger AGN activity than LINERs.

This result may be explained by various ways. Smith et al. (2007) and Imanishi et al. (2008) showed that PAHs can survive even if they are close to AGNs when the AGNs are not dust-free, which gives an answer to how the AGN activity and PAH emission coexist. However, it does not sufficiently explain why stronger AGNs have stronger PAH emission features. One possibility is that Seyfert BEGs and LINER BEGs may not be the separate branches in BEG evolution. Satisfying our results, one possible scenario of BEG evolution is as follows (see also Lee et al. 2010a).

Ph.1 SF BEG phase. Triggered by some mechanisms (possibly interaction or merger; Lee et al. 2006), active (but not very dusty) SF occurs in the progenitor of a BEG, originally consisting of old stars in the main. The NIR continuum is very similar to that of old passive galaxies, but the PAH emission is clearly detected.

Ph.2 Seyfert BEG phase. After the central black hole in a BEG increases its mass by gas accretion, the AGN activity starts. The SF in the BEG starts to be suppressed by the AGN feedback, but at this time, both AGN and SF activities coexist. The NIR continuum is contaminated by the AGN ($\Gamma$ increases), and the PAH emission becomes weaker than that of SF BEGs.

Ph.3 LINER BEG phase. The AGN feedback has truncated most SF by removing ambient gas in the BEG. Since this makes the gas accretion into the central black hole stop also, the AGN activity becomes weak as a natural result. The NIR continuum is intermediate between SF BEGs and Seyfert BEGs, and the PAH emission feature is the weakest among the three phases.

After these three phases, the BEGs may evolve into REGs or bulges of late-type galaxies via the phase of passive BEGs (Lee et al. 2006, 2008; Kannappan et al. 2009). The proposed scenario is consistent with the findings about the relationship between Seyferts and LINERs in several recent studies (Schawinski et al. 2007, 2009; Hickox et al. 2009; Lee et al. 2010a).

6. SUMMARY

We conducted an AKARI/NIR spectroscopic survey of SDSS-selected BEGs. We secured the NIR spectra of 36 BEGs that are well balanced in their SF/Seyfert/LINER composition. We stacked the BEG spectra in its entirety and in bins of several properties, such as color, SSFR, and optical spectral type. This is the first presentation of the BEG NIR (2.5–4.5 $\mu$m) spectra, from which we estimated the NIR continuum slope ($\Gamma$) and the equivalent width of 3.29 $\mu$m PAH emission ($EW_{3.29}$).

In the comparison between the estimated NIR spectral features of the BEGs and those of the model galaxies, the BEGs seem to be old-SSP-dominated metal-rich galaxies with moderate dust attenuation. The dust attenuation in the BEGs may originate from recent SF or AGN activity and the BEGs have a clear feature of PAH emission, the evidence of current SF. BEGs show NIR features different from those of ULIRGs, from which we cannot find any clear relationship between BEGs and ULIRGs.

Figure 11. $\Gamma$ vs. $EW_{3.29}$ of the BEGs stacked in bins of several properties: (a) all, (b) 0.61$(u-r)$ color, (c) SSFR$_{[O_3]}$, and (d) optical spectral type. In each panel, the all-BEGs-stacked result is denoted as a cross. (A color version of this figure is available in the online journal.)
AGN feedback is that SF, Seyfert, and LINER BEGs form an evolutionary sequence: SF → Seyfert → LINER.

REFERENCES

Abraham, R. G., Ellis, R. S., Fabian, A. C., Tanvir, N. R., & Glazebrook, K. 1999, MNRAS, 303, 641

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

Antonuccio-Delogu, V., & Silk, J. 2006, MNRAS, 389, 1750

Baldwin, J. A., Phillips, M. M., & Terlevich, R. 1981, PASP, 93, 5

Best, P. N., Kauffmann, G., Heckman, T. M., Brinchmann, J., Charlot, S., Ivezic, Z., & White, S. D. M. 2005, MNRAS, 362, 25

Bruzual, G., & Charlot, S. 2003, MNRAS, 344, 1000

Calzetti, D., Kinney, A. L., & Storchi-Bergmann, T. 1994, ApJ, 429, 582

Charlot, S., & Fall, S. M. 2000, ApJ, 539, 718

Cherchneff, I., & Barker, J. R. 1989, ApJ, 341, L21

Choi, Y.-Y., Park, C., & Yorke, H. W. 2007, ApJ, 658, 884

Comerford, J. M., et al. 2009, ApJ, 698, 956

De Ruyter, S., Van Winckel, H., Dominik, C., Waters, L. B. F. M., & Dejonghe, H. 2005, A&A, 435, 161

Elmegreen, D. M., Elmegreen, B. G., & Ferguson, T. E. 2005, ApJ, 623, L71

Faber, S. M., & Gallagher, J. S. 1976, ApJ, 204, 365

Ferreras, I., Lisker, T., Carollo, M., & Lilly, S. J. 2005, ApJ, 635, 243

Gallazzi, A., et al. 2006, MNRAS, 370, 1106

Groves, B., Kewley, L., Kauffmann, G., & Heckman, T. 2006, New Astron. Rev., 50, 743

Hammer, F., Flores, H., Elbaz, D., Zheng, X. Z., Liang, Y. C., & Cesarsky, C. 2005, A&A, 430, 115

Hickox, R. C., et al. 2009, ApJ, 696, 891

Ho, L. C. 2005, ApJ, 629, 680

Ho, L. C., Filippenko, A. V., & Sargent, W. L. W. 1997, ApJS, 112, 315

Hony, S. 2002, PhD thesis, Univ. of Amsterdam

Imanishi, M., Nakagawa, T., Ohyama, Y., Shirahata, M., Wada, T., Onaka, T., & Oi, N. 2008, PASJ, 60, S489

Jarrett, T. H., Chester, T., Cutri, R., Schneider, S., Rosenberg, J., Huchra, J. P., & Mader, J. 2000, AJ, 120, 298

Kannappan, S. J., Guie, J. M., & Baker, A. J. 2009, AJ, 138, 579

Kauffmann, G., et al. 2003, MNRAS, 341, 33

Kewley, L. J., & Dopita, M. A. 2003, RevMexAA Conf. Ser., 17, 83

Kewley, L. J., Groves, B., Kauffmann, G., & Heckman, T. 2006, MNRAS, 372, 961

Kim, M., Ho, L. C., & Im, M. 2006, ApJ, 642, 702

Lee, J. H., Lee, M. G., & Hwang, H. S. 2006, ApJ, 650, 148

Lee, J. H., Lee, M. G., Kim, T. H., Hwang, H. S., Park, C., & Choi, Y.-Y. 2007, ApJ, 663, L69

Lee, J. H., Lee, M. G., Park, C., & Choi, Y.-Y. 2008, MNRAS, 389, 1791

Lee, J. H., Lee, M. G., Park, C., & Choi, Y.-Y. 2010a, MNRAS, 401, 1804

Lee, J. H., Lee, M. G., Park, C., & Choi, Y.-Y. 2010b, MNRAS, 403, 1930

Leger, A., & Puget, J. L. 1984, A&A, 137, L5

Menanteau, F., Abraham, R. G., & Ellis, R. S. 2001a, MNRAS, 322, 1

Menanteau, F., Ellis, R., Abraham, R., Berger, A., & Cowie, L. 1999, MNRAS, 309, 208

Menanteau, F., Jimenez, R., & Matteucci, F. 2001b, ApJ, 562, L23

Menanteau, F. et al., 2005, ApJ, 621, 502

Menanteau, F. et al., 2005, ApJ, 620, 697

Murai, K., et al. 2007, PASJ, 59, S309

Okamura, T., et al. 2007, PASJ, 59, S401

Park, C., & Choi, Y.-Y. 2005, ApJ, 635, L29

Peeters, E., Hony, S., Van der Kruit, P. C., Tielens, A. G. G. M., Allamandola, L. J., Hudgins, D. M., & Bauschlicher, C. W. 2002, A&A, 390, 1089

Rafferty, D. A., McNamara, B. R., & Nulsen, P. E. J. 2008, ApJ, 687, 899

Risaliti, G., Imanishi, M., & Sani, E. 2010, MNRAS, 401, 197

Risaliti, G. et al., 2006, MNRAS, 365, 303

Sánchez, S. F., Becker, T., García-Lorenzo, B., Benn, C. R., Christensen, L., Kelz, A., Jahnke, K., & Roth, M. M. 2005, A&A, 429, L21

Sanders, D. B., Soifer, B. T., Elias, J. H., Madore, B. F., Matthews, K., Neugebauer, G., & Scoville, N. Z. 1988, ApJ, 325, 74

Schawinski, K., Thomas, D., Sarazin, M., Karstens, C., Kaviraj, S., Joo, S.-Y., Yi, S. K., & Silk, J. 2007, MNRAS, 382, 1415

Schawinski, K. et al., 2009, ApJ, 690, 1672

Seigler, K. 1984, ApJ, 277, 623

Shan, J., Suton, M., & Lee, L. C. 1991, ApJ, 383, 459

Smith, J. D. T. et al., 2007, ApJ, 656, 770

Stoughton, C., et al. 2002, AJ, 123, 485

Tortora, C., Antonuccio-Delogu, V., Kaviraj, S., Silk, J., Romeo, A. D., & Becciani, U. 2009, MNRAS, 396, 61

Trager, S. C., Faber, S. M., Worthey, G., & González, J. J. 2000, AJ, 119, 1645

Treister, E. et al., 2009, ApJ, 706, 535

Tremonti, C. A., et al. 2004, ApJ, 613, 898

Treu, T., Koopmans, L. V., Bolton, A. S., Burles, S., & Moustakas, L. A. 2006, ApJ, 640, 662

Tzanavaris, P., & Georgantopoulos, I. 2007, A&A, 468, 129

Veilleux, S., Kim, D.-C., & Sanders, D. B. 2002, ApJS, 143, 315

Veilleux, S., Kim, D.-C., Sanders, D. B., Mazzarella, J. M., & Soifer, B. T. 1995, ApJS, 98, 171

Veilleux, S., Sanders, D. B., & Kim, D.-C. 1999a, ApJ, 522, 113

Veilleux, S., Sanders, D. B., & Kim, D.-C. 1999b, ApJ, 522, 139

Voit, G. M. 1992, MNRAS, 258, 841

Weinmann, S. M., van den Bosch, F. C., Yang, X., Mo, H. J., Croton, D. J., & Moore, B. 2006, MNRAS, 372, 11

Williams, R. E., et al. 1996, AJ, 112, 1335

York, D. G., et al. 2000, AJ, 120, 1579