The active galactic nucleus (AGN)–host co-evolution issue is investigated here by focusing on the evolution of the [O\textsc{iii}] λ5007 emission-line profile. A large sample of narrow emission-line galaxies is selected from the Max-Planck Institute for Astrophysics/Johns Hopkins University Sloan Digital Sky Survey DR7 catalog to simultaneously measure both the [O\textsc{iii}] line profile and circumnuclear stellar population in an individual spectrum. By requiring that (1) the [O\textsc{iii}] line signal-to-noise ratio is larger than 30 and (2) the [O\textsc{iii}] line width is larger than the instrumental resolution by a factor of two, our sample is narrowed down to 2333 Seyfert galaxies/LINERs (AGNs), 793 transition galaxies, and 190 star-forming galaxies. In addition to the commonly used profile parameters (i.e., line centroid, relative velocity shift, and velocity dispersion), two dimensionless shape parameters, skewness and kurtosis, are used to quantify the line shape deviation from a pure Gaussian function. We show that the transition galaxies are systematically associated with narrower line widths and weaker [O\textsc{iii}] broad wings than the AGNs, which implies that the kinematics of emission-line gas are different in the two kinds of objects. By combining the measured host properties and line shape parameters, we find that the AGNs with stronger blue asymmetries tend to be associated with younger stellar populations. However, a similar trend is not identified in the transition galaxies. The failure likely results from a selection effect in which the transition galaxies are systematically associated with younger stellar populations than the AGNs. The evolutionary significance revealed here suggests that both narrow-line region kinematics and outflow feedback in AGNs co-evolve with their host galaxies.

Key words: galaxies: active – galaxies: evolution – quasars: emission lines

Online-only material: color figures

1. INTRODUCTION

The emission from the narrow-line region (NLR) of active galactic nuclei (AGNs) is an important tool for the study of the relationship between the activity of the central supermassive black hole (SMBH) and the growth of the host galaxy in which the SMBH resides, both because the NLR emission mainly results from illumination by the central AGN and because the NLR kinematics is believed to be mainly dominated by the gravity of the bulge (see Wilson & Heckman 1985, and references therein; Whittle 1992a, 1992b; Nelson & Whittle 1996 for a review). The gravity-dominated kinematics motivates a number of previous studies to demonstrate that the line width of the AGN’s strong [O\textsc{iii}] λ5007 emission line can be used as a proxy for the stellar velocity dispersion of the bulge (e.g., Tremaine et al. 2002; Ferrarese & Merritt 2000; Magorrian et al. 1998; Gebhardt et al. 2000; Haring & Rix 2004; Graham et al. 2011), the proxy therefore allows one to easily estimate $M_\text{BH}$ in a large sample of AGNs (e.g., Grupe & Mathur 2004; Wang & Lu 2001; Komossa & Xu 2007).

It has been known for a long time that the line profiles of the [O\textsc{iii}] doublets show a blue asymmetry with an extended blue wing and a sharp red falloff in a large fraction of AGNs (e.g., Heckman 1981; Whittle 1985; Wilson & Heckman 1985; Grupe et al. 1999; Tadhunter et al. 2001; Véron-Cetty et al. 2001; Zamanov et al. 2002; Komossa & Xu 2007; Xu & Komossa 2009; Greene & Ho 2005; de Robertis & Osterbrock 1984; Storchi-Bergmann et al. 1992; Arribas et al. 1996; Christoupolou et al. 1997). The blue asymmetry requires a narrow core Gaussian profile (FWHM $\sim$ 200–500 km s$^{-1}$) with a blueshifted, broad Gaussian component (FWHM $\sim$ 500–1000 km s$^{-1}$) to reproduce the observed asymmetric profiles for both [O\textsc{iii}] λλ4959, 5007 emission lines. The spectroscopic monitor revealed a variability timescale from 1 to 10 years for the blue wings of the [O\textsc{iii}] λ5007 lines in two type I AGNs (IZW 1: Wang et al. 2005; NGC 5548: Sergeev et al. 1997), which means that the blue wings are likely emitted from the intermediate-line region located between the traditional broad-line region and the NLR. In addition to the blue asymmetry, the redshifts of the [O\textsc{iii}] doublets are often found to be negative compared with the redshifts measured from both stellar absorption features and H\textbeta emission lines (i.e., [O\textsc{iii}] blueshifts; e.g., Phillips 1976; Zamanov et al. 2002; Marziani et al. 2003; Aoki et al. 2005; Boroson 2005; Bian et al. 2005; Komossa et al. 2008). The rare cases of objects with strong [O\textsc{iii}] blueshifts larger than 100 km s$^{-1}$ are called “blue outliers.”

The popular explanation of the observed [O\textsc{iii}] emission-line profile is that the material outflow from the central AGN plays an important role in reproducing the observed blue asymmetry and blueshift. With the advent of the high spatial resolution of the Hubble Space Telescope, spatially resolved spectroscopic observations of a few nearby Seyfert 2 galaxies indicate that the NLRs show complicated kinematics that could reproduce the observed [O\textsc{iii}] line profiles by the radial outflow acceleration (or deceleration) and/or jet expansion (e.g., Crenshaw et al. 2000, 2010; Crenshaw & Kraemer 2000; Ruiz et al. 2001; Nelson et al. 2000; Hutchings et al. 1998; Das et al. 2005, 2006, 2007; Kaiser et al. 2000; Schlesinger et al. 2009; Fischer et al. 2010, 2011).

Recent systematic studies suggested that the blue asymmetry is related to the activity of the central SMBH. Véron-Cetty et al. (2001) indicated that half of their sample of narrow-line Seyfert 1 galaxies (NLS1s) shows a broad and blueshifted [O\textsc{iii}] λ5007 component in addition to the unshifted narrow core component. Nelson et al. (2004) found a correlation between the blue asymmetry and Eigenvector-I space by studying the [O\textsc{iii}]
\( L/L_{Edd} \) associated with larger blue asymmetries tend to be stronger Fe II emitters presumably having larger Eddington ratios (\( L/L_{Edd} \)).

AGNs are now widely believed to co-evolve with their host galaxies, which is implied by the tight \( M_{BH}-\sigma \) correlation (see the citations in the first paragraph) and by the global evolutionary history of the growth of the central SMBH that traces the star formation history closely from present to \( z \sim 5 \) (e.g., Nandra et al. 2005; Silverman et al. 2008; Shankar et al. 2009; Marziani et al. 2003).

The outflow origin for both blue asymmetry and blueshift naturally gives us a hint that the [O III] emission-line profile (and the inferred NLR kinematics) co-evolves with the stellar population of the host galaxy. Here we report a study that is an effort to examine the evolution of the [O III] line profile. In principle, both broad- and narrow-line AGNs need to be analyzed for a complete study. Although the [O III] line profiles can be easily measured in the spectra of typical type I AGNs, the host galaxy properties are hard to determine because of the strong contamination from the central AGN’s continuum. Since our aim is to study the relationship between the line profile and the host galaxy properties, the narrow emission-line galaxies from the Sloan Digital Sky Survey (SDSS) are adopted in our study because their spectra allow us to simultaneously measure both the [O III] line profile and stellar population properties in an individual object. We adopt high-order dimensionless line shape parameters to describe the line profile in detail.

The paper is organized as follows. The sample selection is presented in Section 2. Section 3 describes the data reduction, including the stellar component removal, the line profile measurements, and the stellar population age measurements. Our analysis and results are shown in Section 4. The implications are discussed in Section 5. A cold dark matter (\( \Lambda \)CDM) cosmology with parameters \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1} \), \( \Omega _m = 0.3 \), and \( \Omega _\Lambda = 0.7 \) (Spergel et al. 2003) is adopted throughout the paper.

2. SAMPLE SELECTION

2.1. General Selection from the MPA/JHU Catalog

We select a sample of narrow emission-line galaxies from the value-added SDSS Data Release 7 (Abazajian et al. 2009) catalog to ensure that the stellar features could be properly separated from each observed spectrum. Second, all the emission lines used in the traditional three Baldwin–Phillips–Terlevich (BPT) diagnostic diagrams\(^2\) are required to be detected with a significance level of at least 3\( \sigma \). Third, the spectral profiles of the [O III] line \( \lambda 5007 \) emission lines are only measured for the galaxies for which [O III] lines have \( S/N > 30 \). Finally, the galaxies with redshifts within the range from 0.11 to 0.12 are removed in the subsequent spectral analysis to avoid the possible fake spectral profile caused by the poorly subtracted strong sky emission line [O I] \( \lambda 5577 \) at the observer frame.

2.2. Instrumental Resolution Selection

After the selection based on the MPA/JHU catalog, we remove from our subsequent statistical comparisons all the galaxies that have [O III] line widths smaller than \( 2 \sigma _{\text{inst}} \) according to our spectral profile measurements (see Section 3 for details). The mean intrinsic resolution used in the above criterion is adopted to be 65 km s\(^{-1} \) according to the SDSS pipeline measurements (e.g., York et al. 2000). There are two reasons for this instrumental resolution selection. First, the cut on line width removes the low-mass star-forming galaxies without bulge. Second, the cut can alleviate the impact on the measured line shape parameters caused by the instrumental resolution. For a pure Gaussian profile, the intrinsic line width \( \sigma \) can be obtained by the equation \( \sigma ^{2} = \sigma _{\text{obs}}^{2} - \sigma _{\text{inst}}^{2} \), where \( \sigma _{\text{obs}} \) and \( \sigma _{\text{inst}} \) are the observed line width and the instrumental resolution, respectively. However, this relationship is only a first-order approximation for the line profiles that deviate from a pure Gaussian profile. Our analytic calculation indicates that the correction of the instrumental resolution depends on the deviation not only for the line width, but also for the other two high-order dimensionless line shape parameters (see Section 4 and the Appendix for details).

2.3. Final Sample

After removing the duplicates in the MPA/JHU catalog, there are in total 3339 entries fulfilling the above selection.

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1 These catalogs can be downloaded from http://www.mpa-garching.mpg.de/SDSS/DR7/.

2 The BPT diagrams were originally proposed by Baldwin et al. (1981), and then refined by Veilleux & Osterbrock (1987); they are commonly used to determine the dominant powering source in narrow emission-line galaxies through their emission-line ratios.
3. SPECTRAL ANALYSIS

3.1. Separation of Stellar Features

The spectra of the selected objects are reduced and analyzed by our principal component analysis (PCA) pipeline (see Wang & Wei 2008 for details). First, each spectrum is corrected for the Galactic extinction using the extinction law with $R_V = 3.1$ (Cardelli et al. 1989), in which the color excess $E(B - V)$ is taken from the Schlegel, Finkbeiner, and Davis Galactic reddening map (Schlegel et al. 1998). Second, each extinction-corrected spectrum is then transformed to the rest frame, along with the flux correction due to the reddening effect, given the redshift provided by the SDSS pipelines (Glazebrook et al. 1998; Bromley et al. 1998). The stellar absorption features are subsequently separated from each rest-frame spectrum by modeling the continuum and absorption features by the sum of the first seven eigenspectra. The eigenspectra are built from the standard single stellar population spectral library developed by Bruzual & Charlot (2003). Each of the spectra is fitted over the rest-frame wavelength range from 3700 to 7000 Å by a $\chi^2$ minimization, except for the regions with strong emission lines (e.g., Balmer lines, [O III] $\lambda\lambda 4959, 5007$, [N II] $\lambda\lambda 6548,6583$, [S II] $\lambda\lambda 6716, 6731$, [O II] $\lambda 3727$, [O III] $\lambda 4363$, and [O I] $\lambda 6300$).

3.2. Emission-line Profile Measurements

3.2.1. Line Profile Parameters

The rest-frame emission-line-isolated spectra are used to parameterize the spectral profiles of their [O III] $\lambda 5007$ emission lines after the stellar components are removed from the observed spectra. The emission-line profile can be parameterized in many possible ways. The widely used methods include the FWHM and the second moment of the line that is defined as

$$
\sigma^2 = \left( \frac{c}{\bar{\lambda}} \right)^2 \frac{\int (\lambda - \bar{\lambda})^2 f_{\lambda} d\lambda}{\int f_{\lambda} d\lambda},
$$

where $\sigma$ is in units of $\text{km s}^{-1}$, and $\bar{\lambda} = \int \lambda f_{\lambda} d\lambda / \int f_{\lambda} d\lambda$, and $f_{\lambda}$ are the line centroid (i.e., the first moment) and the flux density of the continuum-subtracted line flux, respectively. For a pure Gaussian profile, we have a relationship $\text{FWHM} = 2\sqrt{2\ln 2}\sigma \approx 2.35\sigma$, which means that both FWHM and $\sigma$ comparably describe the line broadening if the line profile is a Gaussian function. However, as stated in Greene & Ho (2005), $\sigma$ contains more information on the line profile broadening if the profile deviates from a pure Gaussian profile.

Heckman et al. (1981) defined an asymmetry index $A_{20} = (\text{WL20} - \text{WR20})/\text{(WL20} + \text{WR20})$ to measure the line asymmetry of [O III] emission lines, where WL20 and WR20 are the half-width to the left and right of the line center defined as the 80% peak intensity level. On the basis of the index $A_{20}$, the authors found that blue asymmetry is shown in about 80% of the 36 Seyfert and radio galaxies. Alternatively, the asymmetry index $A_i = [C(i) - C(3/4)]/\text{FWHM}$ is widely used to measure the asymmetry of an AGN’s broad emission lines, where $C(i)$ are profile centroids measured at different levels (see Sulentic et al. 2000 for a review). In addition to the asymmetry, the emission-line shapes of AGNs vary from extremely peaked to very “boxy.” Previous studies used the ratio of line widths at different levels to parameterize such line shapes (e.g., Marziani et al. 1996).

To make the statistical study of the [O III] line profile feasible for a large sample, we adopt the high-order dimensionless line shape parameters to describe the line profile departures from a pure Gaussian function (see Binney & Merrifield 1998 for more details):

$$
\xi_k = \mu_k / \sigma^k \; k \geq 3,
$$
where $\mu_k$ is the $k$-order moment defined as

$$
\mu_k = \left( \frac{c}{\lambda_0} \right)^k \int \frac{(\lambda - \lambda_0)^k}{f_\lambda d\lambda} f_\lambda d\lambda
$$

and $\sigma$ is the second-order moment defined in Equation (1). The first shape parameter $\xi_3$ is the "skewness," which measures the deviation from symmetry. A pure Gaussian profile corresponds to $\xi_3 = 0$. The emission-line shape with a positive value of $\xi_3$ shows a red asymmetry, and the shape with a negative value a blue asymmetry. The second parameter $\xi_4$ is the "kurtosis," which measures the symmetric deviation from a pure Gaussian profile (for a pure Gaussian profile, we have $\xi_4 = 3$). The emission line with the peak profile superposed on a broad base has a value of $\xi_4 > 3$. A value of $\xi_4 < 3$ corresponds to a "boxy" line profile. We refer the readers to Figure 11.5 in Binney & Merrifield (1998) for an explanation of the variations of the values of $\xi_3$ and $\xi_4$ with the line shapes.

3.2.2. Relative Velocity Shifts

The bulk relative velocity shift of the [O iii] emission line is measured relative to the H$\beta$ emission line in each emission-line-isolated spectrum, because the H$\beta$ line can be easily detected and because the line shows a very small velocity shift relative to the galaxy rest frame (e.g., Komossa et al. 2008). The velocity shift is calculated as $\Delta v = \delta \lambda / \lambda_0 c$, where $\lambda_0$ and $c$ are the rest-frame wavelength of the [O iii] $\lambda 5007$ emission line and the velocity of light, respectively. $\delta \lambda$ denotes the wavelength shift of the [O iii] line with respect to the H$\beta$ line. The shift is determined from the measured line centroids ($\bar{\lambda}$) and the rest-frame wavelengths in a vacuum of both lines. With the definition of the velocity shift, a blueshift corresponds to a negative value of $\Delta v$, and a redshift to a positive value.

3.3. Stellar Population Properties

By following our previous studies again, we use the two Lick indices, i.e., the 4000 Å break ($D_0(4000)$) and the equivalent width of the H$\beta$ absorption feature of A-type stars (H$\delta A$), as the indicators of the ages of the stellar populations of the galaxies (e.g., Heckman et al. 2004; Kauffmann et al. 2003c; Kauffmann & Heckman 2009; Kewley et al. 2006; Wang & Wei 2008, 2010; Wild et al. 2007). Both indices are measured in the removed stellar component for each spectrum and are reliable age indicators until a few Gyr after the onset of a burst (e.g., Kauffmann et al. 2003c; Bruzual & Charlot 2003).

3.4. Broad-line AGNs

The sub-sample of partially obscured AGNs associated with broad H$\alpha$ emission lines (i.e., Seyfert 1.8/1.9 galaxies) is selected from the parent AGN and transition galaxy samples. Although the existence of the broad H$\alpha$ emission is directly indicative of the accretion activity of the central SMBH, the underlying AGN’s continuum in these partially obscured AGNs could potentially decrease the two measured indices. These partially obscured AGNs are therefore removed from the subsequent analysis when the two indices are involved.

Following our previous studies (Wang & Wei 2008), the broad-line AGNs are selected by means of the high-velocity wings of the broad H$\alpha$ components on their blue side after the stellar features are removed from the spectra. The red wing is not adopted in the selection because of the superposition of the strong [N ii] $\lambda 6583$ emission line. The partially obscured AGNs are at first automatically selected by the criterion $F_w/\sigma_r > 3$, where $F_w$ is the specific flux of the line wing averaged within the wavelength range from 6500 to 6350 Å in the rest frame and $\sigma_r$ is the standard deviation of the continuum flux within the emission-line-free region ranging from $\lambda 5980$ to $\lambda 6020$. The automatically selected AGNs are then inspected one by one by eye. In total, there are 174 broad-line Seyfert galaxies/LINERs and 55 broad-line transition galaxies.

3.5. Uncertainties Estimation

The MPA/JHU catalog contains many duplicates because of repeated observations. The duplicates allow us to roughly estimate the uncertainties for the line shape parameters and the stellar population age indicators. The duplicates are reduced and measured by the same method as described above. For the three main sub-samples (i.e., AGNs, transition galaxies, and star-forming galaxies), the uncertainties are estimated to be 0.14 ± 0.08 and 0.20 ± 0.14 for the shape parameters $\xi_3$ and $\xi_4$, respectively. The two Lick indices have uncertainties: $\Delta D_0(4000) = 0.03 ± 0.02$ and $\Delta H\delta A = 0.38 ± 0.19$. For the comparison sample, the duplicates provide uncertainties of 0.08 ± 0.05 and 0.13 ± 0.06 for the parameters $\xi_3$ and $\xi_4$, respectively.

4. ANALYSIS AND RESULTS

After obtaining all the required parameters, the relation between the [O iii] line profiles and the stellar population properties is examined.

4.1. [O iii] Line Width and [O iii] $\lambda 5007$ Relative Velocity Shifts: AGNs versus Transition Galaxies

In this section the [O iii] line profiles of the AGNs and the transition galaxies are compared. To avoid the possible systematics caused by the host galaxy properties, we compare the line profiles in a sample of matched galaxy pairs (e.g., Kauffmann et al. 2006). The matched pairs are created according to the SDSS DR4 MPA/JHU AGN catalog. The catalog provides the measurements of galaxy properties for the AGNs that are classified according to the demarcation line given in Kauffmann et al. (2003a). We select the pairs that have $\Delta \log M_*/0.1 < 0.1, \Delta \log \mu_* < 0.1, \Delta C < 0.1, \Delta \sigma_r < 30 \text{ km s}^{-1}$, and $\Delta z < 0.01$, where $M_*$ is the stellar mass in units of $M_\odot$, $\mu_*$ is the effective stellar mass density ($\mu_* = M_*/2\pi r_{50,z}^2$), and $r_{50,z}$ is the half-light radius in the $z$ band in units of $M_\odot$ kpc$^{-2}$, $C$ is the concentration index defined as $C = R_{90}/R_{50}$ which is the ratio of the radius enclosing 90% of the total flux to that enclosing 50% of the flux in the $r$ band, $\sigma_r$ is the stellar velocity dispersion, and $z$ is the redshift. Because there are many more AGNs than transition galaxies in our sample, a large fraction of the transition galaxies have a few AGN pairs. In these cases, one AGN is assigned to a pair by a random selection, and the final distributions are built from 100 Monte Carlo iterations. Finally, there are a total of 163 distinct galaxy pairs in which no galaxy is assigned to a pair more than once.

The left panel in Figure 2 compares the cumulative distributions of the [O iii] line widths in terms of the calculated velocity

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3 The 4000 Å break is defined as $D_0(4000) = \int_{4100}^{4000} f_\lambda d\lambda / \int_{3950}^{3900} f_\lambda d\lambda$ (Bruzual 1983; Balogh et al. 1999). The index H$\delta A$ is defined by Worthey & Ottaviani (1997) as $H\delta A = (4122.25 - 4083.50)(1 - F_1/F_2)$, where $F_1$ is the flux within the $\lambda \lambda 4083.50$–4122.25 feature bandpasses and $F_2$ is the flux of the pseudo-continuum within two defined bandpasses: blue $\lambda \lambda 4041.60$–4079.75 and red $\lambda \lambda 4128.50$–4161.00.
The AGNs and transition galaxies are shown by the red solid and green dotted lines, respectively. The error bars result from our iterations. One can clearly see that the line profiles of the AGNs are systematically wider than those of the transition galaxies. A two-sided Kolmogorov–Smirnov test yields a maximum discrepancy of 0.282 with a corresponding probability of $4.6 \times 10^{-3}$. In fact, the comparison of the parameter $\xi_4$ indicates that the difference in the distributions is likely due to the fact that the transition galaxies have systematically smaller values of $\xi_4$ than the AGNs (see Section 4.3 for more details). That means the transition galaxies are associated with weaker [O III] broad components compared with the AGNs, which implies that the feedback caused by the material outflow is less strong in the transition galaxies than in the AGNs.

The distributions of the [O III] $\lambda$5007 relative velocity shifts of the AGNs and transition galaxies defined in Section 3.2.2 are compared in the right panel of Figure 2. The symbols are the same as in the left panel. A two-sided Kolmogorov–Smirnov test shows that the two samples match at a probability of 77%, although a careful examination suggests that the AGNs marginally tend to be associated with larger negative velocity shifts compared with the transition galaxies.

4.2. Line Shape Parameters $\xi_3$ and $\xi_4$

The bottom left panel in Figure 3 shows the $\xi_4$ versus $\xi_3$ diagram. The AGNs, transition galaxies, and star-forming galaxies are symbolized by the red, green, and blue points, respectively. The overplotted contours present the distribution of the star-forming galaxies in the comparison sample. The two crosses at the left bottom corner show the typical uncertainties for both parameters as roughly estimated from the duplicates. The red solid one indicates the uncertainties for the large line width objects and the black dashed one for the comparison sample. The upper left panel and the right bottom panel show the distributions of the parameters $\xi_3$ and $\xi_4$ for all the sub-samples (including the comparison sample), respectively. The distributions are color-coded for the sub-samples in the same way as in the bottom left panel. As expected from an emission-line profile dominated by the instrumental resolution, the distribution of the comparison sample is strongly clustered around the point (i.e., $\xi_3 = 0$ and $\xi_4 = 3$) associated with a pure Gaussian function. The last column in Table 1 lists the average and median values of $\xi_3$ ($\xi_3 \sim 0.01$) and $\xi_4$ ($\xi_4 \sim 0.01$) for the comparison sample. The same values are listed in the last column in Table 2 but for the parameter $\xi_4$ ($\xi_4 \sim 2.61$ and $\xi_4 \sim 2.58$).

The dispersions are calculated to be 0.14 and 0.43 for the parameters $\xi_3$ and $\xi_4$, respectively. The distribution therefore validates our spectral measurements because the distribution of the comparison sample is highly consistent with the prediction of a pure Gaussian function.

The statistics for both AGNs and transition galaxies are tabulated in Tables 2 and 3. One can find from the tables that the line profiles of these galaxies systematically deviate from that of the control sample (i.e., deviate from a pure Gaussian function).
profile) by not only smaller $\xi_3$ (i.e., a stronger blue asymmetry), but also larger $\xi_4$ (i.e., a stronger broad base). The main panel in Figure 3 shows that both AGNs and transition galaxies form a sequence starting from the pure Gaussian region to the upper left corner. In fact, this phenomenon is qualitatively in agreement with the fact that two Gaussian components, one representing the narrow line core and the other representing the blueshifted broad wing, are usually required to model the observed [O iii] line profiles. A minor fraction of the objects deviate from the sequence by their positive values of $\xi_3$. By inspecting the spectra of these objects one by one by eye, we find that the deviations are mainly a result of contamination at the [O iii] red wing caused by the weak low-ionization emission line He i $\lambda 5016$ (Véron et al. 2002).

It is interesting to see that the star-forming galaxies with $\sigma > 2\sigma_{\text{inst}}$ follow the sequence as well, although most of them have Gaussian line profiles. To validate the deviations in these galaxies, the spectra with $\xi_3 < -0.5$ are then inspected one by one by eye again. To understand the nature of these star-forming galaxies with blue asymmetric [O iii] emission lines, we need to carefully model all the strong emission lines in individual spectra. The issue is outside of the scope of this paper and will be examined in our subsequent studies.

The results from the two-sided Kolmogorov–Smirnov tests are tabulated in Tables 3 and 4 for the parameters $\xi_3$ and $\xi_4$, respectively. Each entry contains the maximum absolute discrepancy between the two sub-samples used and the corresponding probability that the two sub-samples match. Although the AGNs and the transition galaxies show similar distributions for $\xi_3$, the AGNs significantly differ from the transition galaxies in the distribution of parameter $\xi_4$. The fraction of objects with strong broad [O iii] wings is larger in the AGNs than in the transition galaxies.

Previous studies frequently identified a strong correlation between the [O iii] line widths and the [O iii] blueshifts (e.g., Bian et al. 2005; Komossa et al. 2008; Zamanov et al. 2002). The correlation is commonly explained by the material outflows. Similar correlations are also identified in iron coronal lines (Erkens et al. 1997) and optical Fe ii complexes (Hu et al. 2008) in typical type I AGNs. The left panel in Figure 4 plots the velocity shift as a function of the line width for the AGNs (red points) and the transition galaxies (green points). Spearman rank-order tests show a marginal anti-correlation between the velocity shifts and the line widths for the AGNs (with a Spearman correlation coefficient $r_s = -0.088$ at a significance level $P < 10^{-4}$, where $P$ is the probability that there is no correlation between the two variables), but a stronger correlation for the transition galaxies (with $r_s = -0.229$ and $P < 10^{-4}$). As an additional examination, the middle panel in the figure plots the velocity shift against the parameter $\xi_3$. Strong correlations between the two variables can be identified for both AGNs ($r_s = 0.334$ and $P < 10^{-4}$) and transition galaxies ($r_s = 0.513$ and $P < 10^{-4}$), which means that the larger the blueshift is the stronger the blue asymmetry will be. One can see from the correlations that the objects with the largest velocity shifts deviate from the correlations. These objects instead show symmetrical line profiles. In order to further describe their line profiles, the right panel in the figure plots the velocity shift against the parameter $\xi_4$. We find that these [O iii] lines have “boxy” line profiles rather than peaked ones. In fact, a “boxy” line profile could be reproduced by the sum of two or more (distinct) peaks with comparable fluxes and line widths (see examples of spectra in Figure 1 in Greene & Ho 2005).

### 4.3. [O iii] Line Profile versus Stellar Population

The evolution effect on the [O iii] line profile is examined in this section by using the two indices, $D_4(4000)$ and H$\delta_A$, as the indicators of the ages of the circumnuclear stellar populations. As described in Section 3.3, the partially obscured AGNs are excluded from the analysis throughout this section.

The two indices are plotted against the parameter $\xi_3$ (the left panels) and against the relative velocity shift (the right panels) for the AGNs in Figure 5. At first glance, we fail to directly identify any significant correlation between the line profile parameters and the stellar population ages in the four panels. To examine the evolution effect in more detail, we divide the AGN sample into two groups according to their $\xi_3$ values: one group for the galaxies with $\xi_3 > -0.5$ and another...
group for the galaxies with $\xi_3 < -0.5$. The distributions of the $D_n(4000)$ values of the two groups are compared in the upper left panel of Figure 7. The comparison indicates a significant difference between the two groups. The AGNs with a larger amount of blue asymmetry are systematically associated with younger stellar populations. A two-sided Kolmogorov–Smirnov test indicates that the difference between the two distributions is at a significance level of $P < 1 \times 10^{-9}$ with a maximum absolute discrepancy of 0.22. The AGN sample is instead separated into two groups by the relative velocity shift at $\Delta v = -100$ km s$^{-1}$. We identify a marginal trend that the larger the blue velocity shifts are, the younger the associated stellar populations are (see the bottom left panel in Figure 7). The same statistical test yields a probability that the two groups match of $P = 9 \times 10^{-2}$ (with a maximum absolute discrepancy of 0.11).

Figure 6 is the same as Figure 5 but for the transition galaxies. The same methods as the AGN sample are adopted to divide these galaxies into two groups. The right panels in Figure 7 compare the distributions of $D_n(4000)$ for the two groups. The two-sided Kolmogorov–Smirnov tests suggest that the two distributions match at the probabilities $P = 0.02$ for the $\xi_3$ separation and $P = 0.32$ for the $\Delta V$ separation, which is much less significant than for the AGN sample. In fact, these results are easily understood because the transition galaxies are usually systematically younger than the AGNs (see also Kewley et al. 2006; Schawinski et al. 2007; Wang & Wei 2008).

In summary, our results indicate that the AGNs associated with young stellar populations show a wide range in their [O iii] line profiles that vary from a blue asymmetrical shape to a Gaussian function. In contrast, the AGNs associated with old stellar populations always show symmetrical line profiles.

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4 Note that similar results can be obtained for the index $H \delta_A$. 

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5. DISCUSSIONS

5.1. $L/L_{Edd}$ as A Physical Driver

The evolution of the [O iii] $\lambda5007$ emission-line profile is studied using a large sample of narrow emission-line galaxies selected from the MPA/JHU SDSS DR7 catalog. The line profile parameterizing allows us to reveal a trend that AGNs with more significant blue asymmetries tend to be associated with younger stellar populations. We argue that the trend is not driven only by the orientation effect (Antonucci 1993; Elitzur 2007). It is widely accepted that the commonly observed blue asymmetrical and blueshifted [O iii] line profiles are caused by
the wind-driven NLR outflows. The orientation-driven scenario therefore results in an odd corollary that a fraction of the AGNs with young stellar populations have outflow directions closer to the line of sight of observers than the AGNs with old stellar populations, while the starlight components from the host galaxies are believed to be isotropic.

The revealed trend can be alternatively driven by the activity of the central SMBH. In fact, there is a significant amount of observational evidence supporting that the \([\text{O} \text{ iii}]\) line blue asymmetries and blueshifts are correlated with \(L/L_{\text{Edd}}\) or Eigenvector-I space in typical type I AGNs (see the description and citations in Section 1). The relationship between the \([\text{O} \text{ iii}]\) line profile and \(L/L_{\text{Edd}}\) is examined in the current narrow-line AGN sample to present a complete understanding. Similar to the previous studies of narrow-line AGNs, the parameter \(L_{\text{[O} \text{ iii}]/\sigma^4}\) (e.g., Heckman et al. 2004) is used as a proxy of \(\lambda_{\text{Edd}} = L/L_{\text{Edd}}\), where \(L_{\text{[O} \text{ iii]}\) and \(\sigma_4\) are the \([\text{O} \text{ iii}]\) \(\lambda5007\) line luminosity and the bulge velocity dispersion, respectively. The transition galaxies are excluded from the subsequent calculations because of the possible contamination caused by \(\text{H} \text{ II}\) regions. The bolometric luminosity \(L\) is transformed from \(L_{\text{[O} \text{ iii]}}\) through the bolometric correction \(L/L_{\text{[O} \text{ iii]}\approx 3500}\) (see Heckman et al. 2004 for details). By assuming the Balmer decrement for the standard Case B recombination and the Galactic extinction curve with \(R_V = 3.1\), the \([\text{O} \text{ iii}]\) line luminosity is corrected for the local extinction that is inferred from the narrow-line ratio \(H\alpha/H\beta\). The black hole mass is estimated from the \(M_{\text{BH}}-\alpha_4\) calibration: \(\log(M_{\text{BH}}/M_\odot) = 8.13 + 4.02 \log(\sigma_4/200 \text{ km s}^{-1})\) (Tremaine et al. 2002), in which the velocity dispersion is measured for each spectrum through our PCA fittings. The galaxies with \(\sigma_4 < 70 \text{ km s}^{-1}\) are removed from the analysis because the SDSS instrumental resolution is \(\sigma_{\text{inst}} \approx 65 \text{ km s}^{-1}\).

The results are shown in Figure 8. The left panel presents an anti-correlation between \(L_{\text{[O} \text{ iii]}/\sigma^4}\) and \(D_4(4000)\). The larger the Eddington ratio is, the younger the stellar population is, which is consistent with previous studies (e.g., Kewley et al. 2006; Kauffmann et al. 2007). The middle panel plots \(L_{\text{[O} \text{ iii]}/\sigma^4}\) as a function of the parameter \(\xi_3\). When compared with Figure 5, one can find a similar trend in the \(L_{\text{[O} \text{ iii]}/\sigma^4}\) versus \(\xi_3\) plot as that in the \(D_3(4000)\) versus \(\xi_3\) plane. AGNs with a large amount of blue asymmetry tend to have large \(L/L_{\text{Edd}}\). A much stronger trend can be identified in the right panel between \(L_{\text{[O} \text{ iii]}/\sigma^4}\) and the parameter \(\xi_4\). The trend indicates the fact that AGNs with larger Eddington ratios tend to be associated with stronger \([\text{O} \text{ iii}]\) broad components. However, we fail to find a significant trend between \(L_{\text{[O} \text{ iii]}/\sigma^4}\) and the bulk relative velocity shifts \(\Delta\phi\).

Spearman rank-order tests are performed to show either the Eddington ratio or the stellar population is intrinsically related to the line asymmetry. The resulting correlation coefficient matrix is listed in Table 5. All the entries in the table have a probability of null correlation \(P < 10^{-4}\). Although both \(\lambda_{\text{Edd}}\) and \(D_4(4000)\) are correlated with \(\xi_2\) at comparable significance levels, \(\xi_4\) is more strongly correlated with \(\lambda_{\text{Edd}}\) than with \(D_4(4000)\). The stronger correlation therefore indicates that the trend between the line asymmetry and \(D_4(4000)\) is likely physically driven by the evolution of the Eddington ratio (see below).

### 5.2. Evolution of the \([\text{O} \text{ iii}]\) Emission-line Profile

The trend that AGNs with more significant blue asymmetry tend to be associated with younger stellar populations provides a piece of direct evidence supporting the co-evolution of the NLR kinematics and the growth of the host galaxy. AGNs with stronger outflows tend to be at an earlier evolutionary stage as inferred from the stellar population ages. The analysis in the above section further suggests that the trend is likely driven by \(L/L_{\text{Edd}}\). The important evolutionary role of \(L/L_{\text{Edd}}\) has been frequently proposed in recent studies (e.g., Wang & Wei 2008, 2009, 2010; Kewley et al. 2006; Heckman et al. 2004). Putting these pieces together yields an improved co-evolution scenario in which AGNs likely evolve from a high-\(L/L_{\text{Edd}}\) state with strong outflow to a low-\(L/L_{\text{Edd}}\) state with weak outflow as the circumnuclear stellar population continually ages.

This evolutionary scenario is consistent with the current understandings of AGNs. Leighly et al. (1997) reported evidence of outflow evolution in three NLS1s. In comparison with typical broad-line Seyfert galaxies, NLS1s are “young” AGNs (Mathur 2000) typical of smaller \(M_{\text{BH}}\), higher \(L/L_{\text{Edd}}\), larger \([\text{O} \text{ iii}]\) emission-line asymmetries, younger circumnuclear stellar populations possibly at post-starburst phase, and enhanced star formations as recently revealed by observations by Spitzer (e.g., Boroson 2002, 2005; Zamanov et al. 2002; Boroson & Green 1992; Wang et al. 1996; Boller et al. 1996; Sulentic et al. 2000; Xu et al. 2007; Zhou et al. 2005; Wang & Wei 2006).

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5 We refer the readers to the review in Veilleux et al. (2005) for the evidence for outflows in AGNs; see Komossa et al. (2008) for a discussion of the various models.

6 It is commonly believed that the Eigenvector-I space is physically driven by \(L/L_{\text{Edd}}\) (e.g., Boroson & Green 1992; Boroson 2002).
The feedback from central AGNs is frequently involved in the modern numerical and semi-analytical galaxy evolution models to quench the star formation and to blow the gas or dust away through the powerful AGN’s wind (e.g., Springel et al. 2005; Di Matteo et al. 2005; Kauffmann & Heckman 2009; Fabian 1999; Hopkins et al. 2005, 2008a, 2008b; Croton et al. 2006; Somerville et al. 2008; Khlatayan et al. 2008). The numerical simulation performed by Hopkins et al. (2005) suggests a scenario that the powerful AGN’s wind is required to occur in the young AGN phase in which the central SMBH is heavily obscured by the star-forming gas and dust.

5.3. Are Transition Galaxies at an Intermediate Evolutionary Phase?

Transition galaxies are the narrow emission-line galaxies located between the theoretical and empirical demarcation lines in the [O III]/Hβ versus [N II]/Hα diagnostic diagram (Kauffmann et al. 2003a; Kewley et al. 2001). Their emission-line properties are explained by the mixture of the contributions from both star formations and typical AGNs (e.g., Kewley et al. 2006; Ho et al. 1993, see recent review in Ho 2008). Our spectral profile analysis indicates that the transition galaxies differ from the Seyfert galaxies in their [O III] emission-line profiles. The transition galaxies show weaker [O III] broad wings, and narrower [O III] line widths than the Seyfert galaxies, which implies that the two kinds of objects are different from each other in their mass outflow kinematics. The line profile comparison allows us to suspect that the transition galaxies “bridge” the AGN–starburst co-evolution from the early starburst-dominated phase to the late AGN-dominated phase (e.g., Yuan et al. 2010; Wang & Wei 2006; Schawinski et al. 2007, 2009). The evolutionary role of the transition galaxies has been reported in recent studies by many authors. With the large SDSS spectroscopic database, transition galaxies found to be systematically associated with younger stellar populations than Seyfert galaxies (e.g., Kewley et al. 2006; Wild et al. 2007; and also see Figure 6 in this paper). Westoby et al. (2007) found that the distribution of the Hα equivalent widths of the transition galaxies peaks at the valley between the red and blue sequences. By analyzing the millimeter wavelength observation taken by the 30 m IRAM, Schawinski et al. (2009) suggested that the molecular gas reservoir is destructed by the AGN feedback at the early AGN+star-forming transition phase.

6. CONCLUSION

We systematically examined the evolutionary issue of the [O III] λ5007 emission-line profile using a large sample of narrow emission-line galaxies selected from the MPA/JHU SDSS DR7 value-added catalog. The sample is separated into three sub-samples (i.e., star-forming galaxies, transition galaxies, and Seyfert galaxies/LINEs) on the basis of the line ratios given in the catalog. Two shape parameters, skewness (ξ_1) and kurtosis (ξ_2), are additionally used to quantify the profile deviation from a pure Gaussian. Our analysis indicates that (1) the transition galaxies are systematically associated with narrower line widths and with weaker [O III] broad wings than the AGNs and (2) the AGNs with stronger blue asymmetries tend to be associated with younger stellar populations. The evolutionary significance of the [O III] line profile suggests a co-evolution of the outflow feedback and the AGN’s host galaxy.

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APPENDIX

A toy model of the emission-line profile is constructed here to illustrate the effect of the instrumental resolution on the measured line shape parameters. The model is constructed by assuming an observed [O III] emission-line profile that is prescribed by the sum of two pure Gaussian profiles: φ(υ) = φ_1(0, σ_1) + αφ_2(μ, σ_2), where φ_1(0, σ_1) is a normalized Gaussian distribution with the peak at zero and a variance of σ_1^2; φ_2(μ, σ_2) is the same distribution but with the peak shifted at μ and a variance of σ_2^2, and α is a parameter much less than unity. With this two Gaussian component model, φ_1(0, σ_1) represents the narrow core of the emission, and αφ_2(μ, σ_2) the shifted, low-contrast broad wing (we require |μ|/σ_2 ≪ 1 for avoiding double peaked profile). The normalizations of the two distributions yield

\[ φ(υ) = 1 + α. \]

The first moment (i.e., the line centroid) is written as

\[ \mu = \int \upsilon φ(υ)dυ = \int \upsilon φ_1dυ + \alpha \int \upsilon φ_2dυ = \upsilon_μ + α\upsilon_μ, \]

which is not affected by the instrumental resolution. With the first moment, the high-order moments are written as

\[ E{(υ - \mu)^r} = \int (υ - \mu)^rφ_1dυ. \]  

The second moment of the total line profile is therefore inferred to be approximately the linear combination of the square of the two moments of the two distributions:

\[ \int (υ - \mu)^2φdυ = \int (υ - \mu_1)^2φ_1dυ + \alpha \int (υ - \mu_2)^2φ_2dυ = \upsilon_μ^2 + \alpha(1 - \alpha^2)σ_2^2. \]

In the context of the toy model, the linear combination means that the instrumental resolution σ_{inst} can be removed from the measured values according to the equation σ_{inst}^2 = σ_2^2 + (1 + α)σ_{inst}^2, which means that the removal depends on the relative strength of the low-contrast Gaussian profile, i.e., the parameter α.

The third moment of the total profile can be trivially obtained through the integration

\[ \int (υ - \mu)^3φdυ = (α - 3\alpha^2 + 2α^3 - α^4)\upsilon_μ^3 + 3\mu_2α(σ_2^2 - 2α^2σ_1^2 - α^2σ_2^2). \]

By ignoring the terms with high orders of α, the third moment approximately equals αμ^3 + 3αμ(σ_2^2 - σ_1^2). The result suggests that the measured third moment depends only on the relative shift of the low-contrast Gaussian profile, but also on the relative strength denoted by the parameter α. Although the second term in the above result means that the third moment does not depend on the instrumental resolution in our toy model at the first-order approximation: σ_2^2 - σ_1^2 = σ_{obs,2}^2 - σ_{obs,1}^2, the definition of the dimensionless shape parameter ξ_1 introduces a nonlinear dependence on the instrumental resolution in the denominator (see Equation (2) in the main text). By adopting the same approach, the fourth moment is calculated to be

\[ \int (υ - \mu)^4φdυ ≈ \alpha μ^4 + 3(σ_1^2 + ασ_2^2) + 6αμ^2σ_2^2, \]

where one sees that the second and third terms introduce again a nonlinear dependence on the instrumental resolution.

With this toy model, the galaxies for which [O III] λ5007 lines are narrower than 2σ_{inst} are then dropped out from our statistical analysis to avoid the effect of instrumental resolution on the measured line shape parameters.
