UNDERSTANDING THE AGN–HOST CONNECTION IN BROAD Mg II EMISSION-SELECTED AGN–HOST HYBRID QUASARS

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ABSTRACT

We study the issue of active galactic nucleus (AGN)–host connection in intermediate-z (1.2 > z > 0.4) galaxies with hybrid spectra (hybrid QSOs for short). The observed spectra redward of the Balmer limit are dominated by starlight, and the spectra at the blue end by both an AGN continuum and an Mg II broad emission line. This unique property allows us to examine both an AGN and its host galaxy in an individual galaxy simultaneously. First, 15 hybrid QSOs are selected from the Sloan Digital Sky Survey (SDSS) Data Release 6. The spectra are then analyzed in detail for three objects: SDSS J162446.49+461946.7, SDSS J102633.32+103443.8, and SDSS J090036.44+381353.0. Our spectral analysis shows that the current star formation activities are strongly suppressed, and that the latest burst ages range from ~400 Myr to 1 Gyr. Based on the Mg II black hole masses, the three hybrid QSOs are consistent with the $D_n(4000) - L/L_{Edd}$ sequence that was previously established in local AGNs. The three hybrid QSOs are located in the middle range of the sequence, which implies that the hybrid QSOs are at the transition stage not only from young to old AGNs, but also from a host-dominated phase to an AGN-dominated phase.

Key words: galaxies: active – galaxies: starburst – quasars: individual (SDSS J102633.32+103443)

Online-only material: color figures

1. INTRODUCTION

Despite the fact that there are still many unresolved problems, recent numerous observational and theoretical studies have shown that an active galactic nucleus (AGN) plays an important role in galaxy evolution. The mass of a central supermassive black hole (SMBH) is believed to grow simultaneously with the formation of the bulge of the host where the SMBH resides, as is evident from the well established $M_{BH} - \sigma$ relation (e.g., Magorrian et al. 1998; Gebhardt et al. 2000; Tremaine et al. 2002; Ferrarese & Merritt 2000; Ferrarese et al. 2006; Greene & Ho 2006; Ho et al. 2008a, 2008b). Another clue to the coevolution of SMBHs and starbursts is the fact that both quasar activity density and star formation rate (SFR) density apparently peak at $z \approx 2–3$ (e.g., Nandra et al. 2005). By adopting a variety of feedback mechanisms from black hole growth on star formation occurring in the bulge, a series of models was developed to explain the coevolution of an AGN and its host galaxy (e.g., Fabian 1999; Begelman & Nath 2005; Granato et al. 2004; Springel et al. 2005a, 2005b; Hopkins et al. 2006, and references therein).

Understanding in detail how an AGN coevolves with star formation is, however, seriously impeded by the problems caused by the orientation effect (see the review in Antonucci 1993; Elitzur 2007). Briefly, the starlight component is usually masked by the strong continuum and broad emission lines emitting from the central engine in the spectra of type I AGNs. In the contrast, the starlight component can be much more easily detected in type II AGNs; however the AGN continuum and broad lines are blocked by the torus. So far, a variety of approaches has been adopted by different authors to overcome the problem. We refer the reader to Wang & Wei (2008, and references therein) for a recent comment on these approaches. In Wang & Wei (2008) and P. F. Xiao et al. (2009, in preparation), these authors examined the coevolution of AGN and star formation by using the local partially obscured AGNs (i.e., Seyfert 1.8/1.9 galaxies) selected from the MPA/JHU SDSS DR4 catalog (e.g., Kauffmann et al. 2003a, 2003b, 2003c). The spectra of these galaxies show good balance between the AGN and starlight components, which allows the authors to directly determine the properties of both AGN and stellar population simultaneously in an individual object. They then proposed an evolutionary scenario that the Eddington ratio decreases as the circumnuclear stellar population ages (see also Heckman et al. 2004; Kewley et al. 2006, Wild et al. 2007).

We attempt to extend these studies to objects within $1.2 > z > 0.4$ in this paper. Since the emission of evolved stars drops significantly in the short-wavelength region, the broad Mg II $\lambda$2800 emission line could be used to directly estimate the properties of the central SMBH when broad H$\beta$ emission is weak or strongly contaminated by starlight and when H$\alpha$ emission is shifted out of the optical region. Here, we focus on quasars with hybrid spectral properties (hereafter “hybrid QSOs”): (1) the spectrum redward of the Balmer limit is dominated by a starlight component; (2) at the same time, the spectrum at the blue end shows an evident broad Mg II $\lambda$2800 emission line that is emitted from the central AGN. To our knowledge, a similar object is only studied in detail (for stellar populations only) in the particular post-starburst QSO, UN J1025−0040, by Brotherton et al. (1999). Another striking case with a similar spectrum is reported in SDSS J231055−090107 (Canalizo et al. 2006).

In this paper, we first select a sample of 15 hybrid QSOs from the SDSS. The detailed spectral analysis is then performed for three objects: SDSS J163446.49+461946.7 (at $z = 0.576$, abbreviated here as SDSS J1634+4619), SDSS J102633.32+103443.8 (at $z = 0.435$, abbreviated here as SDSS J1026+1034), and SDSS 090036.44+381353.0 (at $z = 0.434$, abbreviated here as SDSS 0900+3813). The spectra of the three objects have high adequate average signal-to-noise ratios (S/Ns) of all the spectra (see Table 1), appropriate Mg II emission profiles and stellar absorption features (especially the
The telescope is equipped with two fiber-fed spectrographs. The Mg features from the SDSS Data Release 6 catalogs (Adelman-McCarthy et al. 1998; Bromley et al. 1998) developed pipelines, spectro2d and specBS (Glazebrook et al. 2000). The survey is carried out by a dedicated wide-field 3″ fiber aperture. The spectra have a resolution of 1800 (corresponding to σλ ≃ 0.5 Å). The spectra are spectrophotometrically calibrated within a wavelength range from 3800 to 9200 Å in the observer’s frame. The spectra are reduced automatically by the SDSS pipelines. The selected sample contains 1946 galaxies and 7694 quasars fulfilling the above criteria. An automatic routine is developed to select the hybrid quasars whose spectra are extremely blue or dominated by extremely hot stars. In the first case, the blue AGN continuum dilutes the 4000 Å drop that is caused by the stellar absorptions. The starlight component is therefore hard to identify and separate from the observed spectra (the same for the second case). The sample is listed in Table 1. For each object, the table shows its plate number, modified Julian date of observation, number of fibers on the plate, redshift, equivalent width of the Mg II emission line, corresponding S/N of Mg II, and average S/N of the whole spectrum. The observed spectra are displayed in Figure 1.

Table 1 Sample of 15 Hybrid QSOs Selected from SDSS DR6

| Name               | Fiber ID | Plate ID | MJD ID | z      | EW(Mg II)$^b$ | S/N Mg II$^b$ | S/N Spec$^a$ |
|--------------------|----------|----------|--------|--------|--------------|---------------|--------------|
| SDSS J074156.79+345405.5 | 394      | 542      | 51993  | 0.448  | 32.3 ± 1.7   | 18.9 ± 0.1    | 5.0          |
| SDSS J074524.97+375436.7 | 170      | 433      | 51873  | 0.406  | 15.2 ± 1.7   | 8.7 ± 0.1     | 5.0          |
| SDSS J081535.89+552558.4 | 590      | 1871     | 53384  | 0.413  | 16.9 ± 2.3   | 7.3 ± 0.4     | 4.7          |
| SDSS J082718.94+29204.3 | 600      | 1207     | 52672  | 0.408  | 19.8 ± 2.1   | 9.3 ± 0.4     | 5.5          |
| SDSS J090036.44+381353.0$^a$ | 478      | 936      | 52705  | 0.434  | 41.9 ± 2.0   | 21.2 ± 0.2    | 5.9          |
| SDSS J093912.82+455358.8 | 380      | 1202     | 52672  | 0.422  | 21.4 ± 1.9   | 11.5 ± 0.4    | 6.2          |
| SDSS J101011.59+444212.0 | 193      | 943      | 52376  | 0.406  | 4.7 ± 1.3    | 3.6 ± 0.3     | 3.9          |
| SDSS J101306.80+294250.1 | 69       | 1953     | 53358  | 0.483  | 7.3 ± 2.1    | 3.5 ± 0.3     | 5.2          |
| SDSS J102633.32+103443.8$^a$ | 142      | 1598     | 53033  | 0.435  | 23.4 ± 2.2   | 10.8 ± 0.4    | 6.0          |
| SDSS J115507.20+351058.7 | 375      | 2099     | 53469  | 0.421  | 371.1 ± 21.8 | 17.0 ± 2.1    | 2.1          |
| SDSS J141324.27+530527.0 | 133      | 1325     | 52762  | 0.455  | 56.8 ± 3.3   | 17.1 ± 2.2    | 2.9          |
| SDSS J154901.16+071247.6 | 272      | 1727     | 53859  | 0.501  | 27.4 ± 2.5   | 10.8 ± 0.4    | 4.2          |
| SDSS J160616.23+232242.1 | 237      | 1852     | 53534  | 0.408  | 23.7 ± 2.7   | 8.8 ± 0.3     | 5.6          |
| SDSS J163446.49+461946.7$^a$ | 163      | 627      | 52144  | 0.576  | 10.8 ± 1.1   | 10.0 ± 0.4    | 5.3          |

Notes.
$^a$ Studied in this paper.
$^b$ The S/N of Mg II emission line measured by the SDSS pipelines.
$^c$ The average S/N of whole observed spectrum.

4000 Å break features). The sample selection and spectral analysis are described in Sections 2 and 3, respectively. Section 4 presents the results and discussion. A ΛCDM cosmology with parameters $h_0 = 0.7$, $\Omega_m = 0.3$, and $\Omega_\Lambda = 0.7$ (Spergel et al. 2003) is adopted throughout the paper.

2. SAMPLE SELECTION

The SDSS is an ambitious project designed to eventually survey one-quarter of the entire sky in images and spectra (York et al. 2000). The survey is carried out by a dedicated wide-field (3°) 2.5 m telescope located at Apache Point Observatory. The telescope is equipped with two fiber-fed spectrographs and a mosaic CCD camera. Each spectrum is taken with a 3′′ fiber aperture. The spectra have a resolution of $R \sim 1800$ (corresponding to $\sigma_{\text{int}} \sim 65 \text{ km s}^{-1}$), and cover a wavelength range from 3800 to 9200 Å in the observer’s frame. The spectra are spectrophotometrically calibrated within an accuracy of ~20% by observing subdwarf F stars in each 3° field of view. The raw spectra are reduced automatically by the developed pipelines, spectro2d and specBS (Glazebrook et al. 1998; Bromley et al. 1998).

First, according to the redshifts determined by the SDSS pipelines, we select galaxies and quasars within $1.2 > z > 0.4$ from the SDSS Data Release 6 catalogs (Adelman-McCarthy et al. 2008). The redshift range ensures that both the Mg II $\lambda 2800$ emission line and 4000 Å feature (at the rest frame) shift into the wavelength coverage at observer’s frame. The Mg II $\lambda 2800$ line emission is then required to be detected above a 3σ significance level according to the emission-line measurements provided by the SDSS pipelines. The selected sample contains 1946 galaxies and 7694 quasars fulfilling the above criteria. An automatic routine is developed to select the hybrid quasars whose spectra have an evident break around the rest-frame wavelength 4000 Å, i.e., $D_n(4000) > 1$, where $D_n(4000) = \int_{3850}^{4000} f_\lambda d\lambda / \int_{3850}^{4085} f_\lambda d\lambda$ (Bruzual 1983; Balogh et al. 1999). The selected spectra of quasars and galaxies are then inspected by eye one by one. Finally, the selection results in a sample of 15 candidates of hybrid QSOs. We emphasize that the selection outlined above provides a representative (though not necessarily complete) sample of hybrid QSOs. Given the $D_n(4000)$ criterion, our selection would miss QSOs whose spectra are extremely blue or dominated by extremely hot stars. In the first case, the blue AGN continuum dilutes the 4000 Å drop that is caused by the stellar absorptions. The starlight component is therefore hard to identify and separate from the observed spectra (the same for the second case). The sample is listed in Table 1. For each object, the table shows its plate number, modified Julian date of observation, number of fibers on the plate, redshift, equivalent width of the Mg II emission line, corresponding S/N of Mg II, and average S/N of the whole spectrum. The observed spectra are displayed in Figure 1.

Except for the three objects SDSS J1634+4619, SDSS J1026+1034 and SDSS 0900+3813, detailed spectral analysis is currently a hard task for most of the candidates listed in the sample, either because of the low average S/Ns of all the spectra or because of the poor Mg II profiles and blurry 4000 Å break features. In order to determine their physical properties, deeper spectroscopic observations are necessary for the remaining objects. At first glance each of the three spectra is dominated by both an underlying power-law continuum and a broad Mg II emission line attributed to an AGN at the blue part, and by a spectrum of an intermediate-mass star (i.e., A to G type) at the red part. The evident starlight component allows us to separate the contribution of the host galaxy from each observed spectrum. Additionally, the properties of black hole accretion could be derived from the evident Mg II broad emission line.

3. SPECTRAL ANALYSIS

The observed spectra are first smoothed with a boxcar of 6 pixels (~10 Å) to enhance the S/N ratios and the accuracy of spectral measurements. The smoothed spectra are then reduced through the standard procedures of the IRAF package, including Galactic extinction and redshift correction. Galactic extinction is corrected for each spectrum by the color

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Notes.
$^a$ Studied in this paper.
$^b$ The S/N of Mg II emission line measured by the SDSS pipelines.
$^c$ The average S/N of whole observed spectrum.

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1 IRAF is distributed by the National Optical Astronomical Observatories, which is operated by the Association of Universities for Research in Astronomy, Inc., under cooperative agreement with the National Science Foundation.
excess $E(B-V)$ adopted from NED\(^2\) assuming an extinction curve with $R_V = 3.1$ (Cardelli et al. 1989). Each Galactic extinction-corrected spectrum is then transformed to the rest frame according to the redshift given by the SDSS pipelines. The reduced spectra at the rest frame are displayed in Figure 2 (see the solid curve in each panel). Each spectrum clearly shows not only a discontinuity at around $4000\, \text{Å}$ caused by the metal absorptions of stars, but also a strong Mg $\text{II}$ broad emission line superposed on an underlying AGN continuum at the blue end. Evident H$\alpha$ and Ca $\text{II}$, K absorption features can be identified in the spectra of both SDSS J1634+4619 and SDSS J1026+1034. Although the spectrum of SDSS 0900+3813 shows relatively weak H$\alpha$ absorption, the Ca $\text{II}$, K absorptions are still strong. The presence of nuclear accretion activity in the three objects is additionally supported by the marginally detectable high-ionization lines, such as [Ne$\text{III}$]λ3868, [Ne$\text{V}$]λ3426, and 3346.

The single stellar population (SSP) models developed by Bruzual & Charlot (2003, BC03) are used to interpret the observed starlight spectra for the three hybrid QSOs. To begin with, we extract a series of spectra from the BC03 SSP models with the Chabrier initial mass function (IMF) at different metallicities. For a given metallicity, we attempt to reproduce each observed starlight component by the linear combination of five instantaneous bursts at different ages. The ages range from 0.4 to 4.0 Gyr (i.e., 0.4, 0.6, 0.8, 1.0, and 4.0 Gyr). Since a starlight spectrum is predicted to evolve slightly after 1.0 Gyr, the 4.0 Gyr old stellar population is used to reproduce the underlying old stellar population. Bursts younger than 0.4 Gyr are not considered in our spectral modeling both because of the evident H$\beta$ and Ca $\text{II}$ absorptions and because of the likely degeneracy between the spectrum of very young stellar population and AGN blue continuum.

In summary, in order to model the observed spectra, our template contains the starlight spectra of the five instantaneous bursts at the given stellar population ages, a power-law continuum and a UV Fe $\text{II}$ template that are both attributed to AGNs, and a Galactic extinction curve (Cardelli et al. 1989). Bruhweiler & Verner (2008) recently calculated a grid of Fe $\text{II}$ emission spectra. The predicted spectrum giving the best fit to the observed I Zw 1 spectrum is adopted in the current study. The adopted Fe $\text{II}$ template is calculated for log[$Z_t$/Z$_{\odot}$] = 11.0, log[Φ($\Phi_{\text{H}}$/cm$^{-2}$s$^{-1}$)] = 20.5, ξ/(1 km s$^{-1}$) = 20, and 830 energy levels. The template is broadened by convolution with a Gaussian profile having the same width as the Mg $\text{II}$ broad emission before our spectral modeling.

A $\chi^2$ minimization is performed over the rest wavelength range from 2900 Å to 5500 Å, except for the range around the strong emission lines (e.g., Mg $\text{II}$ λ2800, H$\beta$, [O $\text{III}$] λ5007 and [O $\text{II}$] λ3727). For each object, the fitting is carried out for several different metallicities (from 0.02 Z$_{\odot}$ to 2.5 Z$_{\odot}$) to test if the results are robust in light of changing metallicity. The fitting at extremely low metallicity (i.e., 0.02 Z$_{\odot}$) is excluded in the subsequent studies for SDSS 0900+3813 because a relatively high metallicity is required to reproduce the observed metal absorption lines. The fittings at solar metallicity (the base models, see below) are illustrated in Figure 2. Figure 3 illustrates the fraction of mass associated with each of the five instantaneous bursts used in our fitting. As shown in the figure, the modeling results at the different metallicities are highly consistent with each other. For SDSS J1634+4619 and SDSS J1026+1034, their spectra can be interpreted by the combination of an old stellar population (greater than 1 Gyr) and

\(^2\) The Schlegel, Finkeiner, and Davis Galactic reddening maps (Schlegel et al. 1998) are adopted for NED.
starlight spectra to measure the Lick indices. For each object, lines (1) and (2) list the redshift and modeled intrinsic extinction, respectively. Lines (2)–(5) list the AGN continuum flux at the rest-frame wavelength 3000 Å, the [O ii] and [O iii] emission line fluxes, and the FWHM of the Mg ii broad emission line. All the fluxes quoted above are corrected for the modeled intrinsic extinction. The fluxes of the [O iii] and [O ii] emission lines are measured by direct integration. The FWHM of the Mg ii emission is determined by a Gaussian fit through the SPLOT task. The measured two Lick indices, D_{4000} and H_β_A,4, are listed in lines (11) and (12). The measured value of the Lick indices is in agreement with our spectral modeling described above.

4.1. Eddington Ratio versus D_{4000} Sequence

The main goal of this paper is to study the coevolution of an AGN and its host galaxy by taking advantage of the spectra of the hybrid QSOs. On account of great progress in the reverberation mapping technique, a variety of empirical relationships have been calibrated and are used to estimate the black hole virial masses (M_{BH}) in AGNs (e.g., Kaspi et al. 2000, 2005; Peterson et al. 2004). The commonly used calibrations have been recently summarized in McGill et al. (2008). The prominent broad Mg ii emission lines allow us to roughly estimate the M_{BH} and Eddington ratios (L/L_{Edd}) for the three hybrid QSOs. Mg ii emission is an important coolant in high-density BLR clouds in AGNs. Comparing with Hβ, the Mg ii emission is, in principle, less contaminated by starlight. In addition, the equivalent width of Mg ii peaks at lower ionizing flux, which means Mg ii is emitted from the region that has a larger distance from an isotropic ionizing source (e.g., Korista et al. 1997).

We estimate the Mg ii-based M_{BH} according to the calibration

\[
M_{BH} = 2.04 \left( \frac{L(3000 \text{ Å})}{10^{44} \text{ erg s}^{-1}} \right)^{0.58} \left( \frac{\text{FWHM(MgII)}}{\text{km s}^{-1}} \right)^{2} M_{\odot}
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**Table 2** Properties of the Three Mg ii Broad Emission Line Selected Hybrid QSOs

| Properties | SDSS J11634+4619 | SDSS J1026+1034 | SDSS 0900+3813 |
|------------|------------------|-----------------|----------------|
| z          | 0.576            | 0.435           | 0.434          |
| E(B−V)     | 0.11             | 0.26            | 0.22           |
| F_{c,3000} /10^{-16} erg s^{-1} cm^{-2} Á^{−1} | 1.12±0.13 | 2.58±0.23 | 2.26±0.32 |
| F_{c,4000}/10^{-16} erg s^{-1} cm^{-2} | 4.85±1.10 | 28.3±6.4 | 9.77±0.08 |
| F_{c,6000}/10^{-16} erg s^{-1} cm^{-2} | ... | 15.4±3.8 | ... |
| rms(FWHM(Mg ii)/km s^{-1}) | 9300±500 | 4500±300 | 5000±500 |
| M_{BH}/M_{⊙} | 6.8×10^8 | 1.8×10^8 | 1.9×10^8 |
| L/L_{Edd} | 0.026            | 0.12            | 0.09           |
| M_{*}/M_{⊙} | 2.4×10^{11} | 1.2×10^{11} | 1.4×10^{11} |
| S.P. Age/Gyr | ~0.6 | ≤0.4 | ~0.8–1.0 |
| D_{4000}(4000) | 1.32 | 1.27 | 1.39 |
| H_β_A | 8.06 | 9.93 | 6.78 |

**Figure 3.** Modeled mass fractions of the adopted five/four instantaneous bursts with different ages. The ages of the bursts range from 0.4 to 4.0 Gyr. Results with different metallicities are shown by different colors, dot/dash types for clarification. (A color version of this figure is available in the online journal.)

(a younger one (a few 100 Myr). Although there are uncertainties in the precise age estimates due to both the metallicity effect and the models used, a ≤400 Myr and a ~600 Myr young stellar population are specifically required in SDSS J1026+1034 and SDSS J1634+4619, respectively. In contrast, SDSS 0900+3813 is dominated by a relatively old stellar population (~1 Gyr), which is in agreement with its relatively weak Hβ absorption feature already mentioned above. Since the spectral modeling results change little when different metallicities are considered, models with solar metallicity are then used as the base models in our subsequent studies.

4. RESULTS AND DISCUSSION

Table 2 lists the results of the spectral measurements that are performed in the rest frame. The residual emission-line spectra are used to measure emission line features, and the modeled
given in Kollmeier et al. (2006), where \( L(3000 \, \text{Å}) \) is the AGN continuum luminosity at the rest-frame wavelength 3000 Å. The \( L(3000 \, \text{Å}) \) is corrected for the intrinsic extinction according to the modeled color excess. The UV continuum-based calibration is adopted here because the total light spectra redward of the Balmer limit are dominated by the contribution from the starlight components. The bolometric luminosities are then obtained from the estimated \( L(3000 \, \text{Å}) \) by multiplying by a factor of 5.9 (McLure & Dunlop 2004). The estimated \( M_{\text{BH}} \) and \( L/L_{\text{Edd}} \) are listed in Table 2 for each object.

The bolometric luminosities estimated from the modeled UV continuum are compared with that from the \([\text{O} \, \text{iii}] \lambda 5007\) emission lines. As a reasonable first approximation, \([\text{O} \, \text{iii}] \) emission is believed to be isotropic in AGNs (Kuraszkiewicz et al. 2000). The isotropy of the \([\text{O} \, \text{iii}] \) emission has been questioned by some studies of radio-loud AGNs (e.g., Baker & Hunstead 1995; Jackson & Rawlings 1997). Despite the large scatter, the \([\text{O} \, \text{iii}] \) luminosity \( \langle L([\text{O} \, \text{iii}] ) \rangle \) was reported to be correlated with the optical continuum luminosity for typical type 1 AGNs (e.g., Kauffmann et al. 2003a). Given the relationship \( L_{\text{bol}}^{\text{UV}} = 3500L([\text{O} \, \text{iii}] ) \), the ratio \( L_{\text{bol}}^{\text{UV}}/L_{\text{bol}}^{\text{O3}} = 5.9L(3000 \, \text{Å})/L_{\text{bol}} \) is estimated to be 0.8 for SDSS J1634+4619, 0.5 for SDSS 1026+1034, and 1.2 for SDSS 0900+3813, which means a high consistency between the two independent estimations.

As an additional test, the host stellar masses \( (M_*) \) are estimated from the modeling of the observed spectra, and also listed in Table 2. Similar to the results recently obtained in Alonso-Herrero et al. (2008), the \( M_* \) of the three hybrid QSOs are close to those of \( z \approx 2 \) AGNs \( (\sim 10^{11} \, M_\odot) \) (e.g., Daddi et al. 2007; Kriek et al. 2007), and higher than those of local AGNs \( (\sim 10^{10} \, M_\odot) \) (e.g., Kauffmann et al. 2003c). The average ratio \( M_{\text{BH}}/M_* \) is \( \sim 0.0019 \) for the three hybrid QSOs, which is highly consistent with the tight linear correlation between \( M_{\text{BH}} \) and the virial bulge mass. The tight correlation established in the local universe has an average ratio \( \langle M_{\text{BH}}/M_{\text{Bulge}} \rangle \sim 0.002 \) (Marconi & Hunt 2003).

The role of \( L/L_{\text{Edd}} \) in AGN evolution was proposed a long time ago (e.g., Grube 2004; Mathur 2000). Wang & Wei (2008) established a smooth \( D_a(4000) - L/L_{\text{Edd}} \) sequence by studying the nearby Seyfert 1.8/1.9 galaxies selected from the MPA/JHU SDSS DR4 catalog. The sequence indicates an evolutionary scenario that a young AGN with high \( L/L_{\text{Edd}} \) evolves into an old AGN with low \( L/L_{\text{Edd}} \) along the sequence as the associated stellar population ages. Similar evolutionary sequences have been proposed by different authors through different methods and technologies (e.g., Wang et al. 2006; Kewley et al. 2006; Wild et al. 2007). As one generally believes that star formation activity decreases as stellar population ages, the sequence is consistent with Watabe et al. (2008) who recently found a close correlation between \( L/L_{\text{Edd}} \) and nuclear starburst luminosity assessed by the near-infrared polycyclic aromatic hydrocarbon (PAH) emission. Similar to our previous studies, \( D_a(4000) \) is plotted against \( L/L_{\text{Edd}} \) by solid stars in Figure 4 for the three hybrid QSOs. The open circles show the \( D_a(4000) - L/L_{\text{Edd}} \) sequence that is established in Wang & Wei (2008). The hybrid QSOs studied in this paper are clearly consistent with the \( D_a(4000) - L/L_{\text{Edd}} \) sequence reported in the local Seyfert galaxies, which implies that the evolution sequence could continue out to \( z \approx 0.5 \).

Note that the three hybrid QSOs are located in the middle range of the evolutionary sequence, which implies that they are at the transition stage not only from young to old AGNs, but also from the host-dominated to the AGN-dominated phase. We propose that the hybrid QSOs are the progenitors of local optical luminous QSOs. The three hybrid QSOs show recent starbursts within 1 Gyr (recall that QSO UN J1025−0400 is associated with a 400 Myr old post-starburst, Brotherton et al. 1999). In contrast, relatively old (or old post-starburst) stellar populations are frequently identified in nearby luminous QSOs. Nolan et al. (2001) found that the off-nuclear \( (\approx 5'' \) ) stellar population is dominated by old stars \( (\approx 8−14 \, \text{Gyr}) \) for optically selected QSOs. Dunlop et al. (2003) observed a sample of local QSOs at \( z \sim 0.2 \) in imaging and spectroscopy. They claimed that the host galaxies of these luminous QSOs are dominated by old stellar populations without recent massive star formation. Canalizo et al. (2006) reobserved the 14 QSOs listed in the sample of Dunlop et al. (2003) with the Keck LRIS spectrograph. Spectra with high S/Ns allowed the authors to identify relatively old post-starbursts \( (0.6−2.2 \, \text{Gyr}) \) in the host galaxies. These timescales are comparable to the recent starburst ages recently inferred from the Hubble Space Telescope (HST)/ACS deep imaging study of host galaxies of five low-redshift QSOs (Bennert et al. 2008). In addition, Tadhunter et al. (2005) detected relatively old post-starbursts \( (0.1−2 \, \text{Gyr}) \) in the off-nuclear regions of a few nearby radio-loud AGNs.

Recent theoretical studies on the issue of coevolution of AGN and its host galaxy suggest that AGNs are hard to detect in the early host-dominated phase. Numerical simulations of galaxy merging including SMBHs predict the theoretical light curves of the central AGN activity and associated star formation activity (e.g., Di Matteo et al. 2005; Springel et al. 2005a, 2005b). At the beginning of evolution, the central AGN activity is predicted to be heavily obscured by the surrounding gas and dust, especially in UV/optical bands. After the obscuration
material is dispersed by the feedback from the accretion activity and emission from young, hot stars fades out (i.e., at about 1 Gyr after the beginning), luminous QSOs are observable because the starlight from the host is overwhelmed by the strong radiation from the luminous QSOs (Hopkins et al. 2005a, 2005b). An alternative possibility is the differential growth of the black hole mass and bulge mass (e.g., Weedman 1983). This scenario is observationally supported by the detection of post-starburst stellar populations in narrow-line Seyfert 1 galaxies with high $L/L_{\text{Edd}}$ (e.g., Wang & Wei 2006; Zhou et al. 2005).

By observing local Seyfert galaxies with high spatial resolution down to 0″.085, Davies et al. (2007) recently suggested that the black hole accretion delays for 50–100 Myr after the onset of star formation. The theoretical models developed by Kawakatu et al. (2003) and Granato et al. (2004) predict that the change in phase from starburst-dominated to AGN-dominated takes place at a few $\times 10^8$ yr after the beginning of the star formation. Of course, we could not entirely exclude the possibility that the lack of extremely young stellar population in our three hybrid QSOs is caused by the adopted $D_n(4000)$ criterion (i.e., $> 1$).

Our studies show that the hybrid QSOs could be an ideal laboratory for studying the coevolution of an AGN and its host galaxy because of their unique spectral properties. Additional deep spectroscopic observations are required to search for more hybrid QSOs, and to test the validity of the $D_n(4000) - L/L_{\text{Edd}}$ sequence, especially in the distant universe. Moreover, observations in the infrared are helpful in constraining the dust content in these objects.

4.2. Star Formation History/Rate

There is accumulating evidence supporting the argument that star formation activity is suppressed in luminous AGNs (e.g., Ho 2005; Wang & Wei 2008; Kim et al. 2006; Martin et al. 2007; Bundy et al. 2005; Schawinski et al. 2007; Zheng et al. 2007). We argue that the current SFRs are significantly suppressed in the three hybrid QSOs. First, the inset panel in Figure 4 shows the $D_n(4000)$ versus $H_\delta_A$ diagram for the three hybrid QSOs. The dot–dashed line shows the stellar population evolution locus for the model with exponentially decreasing SFR at solar metallicity ($\psi(t) \propto e^{-t/4\text{Gyr}}$), and the dashed line the SSP model (BC03). The SSP model for a recent burst that ended 0.1–1 Gyr ago shows an enhanced $H_\delta_A$ value because the optical spectrum is dominated by the emission of A-type stars. All three hybrid QSOs fall close to the single-burst model due to their large $H_\delta_A$ values. Second, [O ii]λ3727 line emission is a good indicator of current SFR for star-forming galaxies (e.g., Kennicutt 1998; Kewley et al. 2004). The spectra of both SDSS J1634+4619 and SDSS J0900+3813 show marginally detectable [O ii]λ3727 emission features, which indicates that the current SFRs could be ignored in these two hybrid QSOs. [O ii]λ3727 emission is strong in SDSS J1026+1034. However, both AGNs and H II regions can contribute to [O ii] emission (e.g., Yan et al. 2006; Kim et al. 2006). The measured line ratio $[O$ II]/[O III] is 0.54 (after correction for the intrinsic extinction), and line ratio [O III]/H$\beta_n = 4.0$. SDSS J1026+1034 is therefore located in the region occupied by typical AGNs.
in the [O ii]/[O iii] versus [O iii]/Hβ diagram (see Figure 7 in Kim et al. 2006). Moreover, the intrinsic [O iii] luminosity is estimated to be $L_{\text{[O iii]}} \approx 2.0 \times 10^{42}$ erg s$^{-1}$. At the given luminosity, the anticorrelation for typical AGNs between $L_{\text{[O iii]}}$ and [O ii]/[O iii] predicts that the line ratio [O ii]/[O iii] varies from 0.03 to 0.32 (see Figure 5 in Kim et al. 2006), which means that star formation activity contributes no more than 20% of the total [O ii] emission. We consequently conclude that the narrow emission lines in SDSS J1026+1034 are mainly due to the central AGN.

4.3. Radio Emission in SDSS J1634+4619

The radio emission of SDSS J1634+4619 is detected by the NRAO VLA Sky Survey (NVSS; Condon et al. 1998) and faint images of the Radio Sky Survey at 20 cm (FIRST) survey (Becker et al. 1995) at 1.4GHz. The map of the FIRST survey shows an unresolved source with integrated flux $\sim 4.30$ mJy including a correction of 0.25mJy caused by Clean-Bias. The position of the radio source deviates from the corresponding optical source by $\sim 36"$. The radio luminosity is calculated to be $P_{\text{[1.4GHz]}} \approx 4.5 \times 10^{24}$ W Hz$^{-1}$ through a k-correction by assuming a spectral shape $S_\nu \propto \nu^{-0.5}$ from the optical to the radio band.

It is well known that decimeter radio emission could be contributed from the supernova explosion of massive stars (i.e., $M \geq 8M_\odot$) with a lifetime of $\approx 10^7$ yr. In fact, the most radio-luminous starburst has a radio luminosity $\log(P_{\text{[1.4GHz]}}) \approx 22.3$–23.4 (Smith et al. 1998). The radio luminosity contributed from the recent starburst could be estimated from the past average SFR as $L_{\text{[1.4GHz]}} \approx 4.0 \times 10^{21}$ SFR($\geq 5 M_\odot$) WH z$^{-1}$ (Condon 1992). Recalling that the observed spectrum has been modeled in terms of the linear combination of five instantaneous bursts, we define the average SFR for each burst as SFR = $\Delta M_\star/\Delta t$, where $\Delta M_\star$ is the star mass formed in each burst, and $\Delta t$ the time step adopted in the spectral modeling. The average SFR of the latest burst is therefore estimated to be $\sim 10^2 M_\odot$ yr$^{-1}$ for SDSS J1634+4619. Given the Salpeter IMF (Salpeter 1955), the starburst-contributed radio luminosity is $\sim 8 \times 10^{22}$ W Hz$^{-1}$, which is one order of magnitude lower than the calculated total radio luminosity.

4.4. A Companion Galaxy Of SDSS J1634+4619?

It is widely accepted that interaction of galaxies can trigger extreme nuclear accretion and star formation activity (e.g., Toomre & Toomre 1972; Larson & Tinsley 1978; Sanders et al. 1988; Stockton 1999; Heckman et al. 1984; Di Matteo et al. 2005; Springel et al. 2005a, 2005b). A recent HST/ACS deep imaging study identified significant fine structures such as shells and tidal tails in a small sample of host galaxies of low-redshift QSOs (Bennert et al. 2008). A companion galaxy in the post-starburst phase ($\sim 800$ Myr) is identified in the particular case UN J1025$-$0040 (Brotherton et al. 1999; Canalizo et al. 2000). The HST image shows an interacting companion for the “Q+A” object SDSS J231055$-$090107 (Canalizo et al. 2006).

The optical images of SDSS J1634+4619 taken by SDSS show an unresolved source neighborhood by a marginally detectable, very faint source to the southwest. Figure 5 shows the $r'$-band image. The intensity contours are overplotted on the image after the background level determined around the source is subtracted. To identify the faint companion more clearly, we project the image along the long sides of the two rectangles overlaid in Figure 5. Figure 6 presents the count distributions along the two directions. As shown in the left panel in Figure 6, the peaks of SDSS J1634+4619 and the possible companion are separated by about 8 pixels. This separation corresponds to a projected physical distance of $\sim 11$ kpc if the companion is at $z = 0.576$. Finally, more deep spectroscopic observations and imagings are necessary to determine whether the companion interacts with SDSS J1634+4619 physically, or is just a foreground star/galaxy.

5. SUMMARY

We selected 15 intermediate-$z$ galaxies with hybrid spectra from SDSS DR6 to study the issue of AGN–host connection. The spectra redward of the Balmer limit are dominated by starlight, and the spectra at the blue end by both an AGN continuum and an Mg II broad emission line. The spectra are analyzed in detail for three objects: SDSS J162446.49+461946.7, SDSS J102633.32+103443.8, and SDSS J090036.44+381353.0. Without intensive current star formation activities, the modeled recent burst ages range from $\sim 400$ Myr to 1 Gyr. Based on the Mg II black hole masses, the three hybrid QSOs are consistent with the $D_\odot(4000) - L/L_{\text{Edd}}$ sequence previously established in local AGNs.

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