Near-infrared spectroscopy of quasars at $z \sim 3$ and estimates of their supermassive black hole masses

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Received 2014 August 6; Accepted 2015 September 21

Abstract

We present the results of new infrared spectroscopic observations of 37 quasars at $z \sim 3$, selected based on the optical $r'$-band magnitude and the availability of nearby bright stars for future imaging follow-up with an adaptive optics system. The supermassive black hole (SMBH) masses ($M_{BH}$) were successfully estimated in 28 out of 37 observed objects from the combination of the Hβ emission linewidth and continuum luminosity at rest-frame 5100 Å. Comparing these results with those from previous studies of quasars with similar redshift, our sample exhibited slightly lower Eddington ratios ($\sim -0.11$ dex in median), and the SMBH masses are slightly higher ($\sim 0.38$ dex in median). The SMBH growth time, $t_{grow}$, was calculated by dividing the estimated SMBH mass by the mass accretion rate measured using optical luminosity. We found, given reasonable assumptions, that $t_{grow}$ was smaller than the age of the universe at the redshift of individual quasars for a large fraction of observed sources, suggesting that the SMBHs in many of our observed
quasars are in the growing phase with high accretion rates. A comparison of the SMBH masses derived from our H$\beta$ data and archived C IV data indicated considerable scattering, as indicated in previous studies. All quasars with measured SMBH masses have at least one nearby bright star, such that they are suitable targets for adaptive optics observations to study the mass relationship between SMBHs and host galaxies’ stellar components at high redshift.

**Key words:** galaxies: active — galaxies: nuclei — quasars: supermassive black holes

### 1 Introduction

The tight correlations between the properties of galaxy spheroidal components (e.g., mass $M_{\text{spheroid}}$, velocity dispersion, and luminosity $L_{\text{spheroid}}$) and the supermassive black hole (SMBH) mass ($M_{\text{BH}}$) in the local universe (Kormendy & Richstone 1995; Marconi & Hunt 2003; McConnell & Ma 2013; see also Kormendy & Ho 2013 for a review) indicate that the formation/growth of galaxies and central SMBHs are closely related (so-called coevolution). Recent multi-wavelength deep surveys have revealed similar downsizing evolution among galaxies, active galactic nuclei (AGNs), and SMBHs in AGNs (Cowie et al. 1996; Kodama et al. 2004; Ueda et al. 2003; Vestergaard et al. 2008), where more luminous, massive galaxies, more luminous AGNs, and more massive active SMBHs in AGNs show their number density peaks at higher redshift. This implies that the histories of cosmic star formation and the mass accretion of SMBHs may be synchronized (Franceschini et al. 1999; Silverman et al. 2008; Zheng et al. 2009). It is important to better constrain observationally how SMBHs and galaxies have coevolved from the early to the current universe.

Depending on various galaxy- and SMBH-growth mechanisms, different redshift (z) evolutions of the $M_{\text{BH}}$/($M_{\text{spheroid}}$) ratio can be predicted. (1) If the outflow from the central SMBH plays a major role in coevolution (Silk & Rees 1998), then the $R_{\text{BH}/\text{spheroid}}$ ratio is predicted to increase at higher redshift, due to the strong suppression of SMBH accretion at a later age (Wyithe & Loeb 2003). (2) When the SMBH and spheroid growths are governed by major merging of gas-rich galaxies, no significant redshift evolution in $R_{\text{BH}/\text{spheroid}}$ is expected (e.g., Robertson et al. 2006; see also Kawakatu et al. 2003). (3) If the transformation of disk stars to bulge stars during major mergers is taken into account, in addition to the star formation triggered by mergers, the growth of the $M_{\text{spheroid}}$ is enhanced in the late stage, relative to SMBH growth. Hence, the $R_{\text{BH}/\text{spheroid}}$ ratio is larger at higher redshift, but smaller than (1) (Croton 2006). The differences among models are larger at higher redshift. Therefore, observational investigation of the $R_{\text{BH}/\text{spheroid}}$ ratio at high redshift is essential to apply constraints to the coevolution models and/or the allowable parameter ranges of the key processes.

In the local universe, the $M_{\text{BH}}$ estimate is obtained via spatially resolved spectroscopy of normal galaxies (e.g., Kuo et al. 2011; van den Bosch & de Zeeuw 2010; Genzel et al. 2010; Walsh et al. 2010; Bender et al. 2005; Cappellari et al. 2002; Miyoshi et al. 1995, see also Genzel et al. 1994; Kormendy & Richstone 1995; Kormendy & Ho 2013 for reviews). However, it is impossible to apply the same method to distant normal galaxies, due to the lack of spatial resolution. Quasars (QSOs; highly luminous AGNs) are useful objects for studying SMBH masses at high redshift, because various strong emission lines from gas clouds, whose dynamics are dominated by the gravitational force of the central SMBHs, can be detected and used to estimate SMBH masses from single epoch spectroscopy, based on the combination of emission linewidths and nearby continuum luminosity (McLure & Jarvis 2002; Vestergaard 2002; Shenmer et al. 2004; Wu et al. 2004; Vestergaard & Peterson 2006; Netzer et al. 2007; Wang et al. 2009; Trakhtenbrot & Netzer 2012; Zuo et al. 2015).

Previous studies of the $R_{\text{BH}/\text{spheroid}}$ ratio at high redshift using QSOs were performed mainly at $z < 2$ (e.g., Häring & Rix 2004; Jahnke et al. 2004, 2009; Decarli et al. 2010; Merloni et al. 2010; Bennert et al. 2011; Cisternas et al. 2011; Schramm & Silverman 2013; Matsuoka et al. 2014). However, to better distinguish among various coevolution scenarios, data at higher redshift may be preferable. On the other hand, detection of the QSO host galaxy to measure the $M_{\text{spheroid}}$ becomes more difficult at higher redshift, because the surface brightness of the host galaxy stellar emission becomes faint in proportion to $(1 + z)^4$. Thus, the optimal redshift range must be determined by taking into account the practical observational limitations.

To estimate $M_{\text{BH}}$ of distant QSOs at $z > 2$, the C IV $\lambda 1549$ emission line is commonly used, because it is redshifted into the optical wavelength range, facilitating observation. However, it often shows a large blueshift and an
asymmetric profile with respect to low ionization lines (e.g., Gaskell 1982; Tytler & Fan 1992; Richards et al. 2002; Shen et al. 2008, 2011). Therefore, it is not obvious whether or not the C IV linewidths precisely reflect the gravitational potential well of the SMBH. In fact, }\text{MBH}\text{ estimations based on C IV may have large uncertainty, due to the scatter observed in the C IV-derived SMBH mass distribution, compared to the better-calibrated Mg II }\lambda\text{2800-}
\text{and H }\beta \text{ }\lambda\text{4861-based SMBH mass estimate (e.g., Baskin & Laor 2005; Netzer et al. 2007; Sulentic et al. 2007; Shen et al. 2008; Marziani & Sulentic 2012). On the other hand, H }\beta \text{ emission shows a smooth line profile, dominated by the gravitational potential of the SMBH, and is best calibrated to estimate }\text{MBH}\text{ in the local universe, based on the reverberation mapping method (e.g., Peterson & Wandel 1999; Kaspi et al. 2000; Peterson et al. 2004; Bentz et al. 2007, 2009). In this study, the H }\beta \text{ emission linewidth and nearby continuum luminosity at }5100 \text{ Å (}L_{5100}\text{)}\text{ were used to estimate }\text{MBH}\text{ of distant QSOs in the most reliable manner. To cover the redshifted H }\beta \text{ emission line within the K band (}2.2 \mu m\text{), the longest high-sensitivity atmospheric window for ground-based observations, the redshift range of the target QSOs was limited to }z < 3.5. Detection of the QSOs’ host galaxy stellar emission at }z \sim 3.5 \text{ was technically feasible using the latest powerful 8–10 m ground-based observation facilities (e.g., Falomo et al. 2005; Peng et al. 2006; Schramm et al. 2008; McLeod & Bechtold 2009; Targett et al. 2011). For these reasons, QSOs at }z < 3.5 \text{ were targeted to constrain their SMBH and galaxy stellar mass ratio, and to better constrain observationally the coevolution of SMBHs and galaxies in the early universe.}

In this paper, we report the results of our spectroscopic observations of }z < 3.5 \text{ QSOs for their }\text{MBH} \text{ estimate. The imaging results related to the host galaxies’ stellar component will be presented in separate papers (T. Kawaguchi et al. in preparation; Y. Saito et al. in preparation). We describe the sample selection in section 2 and the observations and data analysis in section 3. The method used for the }\text{MBH}\text{ estimate is described in detail in section 4, along with the main results. Section 5 provides a discussion of our main findings, which are summarized in section 6. Throughout this paper, we adopt the Vega magnitude system for all infrared data and the standard }\Lambda\text{CDM cosmology, with }\Omega_\Lambda = 0.7, \Omega_M = 0.3, \text{ and }H_0 = 70 \text{ km s}^{-1}\text{ Mpc}^{-1}.\text{ }

2 Observations and data analysis

2.1 Sample selection

All of our samples are radio-quiet QSOs drawn from the seventh data release of the Sloan Digital Sky Survey (SDSS DR7: Abazajian et al. 2009). We first selected QSOs with redshift shown in SDSS DR7 \sim 3.11–3.50, so that the H }\beta \text{ emission line and }5100-\text{Å continuum could be observed within the K band. Next, we set limitations on the optical }r'-\text{band (}0.62 \mu \text{m)} magnitude, }18.5 < r'(\text{SDSS}) < 19. \text{ The faint limit was set to obtain sufficient quality spectra for our discussion within a reasonable amount of exposure time. Assuming that observed luminosity cannot exceed the Eddington luminosity limit of }L_{\text{Edd}} = 3.2 \times 10^8 \text{(}\text{M}/\text{M}_\odot\text{)}L_\odot, \text{ the minimum required }\text{MBH}\text{ is higher for brighter QSOs. The bright limit was set, because observing only the brightest end of the QSOs could strongly bias the data to intrinsically large }\text{MBH}\text{ systems, resulting in a biased view of the }R_{\text{BH/spheroid}}\text{ ratio at high redshift. Radio-loud QSOs were almost excluded because they often show jet-induced, extended, narrow emission-line regions, which could induce considerable uncertainty in the }\text{MBH}\text{ estimate using the emission linewidth. We roughly estimate radio-loudness of our targets from the ratio of their rest-frame luminosities at }5 \text{ GHz to those at }2500 \text{ Å (}\text{L}5\text{GHz)/ L}(2500\text{ Å}) (\text{Stocke et al. 1992}). The }L(2500 \text{ Å})\text{ and }L(5 \text{ GHz})\text{ are derived from the }z'-\text{band magnitude from the SDSS and the }20 \text{ cm flux from the Faint Images of the Radio Sky at Twenty Centimeters (FIRST) survey (Becker et al. 1994), respectively. Since the wavelength of the }z'\text{ and }20\text{ cm correspond to }2500 \text{ Å} \text{ and }5 \text{ GHz, respectively, in the rest frame of }z \sim 3 \text{ QSOs, we do not take into account the }K\text{-correction. Most of our target QSOs (}35 \text{ out of }37\text{) used in this paper have }L(5\text{GHz)/ L}(2500\text{ Å}) < 10, \text{ except for two target QSOs (}J0847+3831\text{ and J1337+3152) which have larger radio loudness.}

To achieve our final goal for studying the coevolution of SMBH and galaxies at high redshift, adaptive optics (AO) imaging data are going to be used to derive the host galaxy’s spheroidal stellar mass, using the Subaru 8.2 m telescope atop Mauna Kea, Hawai’i (latitude \sim +20°). For AO observation, an AO guide star with }R(0.64 \mu \text{m}) < 18 \text{ mag within }60''\text{ from the target is required. In addition, to observe each object for longer than four hours at a higher elevation than }50''\text{ from Mauna Kea, with good AO performance and high spatial resolution, we selected QSOs with declination }-5° < \text{Dec} < +45°. Finally, to subtract the central bright AGN glare with high accuracy, we chose targets that had at least one nearby PSF (Point Spread Function) reference star with a magnitude similar to that of the target QSOs. Approximately }120 \text{ }z \sim 3.5 \text{ QSOs met all of the requirements, among which }37\text{ were chosen for near-infrared spectroscopic observation in this study (table 1).}

2.2 Observations and data reduction

The near-infrared }K\text{-band (}2.2 \mu \text{m)} spectra were obtained using the NASA Infrared Telescope Facility (IRTF 3 m), the
United Kingdom Infrared Telescope (UKIRT 3.6 m), the William Herschel Telescope (WHT 4.2 m), and the Subaru Telescope (8.2 m). Bright targets were observed primarily with the SpeX instrument (Rayner et al. 2003) on the IRTF, the UIST (Ramsay et al. 2004) on the UKIRT, and the LIRIS (Manchado et al. 1998) on the WHT. Fainter QSOs observed with the IRCS instrument (Kobayashi et al. 2000) assisted with the AO system AO188 (Hayano et al. 2010) on Subaru. With the exception of the Subaru IRCS, these instruments enabled us to obtain H-band (1.6 μm) and K-band (2.2 μm) spectra simultaneously. For all targets, Hβ λ4861 and [O III] λλ4959, 5007 emission lines were observed within the K band; however, H-band spectra were used when available to better determine the continuum flux level at the shorter part of these emission lines. We also obtained spectroscopic data of a standard star (spectral type is A, G, or F) for each target (table 1) for telluric correction and flux calibration. To estimate the telluric correction, we divided the quasar spectra with standard star spectra, and then multiplied simple blackbody spectra with...
the temperature corresponding to the spectral type of the standard star derived from Allen’s astrophysical quantities (Tokunaga 2000).

2.2.1 IRTF/SpEX
IRTF/SpEX spectra of 20 targets (table 1) were obtained in the 0.8–2.5 \( \mu \text{m} \) cross-dispersed mode with a 1′6 × 15′0 slit. This mode provides spectral resolution with \( R \sim 375 \). Although the \( R \) was relatively low comparing to other observations, we choose this mode for safer tracking/guiding and for obtaining better S/N ratios. Spectra were taken at two different positions (A and B) along the slit. Each exposure time ranged from 60–300 s, depending on the magnitude of the targets and the weather conditions. Also, one–two coadds were used at each slit position.

The reduction was carried out using the Spectral Extraction Package for SpeX (Spextool: Cushing et al. 2004) that works on IDL. The Spextool goes through almost all data reduction processes, including spectral flat-fielding, sky emission subtraction, bad pixel correction, extraction of one-dimensional (1D) spectra, and wavelength calibration (using argon lines). We first created A – B data and then median-combined multiple A – B data sets to increase the S/N ratios. After extraction of a 1D spectrum, the data at the A and B slit positions were summed using the IDL task xcombspec. Then the xtellcor-basic task in IDL was used for telluric correction and flux calibration. Finally, different order spectra were merged into a single spectrum corresponding to the \( H \) and \( K \) bands (1.41–2.42 \( \mu \text{m} \)).

2.2.2 UKIRT/UIST
UKIRT/UIST spectra of five targets (table 1) were obtained through the 0′6 × 120′0 slit with an \( H + K \) grism. The achieved spectral resolution is \( R \sim 1000 \). The spectra were taken at A and B positions along the slit. Each exposure time was 240 s, and one coadd was adopted at each position for all targets.

Data were reduced using standard IRAF tasks. Initially, frames taken with an A (or B) beam were subtracted from frames subsequently taken with a B (or A) beam. The resulting subtracted frames were added and divided by a spectroscopic flat image. Then bad pixels and pixels impacted by cosmic rays were replaced with the interpolated values from the surrounding pixels. Finally, the spectra of the QSOs and the standard stars were extracted using the IRAF task apall. After wavelength calibration (using argon lines), telluric correction, and flux calibrations, we obtained the final spectra.

2.2.3 WHT/LIRIS
WHT/LIRIS spectra of five targets (table 1) were taken with the 0′75 × 252′0 slit and the \( H + K \) grism. The spectral resolution was \( R \sim 945 \). The exposure time and number of coadds at each slit position (A or B) were 300 s and one coadd, respectively. Data reduction was carried out in the same manner as for UKIRT/UIST.

2.2.4 Subaru/IRCS
Subaru/IRCS spectra of seven targets (table 1) were obtained using the 0′45 × 18′0 slit in the 52-mas mode. We used the \( K \)-grism that covers the 1.93–2.48 \( \mu \text{m} \) range. The spectral resolution was \( R \sim 400 \). The exposure time and number of coadds at each slit position (A and B) were 600 s and 1, respectively. We used IRAF for data reduction similar to that used for UKIRT/UIST and WHT/LIRIS data.

The details of the observations are summarized in table 1. Redshift and \( r' \)-band magnitude are from SDSS catalog. Final spectra are shown in figures 1 and 2. We also obtained imaging data for all targets and standard stars just before or after spectroscopic observations by using the same instruments used for the spectroscopic observations, and measured photometric magnitudes of the targets. The magnitudes derived from our slit spectra that were calibrated by spectroscopic standard star (possibly affected by slit loss) and those from imaging data generally agreed within 0.4 mag (table 2 and figure 3). We adopted the photometric magnitude from the imaging data for flux calibration.

3 Spectral analysis
To estimate \( M_{\text{BHT}} \), we fitted the observed spectra with a model combining the linear continuum, the underlying, very broad Fe II emission line complex (4500–5600 A), the broad and narrow H\( \beta \) \( \lambda 4861 \) emission lines, and two narrow \([\text{O III}]\) \( \lambda\lambda 4959, 5007 \) emission lines (as the forbidden \([\text{O III}]\) emission line originates primarily from the narrow line regions). The fitting of the spectra of the \( z \sim 3 \) QSOs was performed individually using QDP (Tennant 1991)\(^1\) and IDL. First, a tentative linear continuum was determined using several data points that were not strongly affected by H\( \beta \), \([\text{O III}]\), and Fe II emission lines. For the IRTF, UKIRT, WHT targets, data points at rest-frame 4000–4050 A or 4150–4200 A, and 5080–5120 A were used. For the Subaru targets, because the \( H \)-band spectral data were not available, data from rest-frame 4700–4750 A, 5080–5120 A, and 5470–5500 A were adopted. Several data points in the wavelength range considered for continuum determination were significantly affected by the Earth’s atmospheric absorption, depending on the redshifts of individual QSOs, and were considerably noisy. Thus, these noisy data points were excluded from the continuum determination.

\(^{1}\) See also (http://heasarc.gsfc.nasa.gov/ftools/others/qdp/node3.html).
Next, we fitted the [O III] $\lambda \lambda 4959,5007$ doublet emission lines with two narrow Gaussian components. The linewidth and the redshift of the two components were set to be the same. The relative 5007-to-4959 Å strength was fixed at 3.0 (Dimitrijević et al. 2007). Then the H$\beta$ emission line was fitted with two Gaussian (broad and narrow) components. Although some previous studies adopted more complex models (Shemmer et al. 2004; Netzer & Trakhtenbrot 2007; Schulze & Wisotzki 2010), we use only one broad Gaussian and one narrow Gaussian model for H$\beta$-line fitting, because of limited spectral resolution and $S/N$ of our data. For the narrow H$\beta$ emission component, the same linewidth as the [O III] line was adopted. Another Gaussian component with a larger linewidth, corresponding to the broad components of the H$\beta$ emission line, was added. All parameters of this component was set as free parameters. We allowed the velocity shift of the peak wavelength between the narrow H$\beta$ and [O III] lines to be up to 200 km s$^{-1}$, following Netzer et al. (2007). Then Fe II emission line fitting was carried out using the template derived from the nearby well-studied QSO, I Zw 1, from Tsuzuki et al. (2006). We note that our aim is not to try to fit the Fe II emission features accurately, but to obtain a reliable estimate of the H$\beta$ line width and nearby continuum flux, unaffected by the contamination from the Fe II emission lines. The template was convolved with a Gaussian

Fig. 1. All spectra of 28 $z \sim 3$ QSOs with fitted H$\beta$ and the [O III] emission lines in our sample. The abscissa is the rest-frame (bottom) and the observed (top) wavelength in $\mu$m. The ordinate is the flux in $10^{-17}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. The best-fitting model (black line) in each panel is composed of a continuum component, Fe II emission (orange line), and H$\beta$ and [O III] emission lines (blue lines).
Fig. 1. (Continued)
Fig. 1. (Continued)
that had the same linewidth as the broad Hβ emission line, as determined above, because the Fe II emission-line complex originates predominantly from the broad line regions. The fitting wavelength ranges for the Fe II features were rest-frame 4500–4650 Å and 5100–5600 Å. Because not all QSOs have exactly the same Fe II emission line profile as the template used (Fe II spectrum extracted from I Zw 1), we divided the Fe II template into λ< 5008 Å and λ> 5008 Å (the Fe II feature shows a minimum value at 5008 Å in the template), and varied their relative strengths to better fit the spectral features actually observed near the Fe II emission in our QSO spectra. The scaled template was subtracted from the observed spectra. Finally, the Fe II subtracted spectrum was refitted using the approach described above. This time, the peak wavelength shift between the narrow Hβ and [O III] was allowed to be up to 450 km s\(^{-1}\). We determined the final fitting parameters for a linear continuum, Hβ, and the [O III] emission lines. The contribution of the instrumental resolution was removed from the fitted linewidth to obtain the actual Hβ emission linewidth.

Some QSOs were fitted with only a broad Gaussian component for the Hβ emission line, because the \( \chi^2 \) values became larger when both broad and narrow Gaussian components were added. For J2134+0011, the Hβ line and
Fig. 2. Spectra without clearly detected emission lines. The abscissa is the rest frame (bottom) and the observed (top) wavelength in μm. The ordinate is the flux in \(10^{-17} \text{ erg s}^{-1} \text{ cm}^{-2} \text{ Å}^{-1}\). \(\text{H}\beta\) and \([\text{O III}]\) emission lines should be positioned as indicated by the downward arrows in each panel. (Color online)

\([\text{O III}]\) lines were not clearly deblended (figure 1). Therefore, only wavelengths shorter than 4861 Å were used to fit the broad \(\text{H}\beta\) emission line. For some sources, a continuum fit at the longest wavelength is problematic, because our continuum fitting ranges do not cover longer wavelength part. Also, the longer wavelength part of \(\text{Fe II}\) emission is not well fitted for some sources. However, these problematic fits do not affect the \(L_{5100}\) value significantly.

We succeeded in fitting the \(\text{H}\beta\) emission lines for 28 out of the 37 observed objects. Tables 3 and 4 show the flux and luminosity of \(\text{H}\beta\) and \([\text{O III}]\) emission lines, respectively, based on the above best Gaussian fit. In table 5, the redshift values estimated from \(\text{H}\beta\) and \([\text{O III}]\) lines are compared to that from the SDSS; they show good agreement.

4 Results

4.1 \(M_{\text{BH}}\) and \(L_{\text{bol}}/L_{\text{Edd}}\) estimation

The SMBH mass \((M_{\text{BH}})\) of the 28 QSOs (with successful \(\text{H}\beta\) fit) were estimated from the following formula (Vestergaard...
\[
\log_{10}(M_{\text{BH}}/M_\odot) = \log_{10}\left[\frac{\text{FWHM}(H\beta)}{1000 \text{ km s}^{-1}}\right]^2 \\
\quad \times \left[\frac{\lambda L_\lambda(5100 \text{ \AA})}{10^{44} \text{ erg s}^{-1}}\right]^{0.5} + (6.91 \pm 0.02),
\]

(1)

and are summarized in table 6.

We employed a resampling approach to obtain realistic uncertainties of \(L_{5100}\), the full-width at half maximum (FWHM) of the H\(\beta\) broad emission line, and \(M_{\text{BH}}\) (e.g., Schulze & Wisotzki 2010; Assef et al. 2011; Shen & Liu 2012). Namely, we artificially added Gaussian random noise that is scaled by the observed \(S/N\) and refitted them. We attempted this procedure for 100 simulated spectra for each target. The \(L_{5100}\), FWHM, and \(M_{\text{BH}}\) error was estimated from the resulting scatter of the derived \(L_{5100}\), FWHM, and \(M_{\text{BH}}\) values from 100 spectra.

For comparison, we also calculated \(M_{\text{BH}}\) using the different formula proposed by McLure and Jarvis (2002):

\[
\log_{10}(M_{\text{BH}}/M_\odot) = \log_{10}\left[4.74 \left\{\frac{\text{FWHM}(H\beta)}{\text{km s}^{-1}}\right\}^2 \\
\quad \times \left[\frac{\lambda L_\lambda(5100 \text{ \AA})}{10^{44} \text{ erg s}^{-1}}\right]^{0.61}\right].
\]

(2)

The difference of \(M_{\text{BH}}\) related to choice of estimator is typically (median) 0.03 dex (range of \(-0.36\) to +0.03 dex).

Table 6 and figure 4 show a comparison of the \(M_{\text{BH}}\) values derived from both methods, which mutually agree within statistical error.

The AGN bolometric luminosity \(L_{\text{bol}}\) was calculated from the observed \(L_{5100}\) luminosity, using a bolometric correction, \(f_L\) (\(L_{\text{bol}} = f_L \times \lambda \times L_{5100}\)). For Type 1 unobscured luminous AGNs, \(f_L\) was estimated to be 5–13 (e.g., Elvis et al. 1994; Kaspi et al. 2000; Netzer 2003; Marconi et al. 2004; Richards et al. 2006). We adopt a constant ratio of \(f_L = 7\), following Netzer et al. (2007). The AGN bolometric luminosity, relative to the Eddington luminosity for a given \(M_{\text{BH}}\) \(\left[L_{\text{Edd}} = 3.2 \times 10^4 (M_{\text{BH}}/M_\odot) L_\odot\right]\), the so-called Eddington ratio \(L_{\text{bol}}/L_{\text{Edd}}\), is often used to estimate the activity of SMBHs (i.e., the SMBH-mass normalized accretion rate). In the case of \(f_L = 7\), the Eddington ratio is given by

\[
L_{\text{bol}}/L_{\text{Edd}} = \frac{7 \times \lambda L_{5100}}{1.5 \times 10^{38} (M_{\text{BH}}/M_\odot)}.
\]

(3)

The estimated \(L_{\text{bol}}/L_{\text{Edd}}\) of 28 QSOs is summarized in table 6.
Table 2. K-band magnitude.∗

| (1) Object ID (SDSS J) | (2) Spectroscopic K mag | (3) Imaging K mag | (4) UKIDSS K mag | (5) 2MASS K mag |
|------------------------|-------------------------|-------------------|------------------|---------------|
| 014619.97−004628.7     | 16.21                   | 16.69             | 16.59            | —             |
| 031845.17−001845.3     | 16.57                   | 16.38             | 16.47            | —             |
| 072554.52+392243.4     | 17.00                   | —                 | —                | —             |
| 074939.01+433217.6     | 16.24                   | 16.07             | —                | 15.66         |
| 075315.93+154216.6     | 16.53                   | 16.68             | —                | —             |
| 075841.66+174558.0     | 15.56                   | 16.08             | —                | —             |
| 083700.82+350550.2     | 16.03                   | 16.06             | —                | —             |
| 084715.16+383110.0     | 16.07                   | 15.99             | —                | —             |
| 094202.04+042244.5     | 13.71                   | 14.58             | 14.58            | 14.62         |
| 095735.37+353520.6     | 16.31                   | 16.14             | —                | —             |
| 100610.55+370513.8     | 14.45                   | 15.15             | —                | 15.27         |
| 111656.89+080829.4     | 15.62                   | 15.63             | 15.56            | 15.39         |
| 113002.35+115438.3     | 16.19                   | 16.29             | 16.18            | 15.98         |
| 133724.69+315254.5     | 16.08                   | 16.15             | 16.04            | —             |
| 133737.87+021820.9     | 15.15                   | 15.74             | 15.72            | >15.17        |
| 140745.50+403702.2     | 14.59                   | 14.48             | —                | 14.63         |
| 142753.85+002591.1     | 14.65                   | 15.49             | 15.39            | 15.27         |
| 150238.38+030228.2     | 16.21                   | 16.54             | 16.15            | —             |
| 151044.66+321712.9     | 17.38                   | 17.34             | —                | —             |
| 155036.80+053749.9     | 15.51                   | 15.76             | 15.84            | >15.59        |
| 155137.22+321307.5     | 18.29                   | —                  | 1                 | —             |
| 155823.22+353252.2     | 17.43                   | —                  | 1                 | —             |
| 165523.09+184708.4     | 15.38                   | 15.43             | —                | —             |
| 211936.77+104623.9     | 16.88                   | 16.84             | —                | —             |
| 213023.61+122252.2     | 15.06                   | —                  | 1                 | 15.29         |
| 213455.08+001056.8     | 16.72                   | 16.97             | 16.69            | —             |
| 231858.56−005049.6     | 16.85                   | 17.09             | 16.95            | —             |
| 234150.01+144906.0     | 16.15                   | 15.87             | 15.92            | —             |

∗Column (1): object name. Column (2): spectroscopic magnitude based on our data. Flux calibration is carried out by using spectroscopic standard star. Column (3): imaging magnitude based on our data (PSF magnitude). Column (4): UKIDSS magnitude (aperture magnitude). Column (5): 2MASS magnitude (PSF magnitude). Only sources whose SMBH masses (MBH) were estimated are listed. Imaging magnitudes were used for flux calibration.

† Imaging data quality is not good enough to obtain reliable photometric magnitude.

Fig. 3. Comparison of K-band magnitudes estimated using spectroscopic data (abscissa) and imaging data (ordinate). The dashed line represents a 1 : 1 correspondence. (Color online)

4.2 MBH and Lbol/Ledd distributions

The upper panels of figures 5a and 5b show the distribution of MBH and the Eddington ratio (Lbol/Ledd) for our sample, respectively. Netzer et al. (2007) and Shemmer et al. (2004) performed near-infrared spectroscopy of QSOs at z = 2−4, and measured the SMBH masses in 15 and 29 sources, respectively, based on the Hβ method, of which 14 QSOs in total (eight sources in Netzer’s sample, and six sources in Shemmer’s sample) were at z > 3. Our near-infrared spectroscopy tripled the number of z > 3 QSOs, with Hβ-based reliably estimated MBH information.

The MBH and Lbol/Ledd distributions of these 14 QSOs at z > 3 studied by Netzer et al. (2007) and Shemmer et al. (2004) are shown in the lower panels of figures 5a and 5b, respectively, for comparison. The MBH and Lbol/Ledd of the comparison sample are re-calculated using equations (1) and (3) with FWHM(Hβ) and L5100 drawn from the literature [table 2 in Netzer et al. (2007), and table 2 in Shemmer et al. (2004)]. The difference of MBH due to choice of estimator [equation (1) in this paper and equation (1) in Netzer et al. (2007), or equation (1) in
Shemmer et al. (2004)] is typically 0.25 dex (range of 0.19–0.30 dex) for Netzer’s sample and 0.15 dex (range of 0.06–0.23 dex) for Shemmer’s sample. The comparison sample has slightly fainter luminosity than our sample (median value of $L_{\text{bol}} = 7.88 \times 10^{46}$ erg s$^{-1}$ for Netzer’s sample and $L_{\text{bol}} = 1.61 \times 10^{47}$ erg s$^{-1}$ for our sample), and $M_{\text{BH}}$ of the comparison sample is smaller (range of $10^{8.59}–10^{9.59} M_{\odot}$) than our sample (range of $10^{8.81}–10^{10.13} M_{\odot}$) as shown in figure 5a. On the other hand, the Eddington ratios of our sample are systematically smaller than those of the comparison sample, as shown in figure 5b. We performed a Kolmogorov–Smirnov test to check if those distributions are statistically the same or not. $P$ values were calculated to be $P(M_{\text{BH}}) = 0.005$ for the $M_{\text{BH}}$ distributions, and $P(L_{\text{bol}}/L_{\text{Edd}}) = 0.045$ for the $L_{\text{bol}}/L_{\text{Edd}}$ distributions, respectively. The result of the K-S test shows that two samples (our sample and the reference sample) are drawn from different parent distributions for both $M_{\text{BH}}$ mass distributions and $L_{\text{bol}}/L_{\text{Edd}}$ distributions ($K$-$S$ probability of being drawn from the same population <0.05).

There are two possible reasons for the production of the high AGN luminosity, as observed in our QSO sample: (1) the QSO has a modest SMBH mass and a large Eddington ratio, or (2) the QSO has a large SMBH mass and a normal Eddington ratio. If we pick up only the second sample (i.e., QSOs at the higher end of the $M_{\text{BH}}$ distribution), $M_{\text{BH}}/M_{\text{spheroid}}$ ratios could be systematically larger than the typical values (e.g., Lauer et al. 2007, Schulze & Wisotzki 2011, 2014), possibly providing systematically biased results regarding the redshift evolution of the $M_{\text{BH}}/M_{\text{spheroid}}$ ratios. The $M_{\text{BH}}$ values of our sample and of the comparison sample agree within a factor of a few. As shown in table 6 and figure 5, it is unlikely that the majority of our samples have a $M_{\text{BH}}$ much larger than the break (cutoff) of the SMBH mass function at $z = 3.2$ ($\sim 10^{9.7} M_{\odot}$):
Kelly & Shen 2013). The cut-off mass of log $M_{\text{BH}} = 9.7$ was estimated by eye using the mass function at $z = 3.2$ in figure 4 by Kelly and Shen (2013), although it might be risky to believe the mass function estimated by C IV-based $M_{\text{BH}}$ at face values. We compared the H$\beta$-based and C IV-based $M_{\text{BH}}$ (figure 6, left) and found that C IV-based $M_{\text{BH}}$ is not always biased toward large $M_{\text{BH}}$. Therefore, we consider that our QSO sample corresponds to the case (1) and that the Lauer-bias is not affecting our sample so severely for a study of the redshift evolution of $M_{\text{BH}}/M_{\text{spheroid}}$. This suggests that we can use our QSO sample to discuss the redshift evolution of the $M_{\text{BH}}/M_{\text{spheroid}}$ ratios, without obvious strong bias, using the combination of the near-infrared spectroscopy of the $M_{\text{BH}}$ estimate (this paper) and ongoing near-infrared, multi-band, high-spatial-resolution AO imaging observations to estimate $M_{\text{spheroid}}$. If the local scaling relations hold all the way to $z > 3$, the expected $M_{\text{spheroid}}$ for our observed QSOs with $M_{\text{BH}} = 6.5 \times 10^8-1.4 \times 10^{10} M_\odot$, are $4.3 \times 10^{11}-9.0 \times 10^{12} M_\odot$, which are detectable with 8–10 m telescopes, and have actually been detected in our high-spatial-resolution infrared J- and K'-band imaging observations using the Subaru 8.2-m telescope and AO (T. Kawaguchi et al. in preparation; Y. Saito et al. in preparation).

5 Discussion

5.1 Comparison of $M_{\text{BH}}$ estimated from H$\beta$ $\lambda$4861 and C IV $\lambda$1549

The combination of the C IV $\lambda$1549 emission line and continuum luminosity at 1450 Å has often been used to estimate SMBH mass (hereafter, the C IV method) for distant QSOs, because the C IV emission line is redshifted into the optical wavelength range where spectroscopic observations are easier to attain. However, as mentioned in section 1, the C IV emission line often shows an asymmetric profile. This suggests that, in addition to the motion dominated

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**Table 4. [O III] flux and luminosity.**

| Object ID (SDSS J) | [O III] $\lambda$5007 | [O III] $\lambda$4959 | Luminosity [10$^{44}$ erg s$^{-1}$] |
|-------------------|-----------------|-----------------|-----------------|
| 014619.97–004628.7 | 0.361 ± 0.016 | 0.120 ± 0.005 | 0.318 ± 0.014 |
| 031845.17–001845.3 | 0.351 ± 0.004 | 0.117 ± 0.028 | 0.322 ± 0.078 |
| 072554.52+392243.4 | 1.170 ± 0.016 | 0.057 ± 0.005 | 0.158 ± 0.015 |
| 074939.01+433217.6 | 1.127 ± 0.040 | 0.376 ± 0.013 | 0.973 ± 0.035 |
| 075515.93+154216.6 | 0.185 ± 0.161 | 0.062 ± 0.054 | 0.180 ± 0.156 |
| 075841.66+174558.0 | 0.922 ± 0.098 | 0.307 ± 0.033 | 0.814 ± 0.087 |
| 083700.82+350550.2 | 0.422 ± 0.094 | 0.141 ± 0.031 | 0.413 ± 0.092 |
| 084715.04+383110.0 | 0.755 ± 0.031 | 0.252 ± 0.010 | 0.672 ± 0.027 |
| 094202.04+042244.5 | 1.137 ± 0.063 | 0.379 ± 0.021 | 1.090 ± 0.060 |
| 095753.37+353520.6 | 0.173 ± 0.030 | 0.058 ± 0.010 | 0.165 ± 0.028 |
| 100610.55+370513.8 | 1.171 ± 0.046 | 0.390 ± 0.015 | 1.058 ± 0.041 |
| 111656.89+080829.4 | 0.765 ± 0.058 | 0.255 ± 0.019 | 0.707 ± 0.053 |
| 113002.35+115438.3 | 0.212 ± 0.038 | 0.071 ± 0.013 | 0.219 ± 0.039 |
| 133724.69+315254.5 | 0.462 ± 0.022 | 0.154 ± 0.007 | 0.411 ± 0.020 |
| 133757.87+021820.9 | 0.436 ± 0.061 | 0.145 ± 0.020 | 0.433 ± 0.061 |
| 140743.50+403702.2 | — | — | — |
| 142753.85–002951.1 | 0.507 ± 0.050 | 0.169 ± 0.017 | 0.514 ± 0.050 |
| 150238.38+030228.2 | — | — | — |
| 151044.66+321712.9 | — | — | — |
| 155036.80+053749.9 | 0.993 ± 0.017 | 0.331 ± 0.006 | 0.864 ± 0.015 |
| 155137.22+321307.5 | 0.416 ± 0.027 | 0.139 ± 0.009 | 0.370 ± 0.024 |
| 155823.22+353252.2 | 0.110 ± 0.017 | 0.037 ± 0.006 | 0.099 ± 0.015 |
| 165523.09+184708.4 | 0.534 ± 0.028 | 0.178 ± 0.009 | 0.527 ± 0.027 |
| 211936.77+104623.9 | 0.159 ± 0.024 | 0.053 ± 0.008 | 0.148 ± 0.022 |
| 213023.61+122252.2 | 1.535 ± 0.051 | 0.512 ± 0.017 | 1.449 ± 0.048 |
| 213455.08+001056.8 | — | — | — |
| 231858.56–005049.6 | 0.049 ± 0.018 | 0.016 ± 0.006 | 0.044 ± 0.016 |
| 234150.01+144906.0 | 0.013 ± 0.005 | 0.004 ± 0.002 | 0.011 ± 0.004 |

* Column (1): object name. Column (2): flux of [O III] $\lambda$5007 emission line. Column (3): flux of [O III] $\lambda$4959 emission line. Column (4): luminosity of [O III] $\lambda$5007 emission line. Column (5): luminosity of [O III] $\lambda$4959 emission line. The values were calculated from fitting results.
by the gravitational potential of SMBH, some other non-gravitational component may be contaminated, such as outflow (Vestergaard & Peterson 2006; Marziani & Sulentic 2012). In fact, several previous studies indicated significant scatter about the comparison of SMBH masses estimated using the Hβ method and the C IV method (e.g., Netzer et al. 2007; Shen et al. 2008; Ho et al. 2012; Shen & Liu 2012; Trakhtenbrot & Netzer 2012).

Shen et al. (2011) reported C IV-based BH masses for our QSO sample, using the following formula (Vestergaard & Peterson 2006):

\[
\log_{10}(M_{\text{BH}}/M_\odot) = \log_{10} \left( \frac{\text{FWHM(C IV)}}{1000 \, \text{km s}^{-1}} \right)^2 
  \times \left[ \frac{\lambda L_\odot (1350 \, \text{Å})}{10^{44} \, \text{erg s}^{-1}} \right]^{0.53} + (6.66 \pm 0.01). (4)
\]

We adopt their estimates to compare with our \(M_{\text{BH}}\) using the Hβ method. The FWHM of the C IV emission line and C IV-based \(M_{\text{BH}}\) of our targets are shown in Table 7. For two QSOs, C IV data are not available in Shen et al. (2011). The left-hand panel of figure 6 shows a comparison between SMBH masses obtained by the two methods for our sample. The scatter is large (0.41 dex) and no significant correlation between Hβ-based and C IV-based \(M_{\text{BH}}\) is observed. Shen et al. (2008) compared BH masses estimated using different methods for \(\sim 60000\) QSOs at \(0.1 \leq z \leq 4.5\), and found that while \(M_{\text{BH}}\) obtained by the Hβ- and Mg II-methods are tightly correlated, a comparison between C IV-based and Mg II-based \(M_{\text{BH}}\) shows large scatter with \(\sim 0.34\) dex (see also Shen et al. 2011). Given these results, the large scatter shown in the left-hand panel of figure 6 for our QSO sample is most likely due to the large uncertainty associated with C IV-based \(M_{\text{BH}}\). For a reliable \(M_{\text{BH}}\) estimate for \(z \sim 3\) QSOs, the Hβ-method based on near-infrared spectroscopy is preferred over the C IV-method based on optical spectroscopy.

The right-hand panel of figure 6 is the same plot as that shown in the left-hand panel of figure 6; however, the marks are distinguished, depending on the Eddington ratio. The samples with high Eddington ratios appear to be distributed slightly to the upper side than those with low Eddington ratios, indicating that the C IV-based \(M_{\text{BH}}\) was larger than Hβ-based \(M_{\text{BH}}\) for sources with high Eddington ratios. Figure 7 shows the relationship between the Eddington ratio and the linewidth ratio \(\text{FWHM(C IV)/FWHM(Hβ)}\). A weak correlation is seen: \[\log(\text{FWHM(C IV)/FWHM(Hβ)}) = (0.32 \pm 0.15) \times \log(L_{\text{bol}}/L_{\text{Edd}}) + (0.03 \pm 0.08)\] for our sample only or \[\log(\text{FWHM(C IV)/FWHM(Hβ)}) = (0.35 \pm 0.11) \times \log(L_{\text{bol}}/L_{\text{Edd}}) + (0.05 \pm 0.06)\] for all plotted samples. This correlation indicates that objects with a larger Eddington ratio have a wider C IV linewdith, compared to Hβ. QSOs with higher Eddington ratios can have stronger radiation pressure and thereby stronger outflow motion of gas than those with lower Eddington ratios.

The C IV line-emitting region is further inside than the Hβ line-emitting region (Peterson & Wandel 1999). It may be possible that this outflow-origin motion broadens the C IV line profile, compared to the SMBH's gravitational motion alone, resulting in a larger \(M_{\text{BH}}\) estimate than the Hβ-based method.

### Table 5. Redshift comparison.

| Object ID (SDSS J) | Hβ [O III] \(\lambda_{5007}\) |
|-------------------|---------------------------------|
|                   |                                 |
| 014619.97−004628.7 | 3.173                            |
| 031845.17−001845.3 | 3.225                            |
| 072534.52+392243.4 | 3.258                            |
| 074939.01+433217.6 | 3.144                            |
| 075315.93+154216.6 | 3.288                            |
| 075841.66+174558.0 | 3.182                            |
| 083700.82+350550.2 | 3.322                            |
| 084715.16+383110.0 | 3.189                            |
| 094202.04+042244.5 | 3.287                            |
| 095753.37+353520.6 | 3.287                            |
| 100610.55+370513.8 | 3.203                            |
| 111666.89+080829.4 | 3.240                            |
| 113002.35+115438.3 | 3.434                            |
| 133724.69+315254.5 | 3.192                            |
| 133737.87+021820.9 | 3.358                            |
| 140745.50+403702.2 | 3.168                            |
| 142753.85−002951.1 | 3.373                            |
| 150238.38+030226.2 | 3.370                            |
| 151044.66+321712.9 | 3.478                            |
| 155036.80+053749.9 | 3.159                            |
| 155137.22+321307.5 | 3.143                            |
| 155823.22+353252.2 | 3.191                            |
| 165523.09+184708.4 | 3.375                            |
| 211936.77+104623.9 | 3.274                            |
| 213023.61+112252.2 | 3.267                            |
| 213455.08+001056.8 | 3.289                            |
| 231858.56−005049.6 | 3.211                            |
| 234150.01+144906.0 | 3.170                            |

*Columns (1): object name. Column (2): redshift measured by broad Hβ emission line. Column (3): redshift measured by [O III] \(\lambda_{5007}\) emission line. Column (4): SDSS redshift.

5.2 Growth time of SMBHs

From the AGN bolometric luminosity, we can obtain information on the mass accretion rate. When the measured SMBH mass is divided by the accretion rate, the time scale of SMBH growth can be derived \(t_{\text{grow}}\).

Following Netzer
Table 6. Observed and derived properties related to SMBHs.∗

| Object ID (SDSS J) | FWHM(Hβ) [10^3 km s^{-1}] | λL_{[1]} (5100 Å) [10^6 erg s^{-1}] | log M_{BH} [M_{⊙}] | log L_{bol}/L_{Edd} | t_{grow}/t_{universe} | log M_{BH} [M_{⊙}] (McL) |
|-------------------|-----------------------------|-----------------------------------|-------------------|-----------------|-------------------|---------------------------|
| 014619.97−004628.7 | 6.92 ± 1.30 | 1.61 ± 0.09 | 9.68 ± 0.17 | −0.804 | 1.76 | 9.69 ± 0.17 |
| 031845.17−001845.3 | 4.79 ± 0.48 | 1.43 ± 0.24 | 9.34 ± 0.09 | −0.516 | 0.87 | 9.34 ± 0.09 |
| 072554.52+392243.4 | 4.32 ± 0.41 | 1.27 ± 0.03 | 9.23 ± 0.08 | −0.457 | 0.76 | 9.23 ± 0.08 |
| 074939.01+433217.6 | 7.14 ± 0.33 | 2.33 ± 0.12 | 9.80 ± 0.06 | −0.764 | 1.63 | 9.82 ± 0.06 |
| 075515.93+154216.6 | 2.70 ± 0.80 | 1.47 ± 0.32 | 8.81 ± 0.28 | 0.026 | 0.23 | 8.81 ± 0.28 |
| 075841.66+174558.0 | 4.64 ± 1.03 | 1.75 ± 0.16 | 9.34 ± 0.20 | −0.428 | 0.70 | 9.35 ± 0.20 |
| 083700.82+350550.2 | 5.18 ± 0.53 | 2.73 ± 0.20 | 9.55 ± 0.09 | −0.445 | 0.80 | 9.59 ± 0.09 |
| 084715.16+333110.0 | 4.29 ± 0.46 | 2.67 ± 0.12 | 9.38 ± 0.09 | −0.284 | 0.51 | 9.41 ± 0.09 |
| 094202.04+042244.5 | 5.34 ± 0.22 | 11.45 ± 0.23† | 9.89 ± 0.03† | −0.162 | 0.44 | 10.00 ± 0.03 |
| 095735.37+333520.6 | 6.07 ± 0.71 | 2.80 ± 0.07 | 9.69 ± 0.11 | −0.574 | 1.08 | 9.73 ± 0.11 |
| 100610.55+370513.8 | 5.94 ± 0.40 | 6.23 ± 0.08 | 9.85 ± 0.06 | −0.387 | 0.71 | 9.93 ± 0.06 |
| 111656.89+080829.4 | 3.34 ± 0.22 | 5.36 ± 0.24 | 9.32 ± 0.05 | 0.078 | 0.22 | 9.39 ± 0.05 |
| 113002.35+115438.3 | 6.05 ± 0.42 | 2.28 ± 0.15 | 9.65 ± 0.06 | −0.623 | 1.26 | 9.67 ± 0.06 |
| 133724.69+315254.5 | 5.73 ± 0.24 | 2.21 ± 0.05 | 9.60 ± 0.04 | −0.587 | 1.06 | 9.62 ± 0.04 |
| 133757.87+021820.9 | 5.18 ± 1.09 | 3.51 ± 0.17 | 9.59 ± 0.22 | −0.376 | 0.69 | 9.63 ± 0.22 |
| 140745.50+403702.2 | 6.72 ± 0.17 | 13.79 ± 0.06 | 10.13 ± 0.02 | −0.389 | 0.74 | 10.24 ± 0.02 |
| 142755.85+002951.1 | 5.49 ± 0.87 | 5.13 ± 0.19 | 9.73 ± 0.13 | −0.351 | 0.73 | 9.80 ± 0.13 |
| 150238.38+030228.2 | 5.28 ± 0.21 | 1.49 ± 0.07 | 9.44 ± 0.03 | −0.598 | 1.13 | 9.45 ± 0.03 |
| 151044.66+321712.9 | 5.04 ± 0.60 | 0.67 ± 0.04 | 9.22 ± 0.10 | −0.725 | 1.51 | 9.19 ± 0.10 |
| 155036.80+053749.9 | 6.11 ± 0.29 | 3.30 ± 0.06 | 9.74 ± 0.04 | −0.552 | 1.00 | 9.78 ± 0.04 |
| 155137.22+323107.5 | 6.70 ± 1.12 | 0.96 ± 0.07 | 9.54 ± 0.18 | −0.889 | 2.11 | 9.52 ± 0.18 |
| 155823.22+335225.2 | 8.49 ± 2.98 | 0.80 ± 0.04 | 9.67 ± 0.28 | −1.098 | 3.52 | 9.65 ± 0.28 |
| 165523.09+184708.4 | 5.93 ± 0.21 | 5.19 ± 0.08 | 9.81 ± 0.03 | −0.426 | 0.80 | 9.88 ± 0.03 |
| 211936.77+104623.9 | 4.72 ± 0.78 | 1.38 ± 0.03 | 9.31 ± 0.16 | −0.501 | 0.85 | 9.31 ± 0.16 |
| 213023.61+122522.5 | 4.39 ± 0.35 | 7.43 ± 0.24 | 9.63 ± 0.07† | −0.090 | 0.35 | 9.71 ± 0.06 |
| 213455.08+001056.8 >3.09 ± 0.31† | 1.34 ± 0.03 >8.95 ± 0.09 <−0.157 | >0.36 >8.95 ± 0.08 |
| 231858.56−005049.6 | 5.21 ± 0.75 | 1.10 ± 0.03 | 9.35 ± 0.13 | −0.650 | 1.19 | 9.35 ± 0.13 |
| 234150.01+144906.0 | 7.49 ± 4.36 | 3.59 ± 0.09 | 9.72 ± 0.69 | −0.496 | 0.88 | 9.77 ± 0.69 |

∗Column (1): object name. Column (2): full-width at half maximum (FWHM) of broad Hβ emission line. Column (3): continuum luminosity at 5100 Å. Column (4): decimal logarithm of SMBH mass. Statistical errors were estimated by resampling approach (subsection 4.1; Schulze & Wisotzki 2010; Assel et al. 2011; Shen & Liu 2012). Column (5): decimal logarithm of Eddington ratio. Column (6): ratio of SMBH growth time (t_{grow}) and the age of the universe (t_{universe}). Columns (7): Eddington ratio in subsection 4.2. (1) If t_{grow}/t_{universe} < 1, then the measured M_{BH} can be reproduced with the estimated mass accretion rate. On the other hand, (2) if t_{grow}/t_{universe} > 1, the measured M_{BH} cannot be reproduced with the estimated mass accretion rate, requiring a more active phase in the past at higher redshift than the QSO’s redshift. This means that QSOs are not sufficiently active at the QSO redshift. Most of

...
our sample have less than 1 $t_{\text{grow}}/t_{\text{universe}}$ values. The range of $t_{\text{grow}}/t_{\text{universe}}$ values for our sample is 0.22–3.52, and most of our sample have similar values to those of Netzer et al. (2007) (0.45–2.27). QSOs in Shemmer et al. (2004), however, have systematically smaller $t_{\text{grow}}/t_{\text{universe}}$ values (0.05–0.16) than ours, which could be due to their sample being selected only from luminous sources ($L > 10^{46}$ erg s$^{-1}$). Some of objects, with $t_{\text{grow}}/t_{\text{universe}} > 1$, in our and Netzer’s samples should have experienced a rapidly growing phase in the past, while Shemmer’s sample and most of our sample are in a rapidly growing phase at $z \sim 3$.

6 Summary

We present new near-infrared spectroscopic observations of 37 QSOs at $z \sim 3$. We successfully estimated the SMBH masses of 28 out of 37 observed QSOs, using the well-calibrated H$\beta$-method, based on a broad H$\beta$ emission

Fig. 4. Comparison of $M_{\text{BH}}$ derived from a different formula (table 6). The abscissa and ordinate are the values derived based on Vestergaard and Peterson (2006), and McLure and Jarvis (2002), respectively. Arrows mean lower limits. The dashed line represents a 1 : 1 correspondence. (Color online)

Fig. 5. (a) Histogram of $M_{\text{BH}}$ estimated in this study (upper panel) and in the literature (Netzer et al. 2007; Shemmer et al. 2004) for only $3 < z < 4$ sources (lower panel). A lower limit object is shown as a shaded area. (b) Comparison of the $L_{\text{bol}}/L_{\text{Edd}}$ distribution for our sample (upper panel) and Netzer’s sample at $z > 3$ (lower panel). An upper limit object is displayed by a shaded area. In the lower panels of both (a) and (b), open and filled histograms correspond to Netzer’s sample and Shemmer’s sample, respectively. (Color online)

Fig. 6. Left: comparison of the SMBH masses ($M_{\text{BH}}$) estimated from the H$\beta$ method (abscissa) and the C$\IV$ method (ordinate). C$\IV$ data are from Shen et al. (2011). Two QSOs are not plotted here due to lack of C$\IV$ data. The right arrow means a lower limit. The dashed line represents a 1:1 correspondence. Right: the same plot as the left-hand figure but with the Eddington ratio information added. The open circles are targets with high Eddington ratios with log ($L_{\text{bol}}/L_{\text{Edd}}$) $> -0.5$. The filled circles are those with low Eddington ratios with log ($L_{\text{bol}}/L_{\text{Edd}}$) $< -0.5$. The open triangles correspond to Netzer’s and Shemmer’s samples which has a high Eddington ratio of log ($L_{\text{bol}}/L_{\text{Edd}}$) $> -0.5$. The filled triangles are those with low Eddington ratios of log ($L_{\text{bol}}/L_{\text{Edd}}$) $< -0.5$. For two QSOs in our sample and five QSOs in Netzer and Shemmer’s sample, C$\IV$ data are not available in Shen et al. (2011). The right arrow indicates a lower limit. We find that samples with high Eddington ratios appear to be distributed in the upper-left side compared to those with low Eddington ratios which distribute in both the upper left- and lower right-hand sides. (Color online)
linewidth and nearby continuum luminosity. A summary of the main results is given below.

(1) A comparison of our work to similar studies of \( z \approx 2-4 \) QSOs by Netzer et al. (2007) and Shemmer et al. (2004) indicated that our sample had slightly larger \( M_{\text{BH}} \) and smaller Eddington ratios than the comparison sample. Also, it is unlikely that most of our sample have \( M_{\text{BH}} \) much larger than the break of the BH mass function at that redshift. Given that all our QSOs have at least one nearby bright star, high-spatial-resolution AO observations to investigate the detailed properties of the host galaxies are possible and ongoing. Our sample is suited to an investigation of \( M_{\text{BH}}/M_{\text{spheroid}} \) evolution at \( z \approx 3 \), without obvious selection bias.

(2) A comparison of the \( \text{H}\beta \)-based SMBH mass estimate through near-infrared spectroscopy and previous \( \text{CIV} \)-based SMBH mass estimates using optical spectroscopy showed large scatter and no significant correlation. QSOs with higher Eddington ratios tended to display higher \( \text{CIV} \)-derived \( M_{\text{BH}} \) than \( \text{H}\beta \)-derived \( M_{\text{BH}} \), due possibly to effects other than the motion dominated by the gravitational potential of SMBHs. As argued in previous studies, the use of \( \text{CIV} \) for the \( M_{\text{BH}} \) estimate could introduce large uncertainty. \( \text{H}\beta \)-based \( M_{\text{BH}} \) estimation using near-infrared spectroscopy is desirable for reliable \( M_{\text{BH}} \) estimates of \( z \approx 3 \) QSOs.

### Acknowledgement

We appreciate the anonymous referee for his/her useful comment. We are grateful to S. Hayashi for the observation time with the Subaru and K. Imase for supporting observations in the early phase of the study. We wish to thank K. Aoki for general discussions about QSOs, and A. Schulze for helpful discussions about possible bias of our sample. This work was partly supported by the Grants-in-Aid of the Ministry of Education, Science, Culture, and Sport [23540273(MI), 19740105(TK), 09J07156(TM)], and the Grants-in-Aid for Young Scientists [25800999(NK)]. This work was also supported in part by a Japanese Society for the Promotion of Science (JSPS) Core-to-Core Program “International Research Network for Dark Energy”. Use of the UKIRT for observations was supported by the National Astronomy Organization of Japan (NAOJ).

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