The Most Massive Active Galactic Nuclei at 1 ≤ z ≤ 2

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Abstract
We obtained near-infrared spectra of 26 Sloan Digital Sky Survey quasars at 0.7 < z < 2.5 with reported rest-frame ultraviolet MBH ~ 10^10 M⊙ to critically examine the systematic effects involved with their mass estimations. We find that active galactic nuclei (AGNs) heavier than 10^10 M⊙ often display double-peaked Hα emission, extremely broad Fe II complex emission around Mg II, and highly blueshifted and broadened C IV emission. The weight of this evidence, combined with previous studies, cautions against the use of MBH values based on any emission line with a width over 8000 km s^-1. Also, the MBH estimations are not positively biased by the presence of ionized narrow line outflows, anisotropic radiation, or the use of line FWHM instead of σ for our sample, and unbiased with variability, scatter in broad line equivalent width, or obscuration for general type-1 quasars. Removing the systematically uncertain MBH values, ~10^{10} M⊙ black holes (BHs) in 1 < z < 2 AGNs can still be explained by anisotropic motion of the broad line region from ~10^{9.5} M⊙ BHs, although current observations support that they are intrinsically most massive, and overmassive to the host’s bulge mass.

Key words: galaxies: active – galaxies: evolution – quasars: supermassive black holes

Supporting material: data behind figure

1. Introduction
Since the identification of supermassive black holes (BHs) at the center of galaxies, their typical mass (MBH) values have been measured in the 10^{6–9} M⊙ range (e.g., Kormendy & Richstone 1995). The more recent discovery of ~10^{10} M⊙ BHs (McConnell et al. 2011) in quiescent galaxies further extended the mass limit, pushing the previous ~10^{9} M⊙ boundary to heavier regimes. These extremely massive BHs (~10^{9.5} M⊙, hereafter EMBHs) give constraints to how massive a BH can grow through accretion within the inner galaxy (e.g., Inayoshi & Haiman 2016; King 2016). Also, the EMBHs are thought to reside in ~10^{12} M⊙ giant elliptical host galaxies lying on the present-day MBH–σ* relation (e.g., Ferrarese & Merritt 2000; Gebhardt et al. 2000), though we note there are exceptions to the expectation that BH growth closely follows that of the host (e.g., van den Bosch et al. 2012; Seth et al. 2014; Walsh et al. 2015).

Direct evidence for the existence of 10^{10} M⊙ BHs was initially reported in a handful of nearby quiescent galaxies (e.g., NGC 3842 and NGC 4889, McConnell et al. 2011; NGC 1277, van den Bosch et al. 2012), albeit with the validity of some of the measurements being questioned (Emsellem 2013). Even if we consider that the measured values are acceptable, the EMBHs tend to lie above the MBH–σ* or, more frequently, the MBH–L_{bulge} relations extrapolated from lower-mass BHs (e.g., Gültekin et al. 2009; Kormendy & Ho 2013), by up to an order of magnitude (see also Savorgnan & Graham 2016 on measurement issues for L_{bulge}). To explain the high mass of EMBHs with respect to their host galaxies, Volonteri & Ciotti (2013) suggest that EMBHs are formed through frequent dry mergers. However, this does not solve the problem entirely because such mergers might not necessarily induce strong active galactic nucleus (AGN) activity in EMBHs found up to at least z = 5 (e.g., Jun et al. 2015, hereafter J15; Wu et al. 2015).

These observational and theoretical considerations lead to the natural question of whether the estimates of MBH ~ 10^{10} M⊙ in AGNs are reliable. The MBH estimators applied to high-redshift quasar spectra have mainly relied on UV-based spectral features that are secondarily calibrated to hydrogen Balmer line-based estimators. One possibility is that the UV-based MBH values are overestimated somehow. Independent MBH estimates from Balmer line-based estimators would enhance the reliability of 10^{10} M⊙ BHs in distant quasars. Unfortunately, direct comparison between the UV-based versus Balmer-based MBH estimates has been scarce for EMBHs. Previous studies have been largely limited to MBH < 10^{9.5} M⊙ (e.g., Netzer et al. 2007; Shang et al. 2007; Dietrich et al. 2009; Greene et al. 2010; Ho et al. 2012; Park et al. 2013), and such studies are controversial regarding the scatter between C IV and Balmer-based estimators while consistent on the agreement between Mg II and Balmer-based MBH values. The most extensive study in this respect was done by Shen & Liu (2012, hereafter S12) where the sample includes dozens of EMBHs, though with few BHs above 10^{10} M⊙.

In order to understand the mass growth of EMBHs, accurate MBH measurements over a range of redshifts is vital. In the distant universe, however, direct dynamical measurement of MBH becomes difficult for quiescent galaxies, as it is hard to resolve the gravitational sphere of influence from the BH. Instead, broad line gas kinematics are used to estimate the MBH of AGNs, where this method gives more uncertain results. MBH measurements for AGNs are based on the reverberation mapping technique (Blandford & McKee 1982; Peterson 1993) which measures the time delay of the broad line emission to the incident continuum and thus estimates the size of the broad line region (R_{BLR}). The R_{BLR} values for H/β are further calibrated by...
the radius–luminosity relationship \( R_{\text{BLR}}-L \) relation, Kaspi et al. 2000; Bentz et al. 2006, which allows the estimation of \( M_{\text{BH}} \) from a single-epoch measurement of optical continuum/line luminosity and broad line width. High-redshift AGNs have their rest-frame optical (rest-optical) emission redshifted to the infrared, and their rest-frame ultraviolet (rest-UV) emission redshifted into the optical. The single-epoch mass estimators are thus secondarily calibrated in the UV assuming that the UV continuum luminosity and broad emission line (CIV or MgII) widths follow the optical \( R_{\text{BLR}}-L \) relation and optical line widths respectively, as a linear or power-law relation. Ongoing studies tentatively find that the slope of the CIV \( R_{\text{BLR}}-L \) relation follows that of the optical relation, and extends up to the most luminous quasars (Kaspi et al. 2007; Sluse et al. 2011; Chelouche et al. 2012). However, the UV continuum luminosities and line widths are not tightly correlated with the optical quantities, introducing an intrinsic scatter of ~0.4 dex when comparing CIV and Balmer \( M_{\text{BH}} \) measurements (e.g., J15).

In addition to the issues regarding the reliability of the rest-UV \( M_{\text{BH}} \) measurements, the rest-optical \( M_{\text{BH}} \) measurement from single-epoch spectroscopy itself has limitations on its accuracy due to the systematic uncertainties in deriving the mass equation. Bearing in mind that the single-epoch \( M_{\text{BH}} \) values have sizeable errors from the poorly constrained constant (virial factor, hereafter \( f \)-factor) in the mass equation \( (0.3-0.4 \text{ dex systematic uncertainty, e.g., Kormendy \\& Ho 2013; McConnell \\& Ma 2013) and the } R_{\text{BLR}}-L \text{ relation (0.1-0.2 \text{ dex intrinsic scatter, Bentz et al. 2013), it is possible that the } M_{\text{BH}} \text{ values of the most extreme AGNs could have been biased to high values if they were selected to have outlying } f \text{-factors or } R_{\text{BLR}} \text{ values with respect to the calibrations. Indeed, theoretical and technical issues that could positively bias the } M_{\text{BH}} \text{ measurements have been reported, from accretion disk modeling (Laor \\& Davis 2011; Wang et al. 2014) or profile fit methodology (Peterson et al. 2004; Collin et al. 2006). Furthermore, potential limitations of automated spectral fitting of a large sample of spectra failing to model unusual spectral features (e.g., Shen et al. 2008), or using single-epoch spectroscopy to derive representative AGN properties, should be carefully checked, especially at extreme mass values.

In this paper, we present rest-optical spectra of 26 quasars at \( 0.7 < z < 2.5 \) with UV-based \( \sim 10^{10} M_\odot \) \( M_{\text{BH}} \) measurements, obtained with the NASA Infrared Telescope Facility (IRTF). We aim to double check the consistency of the massive end UV–optical \( M_{\text{BH}} \) estimates, and examine if the measurements could be systematically biased to unusually high masses from spectral features and during application of the mass estimator. We describe the sample selection and data acquisition of extremely massive AGNs (Section 2), the spectral analysis in determining \( M_{\text{BH}} \) (Section 3), the results (Section 4) and implications on the measured \( M_{\text{BH}} \) values (Section 5).

Throughout, we adopt a flat \( \Lambda \)CDM cosmology with \( H_0 = 70 \text{ km s}^{-1}\text{Mpc}^{-1} \), \( \Omega_m = 0.3 \), and \( \Omega_\Lambda = 0.7 \) (e.g., Im et al. 1997).

2. Data

2.1. Sample Description and Observations

We selected the extremely massive AGN sample from the Sloan Digital Sky Survey (SDSS) type-1 quasar catalog (DR7, Schneider et al. 2010). The spectral fitting results and the \( M_{\text{BH}} \) estimates in Shen et al. (2011) were adopted for target selection, using the H\( \beta \) line at \( z < 0.8 \), MgII at \( 0.8 < z < 2.0 \), and CIV at \( z > 2.0 \). We identified the sample by applying the following selection criteria:

1. Mass selection of \( M_{\text{BH}} > 5 \times 10^9 M_\odot \)
2. Redshift cut of \( 0.7 < z < 2.5 \) to place the broad H\( \alpha \) and H\( \beta \) lines within the near-infrared (NIR) spectroscopic windows, excluding redshifts where both H\( \alpha \) and H\( \beta \) are close to NIR telluric absorption (1.1 < \( z \) < 1.3 and 1.6 < \( z \) < 2.2)
3. Continuum signal-to-noise ratio (S/N) cut of 20 or higher from the SDSS spectra for good line width and flux measurements, \( H \)-band magnitude <17.8 AB mag, bright enough for IRTF observations
4. Removal of objects flagged or visually inspected to show double-peaked H\( \beta \) lines, severely absorbed MgII or CIV, and obvious mismatch between the model and the spectrum

yielding 1254 quasars sufficing the \( M_{\text{BH}} \) and redshift cut, and 261 objects with further sensitivity limits and flags, among which we arbitrarily selected 26 objects spanning the optical continuum luminosities\(^4\) of \( L_{5100} = 10^{45.7-47.2} \text{ erg s}^{-1} \), for IRTF observations. Figure 1 shows the redshift–\( M_{\text{BH}} \) distribution of our sample.

We used the SpeX instrument (Rayner et al. 2003) on the IRTF to obtain the NIR spectra of the targets. The \( 0.8-2.4 \mu \text{m} \) cross-dispersed mode (SXD) was chosen, with a slit width of \( 0.8 \) or \( 1.6 \) depending on the seeing conditions. This yields a spectral resolution of \( R = 750 \) or 375 throughout the observed wavelengths, which is tuned for sensitivity over resolution for the broad AGN emission lines and continuum features. The exposure times for the targets were aimed to give a continuum S/N per resolution element of at least 10 around H\( \beta \), and 5 around H\( \alpha \). We carefully checked each field to avoid neighbor

\(^4\) Throughout this paper we use subscript numbers on the monochromatic luminosity to indicate its wavelength, such as \( L_{\lambda_{5100}} = L(5100 \text{ Å}) \).
source contamination when nodding the spectrum along the 15\arcsec slit length. The observations were performed during three full and three half nights in 2011 December, 2012 February/December along with another program, summing to a total on-source integration of 9.3 hr for all the targets (0.1–0.6 hr per target). The weather conditions were overall photometric but atmospheric seeing varied from 0.6–2\arcsec. We nodded the spectra in AB mode with a 90–180 s frame time for good dark and sky subtraction, and observed A0 V type standard stars near to the target for telluric absorption correction (Vacca et al. 2003) and flux calibration. Also, a set of flat-field and argon arc wavelength calibration data were taken. We summarize the IRTF observations in Table 1.

In addition to the NIR spectroscopy, we compiled the optical spectra of quasars from the SDSS database (DR12 including both the SDSS-I/SDSS-II and the SDSS-III BOSS data, Alam et al. 2015) in order to calculate the $M_{BH}$ values from C IV and Mg II lines and to compare them with masses from hydrogen Balmer lines or previous rest-UV measurements. Also, broadband photometric data from GALEX GR7, SDSS DR12, 2MASS PSC, UKIDSS DR10, and WISE AllWISE releases (Martin et al. 2005; Skrutskie et al. 2006; Lawrence et al. 2007; Wright et al. 2010; Alam et al. 2015) were collected to supplement the spectra with monochromatic continuum luminosities. The latest spectra (SDSS-III BOSS over SDSS-I/SDSS-II) and photometry (UKIDSS over 2MASS) were used when the target had overlapping data, while multiple spectra from the same instrument were averaged.

### Table 1
Summary of IRTF Observations

| Name     | Coordinates | $z$  | $H$ | $t_{exp}$ | $R$ |
|----------|-------------|-----|-----|----------|-----|
| J0102-00 | J010205.89+001157.0 | 0.727 | 16.85 | 30 | 750 |
| J0110-05 | J010943.56+052953.9 | 0.944 | 17.07 | 9 | 375 |
| J0748-22 | J074815.44+220059.5 | 1.000 | 16.30 | 24 | 750 |
| J0840-23 | J083937.85+223940.7 | 1.312 | 16.25 | 18 | 750 |
| J1057-31 | J105705.16+311909.7 | 1.329 | 17.30 | 24 | 750 |
| J0203-13 | J020356.11+124928.0 | 1.352 | 17.49 | 30 | 750 |
| J0319-07 | J031926.24–072808.8 | 1.391 | 16.78 | 30 | 375 |
| J1055-28 | J105400.84+273306.0 | 1.453 | 17.12 | 18 | 750 |
| J0741-16 | J074527.78–100807.7 | 1.465 | 16.76 | 24 | 750 |
| J0400-07 | J040022.40–064928.6 | 1.516 | 16.58 | 30 | 375 |
| J0855+05 | J085515.59+045232.8 | 1.541 | 17.08 | 18 | 750 |
| J0741+32 | J074043.47+314201.2 | 1.546 | 17.70 | 24 | 750 |
| J1152+52 | J115215.68+520238.6 | 2.221 | 15.44 | 6 | 750 |
| J1339+11 | J133928.39+105030.3 | 2.250 | 17.18 | 12 | 750 |
| J0905+24 | J090444.34+233354.1 | 2.258 | 16.62 | 30 | 750 |
| J0257+00 | J025644.69+012464.0 | 2.264 | 17.78 | 24 | 750 |
| J2123+01 | J212349.70–005052.9 | 2.282 | 15.90 | 12 | 750 |
| J0052+01 | J005202.41+011292.2 | 2.283 | 17.07 | 18 | 750 |
| J1121+00 | J111517.78+002457.5 | 2.335 | 17.58 | 36 | 375 |
| J1027+30 | J102648.16+295410.9 | 2.349 | 16.92 | 24 | 750 |
| J0651+38 | J065101.23+380756.9 | 2.355 | 17.75 | 30 | 375 |
| J1036+11 | J103546.03+110546.5 | 2.368 | 16.45 | 18 | 750 |
| J0752+43 | J075158.65+425229.2 | 2.466 | 17.64 | 24 | 375 |
| J0946+28 | J094602.31+274407.1 | 2.476 | 16.66 | 18 | 750 |

Note: $z$ is the redshift of the H$\alpha$ line (Section 3), $H$ is the H-band AB magnitude, $t_{exp}$ is the total exposure time in minutes, and $R$ is the spectral resolution.

2.2. Data Reduction

We reduced the IRTF spectra using the IDL-based package SpeXtool (version 3.4, Cushing et al. 2004). It involves pre-processing (linearity, flat correction), spectral extraction, wavelength and flux calibration, combining multiple spectral frames, telluric correction, order merging, and spectrum cleaning. The standard package configuration was adopted, with a seeing-dependent, 0.7–1.2 Gaussian spatial extraction radius set equal for the target and standard star spectra. We found up to a $\sim 10\%$–20\% level of flux difference at overlaps between different orders of the cross-dispersed spectra, which were leveled using the SpeXtool package. Moreover, we checked the accuracy of standard star flux calibration by convolving each flux-calibrated IRTF spectrum by the broad SDSS/UKIRT filter response curves, and comparing the spectroscopic flux to that from the photometry. Overall, we find the mean and rms scatter of the spectroscopic to photometric flux ratio to be $0.97 \pm 0.36$ when averaged over the set of griz filters (not taking into account the u-band because the shortest-wavelength cutoff is different for the photometry and the spectroscopy), and $0.91 \pm 0.35$ for the YJHK filters. In order to reduce the scatter between the spectral and photometric fluxes, we linearly interpolated the flux ratios and gave multiplicative corrections to the SDSS and IRTF spectra, where the mean and rms scatter of the spectroscopic to photometric flux ratio change to 1.00 $\pm$ 0.00 and 1.01 $\pm$ 0.07 for the griz and YJHK bands, respectively.

We plot the flux-calibrated spectra together with the photometric data points in Figure 2. The SDSS and IRTF spectra meet fairly well at their boundaries though the short-wavelength ($\sim 1 \mu m$) IRTF data are noisy due to some of the data being taken in bright lunar phases and the weaker sensitivity of higher-order spectra. The average and 1-$\sigma$ scatter of the continuum S/N are $89 \pm 30$ and 15 $\pm$ 11 for the SDSS and IRTF spectra, suitable for measuring $M_{BH}$ for most of the targets except for some from the H$\beta$ line. We applied Galactic extinction corrections assuming the total-to-selective extinction ratio of $R_V = 3.1$ and the $(B–V)$ values from Bonifacio et al. (2000) that revised the values in the Schlegel et al. (1998) extinction map.

3. Analysis

In order to estimate the single-epoch $M_{BH}$ values from H$\beta$, H$\alpha$, Mg II, C III], and C IV lines, we fit the broad line regions from the joint SDSS/IRTF spectra.6 We start from the rest-frame 4200–5600 Å fit around H$\beta$ for which we used a power-law for the continuum, broad Fe II component, and broad and narrow Gaussian components for the line. After fitting the power-law continuum determined by 4100–4300 and 5500–5700 Å windows and subtracting it from the spectrum, we determined the width (FWHM = 900–20,000 km s$^{-1}$) and height of the Fe II complex using the Boroson & Green (1992) template while iteratively updating the continuum. We utilized the 4450–4650 and 5150–5350 Å regions to derive the height and the full fitting range to obtain the width of the Fe II, through a least squares fits to the continuum subtracted spectrum. The H$\beta$ emission was fit by a single narrow (full width at half

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6 Throughout this paper we measure the S/N per wavelength element $\Delta \lambda = \lambda / 750$ unless quoting the numbers from references.

6 Throughout, we used the IDL-based package MPFIT (Markwardt 2009) for all least-squares fitting unless stated otherwise.
Figure 2. Reduced observed-frame SDSS (gray) and IRTF (black) spectra of the sample, binned to $R \sim 400$ for display purposes. Gray shaded regions are wavelengths with strong NIR telluric absorption. The photometric data points from SDSS, 2MASS, or UKIDSS are overplotted (filled cyan circles), together with the rest-frame 5100 Å continuum fluxes (open cyan circles). The H$\alpha$, H$\beta$, Mg II, C III], and C IV emission lines are marked in thin red, yellow, green, blue, and purple lines, respectively. The data used to create this figure are available.
maximum, or FWHM < 1000 km s\(^{-1}\) hereafter\(^7\)) Gaussian and double broad (FWHM = 2000–15,000 km s\(^{-1}\) hereafter) Gaussian components, double narrow Gaussians for each [O III] \(\lambda 4957, 5007\) doublet, and H\(\beta\) by a single narrow and single broad Gaussian. When some of the [O III] profiles were broader than their limit, the FWHM limit was relaxed to FWHM < 2000 km s\(^{-1}\). To obtain a better quality fit, we used a common redshift for the narrow H\(\beta\), one of the double narrow [O III] \(\lambda 4957\) and one of the double narrow [O III] \(\lambda 5007\), one of the double broad H\(\beta\), and also the broad and narrow H\(\gamma\), while leaving the rest of the components’ redshift free. In addition, the centers of each Gaussian component were constrained to lie within 1000 km s\(^{-1}\) of the H\(\alpha\) redshift. We masked out or slightly modified the fitting range to exclude noisy regions that yielded a poor initial fit, and removed the fits where S/N < 5. We obtained the monochromatic luminosity \(L_{5100}\) and its error from the best-fit model to the spectra with S/N > 5. At S/N < 5 we fit the photometric magnitudes at rest-frame 3000–10,000 \(\AA\) by a power-law continuum, correcting for the H\(\alpha\) line contribution using the \(JHK\) filter response curves and the best-fit model to the \(H\alpha\) spectra, to obtain \(L_{5100}\) depicted in Figure 2.

Next, we fit the rest-frame 6000–7100 \(\AA\) region including the H\(\alpha\) emission. We fixed the height and width of the Fe II complex from the H\(\beta\) region (or the Mg II region when S/N < 5) since they are weaker and harder to constrain around the H\(\alpha\) emission. A power-law continuum, single narrow Gaussian and double broad Gaussians for the H\(\alpha\), single narrow Gaussian for each [O I] \(\lambda 6300, 6364\), [N II] \(\lambda 6548, 6583\), and [S II] \(\lambda 6716, 6731\) doublet, were simultaneously fitted to the Fe II subtracted spectrum. We used the width of the [O III] \(\lambda 5007\) from the H\(\beta\) fit to fix the width of the crowded assembly of narrow [O I] doublet, [N II] doublet, H\(\alpha\) singlet, and [S II] doublet emission. When the [O III] width was not reliably measured due to poor resolution/sensitivity, we used the mean FWHM of the narrow H\(\alpha\), 400 km s\(^{-1}\), out of \(z < 0.37, S/N > 20\) SDSS quasars from Shen et al. (2011). The relative strengths of the narrow [O I], [N II], and [S II] lines were fixed to the values from Vanden Berk et al. (2001). The centers of the narrow lines and one of the double broad H\(\alpha\) components were tied to the same redshift. Also, the centers of every component were restricted to within 1000 km s\(^{-1}\) of the H\(\alpha\) redshift, which was determined by the peak of the broad H\(\alpha\) model profile.

We notice that some objects show double-peak features on top of the smooth, broad H\(\alpha\), exhibiting relatively wide line widths (FWHM \(\geq 8000\) km s\(^{-1}\)) when fitted together (Section 4.2.1). They resemble the disk emitters explained by a rotating accretion disk source pronounced in a small fraction of H\(\alpha\) spectra, where the broad line luminosity or width using the full profile can overestimate the contribution from the BLR (e.g., Figure 1 in Chen & Halpern 1989; Figure 4 in Eracleous & Halpern 1994). In order to quantify which sources are likely disk emitters, we modeled again the broad H\(\alpha\) spectra using a three-component profile: one signal broad Gaussian, assumed to be the profile from the random motion of the BLR, and double broad Gaussians centered blue- and redward from the H\(\alpha\) redshift by more than 2000 km s\(^{-1}\) which we assume to be the rotating disk emitter components. We define an emission line to be double-peak when non-zero blue- and redshifted broad Gaussian components make up more than half of the total broad H\(\alpha\) luminosity, the triple component model is favored over the single or double component fit with a statistically smaller reduced chi-square (a \(F\)-distribution probability of over 0.99), and the disk emitter components are clearly detached in order to distinguish from a simple wide and non-Gaussian BLR model. The criteria give seven classified double-peaked emitters.\(^8\)

Third, we fit the rest-frame 2200–3100 \(\AA\) region surrounding the Mg II emission. We used the Fe II template from Tsuzuki et al. (2006) because it provides data closer to the center of the Mg II emission than Vestergaard & Wilkes (2001). Following a methodology similar to the H\(\beta\) fitting, we iteratively subtracted the continuum and Fe II complex before fitting the Mg II, determined through 2150–2250 and 3050–3150 \(\AA\) windows for the continuum, 2150–2410, 2460–2700, and 2900–3150 \(\AA\) windows for the Fe II height, and the full fitting range for the Fe II width. Afterward, we fitted the Mg II emission with double broad Gaussians and the [Ne IV]/Fe III near 2420–2440 \(\AA\) with a single broad Gaussian. We required the centers of the Mg II and [Ne IV]/Fe III model components to lie within 1000 km s\(^{-1}\) of the H\(\alpha\) redshift, with exceptions for 5094+28 and J1522 +52 where the Mg II centers are blueshifted by more and relaxed to lie between −3000 and 1000 km s\(^{-1}\). The Mg II spectra showing absorption features, discontinuity between the SDSS/IRTF spectra, or imperfect Fe II subtraction, were masked or adjusted in the fitting range. We derived \(L_{3000}\) and its error from the best-fit model to the Mg II region.

Lastly, we fit the rest-frame 1445–1705 \(\AA\) region around the C IV emission. When the C IV was unavailable or severely absorbed, we fit the rest-frame 1670–2050 \(\AA\) region around C III] to use the FWHM as a surrogate to that of C IV (S12). We fixed the height and width of the Fe II complex from those nearby the Mg II because this feature is weaker around the C IV and C III]. We used a power-law continuum and double broad Gaussians for the C IV and C III]. For the C IV region we used single broad Gaussians to fit the 1600 \(\AA\) feature (Laor et al. 1994), and the blended He II and O III] emission around 1650 \(\AA\). For the C III] region we used single broad Gaussians to model each of N IV\(\lambda 1718, 1730\), Fe II\(\lambda 1786\) (UV191), Si III\(\lambda 1816, Al III\(\lambda 1857,\) and Si iii\(\lambda 1891\). We masked or changed the fitting range of the C IV/C III] spectra showing strong absorption features, and clipped the spectra showing weaker absorption features by redoing the fit after removing the data below 2.5–\(\sigma\) from the fit. We found the C III] centers to lie between −2000 and 1000 km s\(^{-1}\) of the H\(\alpha\) redshift, but C IV is often more blueshifted, so its centers were set between −8000 and 2000 km s\(^{-1}\). Depending on the spectral coverage, either \(L_{1350}\) or \(L_{1450}\) was calculated based on their similarity (Vestergaard & Peterson 2006) as is expected from the small lever arm between them. When the 1350 \(\AA\) was available we computed the error-weighted average of the 1340–1360 \(\AA\) fluxes, and if only 1450 \(\AA\) was covered, the 1440–1460 \(\AA\) fluxes were used as an approximate measure of \(L_{1350}\). When neither was available, we extrapolated the continuum and Fe II emission from the C III] fit down to 1450 \(\AA\) while propagating the errors from the fit.

\(^{8}\) We note that our criteria indicate, but do not verify with highly sensitive spectra or sophisticated modeling, that these sources are disk emitters; thus we use the term double-peaked emitter throughout. These H\(\alpha\) based double-peaked emitters are likely to be similar in their properties to the H\(\beta\) based double-peaked emitters that we did not include in our sample (Section 2.1). However, we kept them in our analysis to see how they affect \(M_{\text{BH}}\) estimates.
Figure 3. Spectral fitting of Hα, Hβ, Mg II, and C IV or C III] line regions (from left to right). Five spectra with S/N < 5 near the Hβ, one with a large discontinuity between the SDSS/IRTF data near the Mg II, and three without C IV or C III] coverage, are omitted. On top of the resolution-matched spectra are the model narrow lines (thin black), broad lines (thick black lines for individual broad components, colored for the sum of the broad components used to derive $M_{\text{BH}}$), the continuum (black line in the upper spectrum), the Fe II complex (black curve on top of the continuum), and the sum of the total line components (black line in the lower spectrum). Masked regions are highlighted below the lower spectrum (thick lines colored identical to the broad emission), and the monochromatic luminosities, $L_{5100}$, $L_{3000}$, $L_{1350}/L_{1450}$ on the upper spectrum (cyan dots). Extrapolations to the $L_{1350}/L_{1450}$ are shown (black dashed line).
Figure 3. (Continued.)
Figure 3. (Continued.)
In Figure 3 we plot the fit to the spectra around the broad emission lines for each object, and in Tables 2 and 3 we summarize the spectral measurements. Once the spectral fitting was performed around each broad line, we derived the broad line FWHM and line dispersion (hereafter \( \sigma \)). The errors on FWHM were determined by equating the FWHM of the combined double Gaussian model as a linear combination of the constituent single Gaussian FWHMs (interpolated or extrapolated, depending on the relative magnitude of the FWHMs), and propagating the errors from each single FWHM measurement. For \( \sigma \) and its error, we used the second moment of the model fit fluxes up to the point they are equal to the flux errors; this corresponds to \( \pm 2.0 \) FWHM from the broad line center on average. Out of the 26 objects in our sample, we compile 21, 26, 25, and 23 line widths from H\( \beta \), H\( \alpha \), Mg II, and C IV/C III], respectively. We note that some of the broad component’s FWHM values are close to the lower limit of 2000 km s\(^{-1}\) and are intermediate in width, e.g., H\( \alpha \) in J1057 +31 and Mg II in J1053+34. These could be confused with narrow lines with strong outflows, where we test the possible change in the \( M_{\text{BH}} \) values in Section 4.2.4. Meanwhile, the spectroscopic continuum luminosities are corrected for the photometric calibration uncertainty (\( \sim 0.02 \) mag) involved when scaling the spectra (Section 2.2).

### 4. Results

#### 4.1. \( M_{\text{BH}} \) Estimation of Our Sample

The determined continuum luminosities and broad line FWHMs are plugged into single-epoch \( M_{\text{BH}} \) estimators for AGNs from J15 for each emission line measurement, assuming the constant \( f = 5.1 \pm 1.3 \) from Woo et al. (2013) and the \( R_{\text{BLR-L}} \) relation from Bentz et al. (2013)

\[
\log \left( \frac{M_{\text{BH}}}{M_\odot} \right) = a + \log \left( \frac{f}{5.1} \right) + b \log \left( \frac{L}{10^{44} \text{ erg s}^{-1}} \right) + c \log \left( \frac{\text{FWHM}}{10^3 \text{ km s}^{-1}} \right),
\]

where \( (a, b, c) \) values using the combination of \((L, \text{FWHM})\) below are

\[
(a, b, c) =
(\text{J1500}, \text{FWHM}_{\text{H} \beta}) : (6.94 \pm 0.12, 0.533 \pm 0.034, 2)
(\text{J1500}, \text{FWHM}_{\text{H} \alpha}) : (7.05 \pm 0.12, 0.533 \pm 0.034, 2.12 \pm 0.03)
(1000, \text{FWHM}_{\text{H} \alpha}) : (6.72 \pm 0.12, 0.511 \pm 0.033, 2.12 \pm 0.03)
(1300, \text{FWHM}_{\text{Mg} II}) : (6.62 \pm 0.12, 0.548 \pm 0.035, 2.45 \pm 0.06)
(1350, \text{FWHM}_{\text{C IV}}) : (6.67 \pm 0.15, 0.547 \pm 0.037, 2.11 \pm 0.1)).
\]

Because some of the Balmer lines covered by the IRTF spectra have marginal sensitivity and the H\( \beta \) line is a few times weaker than H\( \alpha \), we compare the intrinsic scatter \( \sigma_{\text{int}} \) between the H\( \alpha \) and H\( \beta \) lines.
**Table 3**

Luminosities and $M_{\text{BH}}$ Values

| Name          | $\log L_{1350/1450}$ | $\log L_{3000}$ | $\log L_{5000}$ | $\log L_{644}$ | $M_{\text{BH},C IV}$ | $M_{\text{BH},M IV}$ | $M_{\text{BH},H\alpha}$ | $M_{\text{BH},H\beta}$ | $\text{Flags}$ |
|---------------|----------------------|------------------|------------------|---------------|----------------------|----------------------|----------------------|----------------------|------------------|
| J1012+00      | 4.58 ± 0.009         | 4.58 ± 0.008     | 4.44 ± 0.042     | 9.03 ± 0.14   | 9.56 ± 0.13          | 9.53 ± 0.14          |                     |                     | DPE              |
| J1010−05      | 4.61 ± 0.010         | 4.67 ± 0.008     | 4.67 ± 0.052     | 9.95 ± 0.16   | 9.83 ± 0.14          | 9.90 ± 0.10          |                     |                     | <9.95            |
| J0748+22      | 4.62 ± 0.009         | 4.62 ± 0.009     | 4.83 ± 0.025     | 9.40 ± 0.19   | 9.93 ± 0.19          | 9.40 ± 0.15          |                     |                     |                 |
| J0840−23      | 4.61 ± 0.029         | 4.67 ± 0.010     | 4.56 ± 0.010     | 10.07 ± 0.21  | 10.13 ± 0.16         | 9.93 ± 0.19          |                     |                     |                 |
| J1057+31      | 4.61 ± 0.008         | 4.66 ± 0.015     | 4.83 ± 0.014     | 9.06 ± 0.22   | 10.46 ± 0.29         | 9.31 ± 0.19          |                     |                     |                 |
| J0203−13      | 4.59 ± 0.045         | 4.59 ± 0.012     | 4.84 ± 0.023     | 9.70 ± 0.21   | 10.49 ± 0.48         | 9.31 ± 0.19          |                     |                     |                 |
| J0319−07      | 4.60 ± 0.029         | 4.64 ± 0.010     | 4.87 ± 0.033     | 9.85 ± 0.20   | 9.96 ± 0.16          | 9.52 ± 0.22          |                     |                     |                 |
| J1053+34      | 4.62 ± 0.027         | 4.61 ± 0.008     | 4.51 ± 0.054     | 10.08 ± 0.22  | 10.17 ± 0.16         | 10.41 ± 0.14         |                     |                     |                 |
| J1035+45      | 4.70 ± 0.049         | 4.68 ± 0.010     | 4.46 ± 0.012     | 10.08 ± 0.21  | 9.73 ± 0.16          | 9.67 ± 0.15          |                     |                     |                 |
| J1055+28      | 4.69 ± 0.076         | 4.65 ± 0.012     | 4.73 ± 0.055     | 9.94 ± 0.21   | 9.88 ± 0.16          | 10.27 ± 0.45         |                     |                     | <9.93            |
| J0146+10      | 4.61 ± 0.048         | 4.61 ± 0.011     | 4.88 ± 0.051     | 9.34 ± 0.19   | 9.91 ± 0.16          | 9.92 ± 0.17          |                     |                     |                 |
| J0800−07      | 4.86 ± 0.038         | 4.63 ± 0.009     | 4.96 ± 0.041     | 10.00 ± 0.21  | 9.70 ± 0.16          | 9.68 ± 0.15          |                     |                     |                 |
| J0855−05      | 4.70 ± 0.128         | 4.66 ± 0.013     | 4.49 ± 0.031     | 10.04 ± 0.22  | 10.15 ± 0.16         | 9.87 ± 0.18          |                     |                     |                 |
| J0741+32      | 4.50 ± 0.008         | 4.53 ± 0.010     | 4.54 ± 0.014     | 9.71 ± 0.21   | 9.97 ± 0.16          | 9.73 ± 0.18          |                     |                     | <10.02           |
| J1152+52      | 4.71 ± 0.008         | 4.71 ± 0.013     | 4.74 ± 0.026     | 10.18 ± 0.24  | 10.57 ± 0.19         | 10.34 ± 0.20         |                     |                     |                 |
| J1339+11      | 4.70 ± 0.008         | 4.68 ± 0.023     | 4.51 ± 0.040     | 10.00 ± 0.21  | 9.80 ± 0.17          | 9.88 ± 0.33          |                     |                     |                 |
| J0905+24      | 4.95 ± 0.008         | 4.93 ± 0.011     | 4.49 ± 0.011     | 9.96 ± 0.21   | 9.44 ± 0.17          | 9.88 ± 0.15          |                     |                     |                 |
| J0257+00      | 4.89 ± 0.008         | 4.67 ± 0.013     | 4.50 ± 0.028     | 10.01 ± 0.21  | 9.73 ± 0.16          |                     |                     |                     | <10.16           |
| J2123+01      | 4.74 ± 0.008         | 4.76 ± 0.010     | 4.62 ± 0.023     | 10.32 ± 0.22  | 9.89 ± 0.18          | 10.37 ± 0.21         |                     |                     |                 |
| J0052+11      | 4.68 ± 0.008         | 4.68 ± 0.011     | 4.54 ± 0.024     | 9.99 ± 0.21   | 9.71 ± 0.17          |                     |                     |                     |                 |
| J2112+00      | 4.61 ± 0.008         | 4.62 ± 0.013     | 4.49 ± 0.028     | 9.96 ± 0.20   | 9.29 ± 0.17          | 9.66 ± 0.18          |                     |                     |                 |
| J1027+30      | 4.84 ± 0.008         | 4.67 ± 0.013     | 4.52 ± 0.028     | 9.85 ± 0.20   | 9.38 ± 0.17          | 10.11 ± 0.18         |                     |                     |                 |
| J0651+38      | 4.65 ± 0.008         | ...              | 4.68 ± 0.040     | 9.66 ± 0.20   | ...                 |                     |                     |                     |                 |
| J1036+11      | 4.68 ± 0.008         | 4.67 ± 0.012     | 4.59 ± 0.016     | 9.87 ± 0.20   | 9.53 ± 0.17          | 9.72 ± 0.17          |                     |                     |                 |
| J0752+43      | 4.68 ± 0.008         | 4.63 ± 0.012     | 4.90 ± 0.063     | 9.90 ± 0.20   | 9.59 ± 0.16          | 10.03 ± 0.16         |                     |                     |                 |
| J0946+28      | 4.70 ± 0.008         | 4.72 ± 0.017     | 4.76 ± 0.016     | 10.57 ± 0.27  | 10.14 ± 0.19         | 9.94 ± 0.19          |                     |                     |                 |

**Note.** The monochromatic continuum and broad line luminosities (erg s$^{-1}$), and $M_{\text{BH}}$ values (M$_\odot$). Upper limits to the $M_{\text{BH}}$ values are associated with double-peaked H$\alpha$ emission marked as DPE in the Flags column. Extremely broad (>20,000 km s$^{-1}$) Fe II, highly blueshifted (>2000 km s$^{-1}$) C IV, and broad (>1000 km s$^{-1}$) [O III], are flagged Fe II, C IV, and [O III], respectively.
and Hβ line-based $M_{\text{BH}}$ values, for the continuum sensitivity bins $5 < S/N_{\text{H}β} < 10$ and $S/N_{\text{H}β} > 10$. We find $\sigma_{\text{int}} = 0.21$ dex and $\sigma_{\text{int}} < 0$ for the two sensitivity bins so that larger systematic uncertainties are affecting the $M_{\text{BH}}$ values at lower sensitivity (e.g., Denney et al. 2009). This effect should be negligible in the Mg II, C IV, or C III] masses derived under much higher sensitivity, all at $S/N > 35$. We thus limit the usage of Hβ $M_{\text{BH}}$ values to $S/N_{\text{H}β} > 10$, and average with the Hα-based masses when used for comparison with the rest-UV $M_{\text{BH}}$ values.

The estimators from J15 were calibrated to yield consistent rest-UV to rest-optical $M_{\text{BH}}$ values over a wide range of luminosity and redshift, suitable for this study. We further examine where the measured continuum luminosities and broad line FWHMs of our sample with extremely large masses fall with respect to the quasars with similar luminosities. In Figures 4 and 5, we plot the continuum–line luminosity relations, FWHM relations, and the $M_{\text{BH}}$ relations based on the Hα, Hβ, Mg II, and C IV lines, from this work and existing observations of similarly luminous quasars (S12, J15, Shen 2016). The offset and $\sigma_{\text{int}}$ of the combined data with respect to the best-fit relations in previous works are printed on each panel. From Figure 4 we find that our objects, together with similarly luminous quasars, follow the luminosity and line width relations of J15. The data show negligible offset, and $\sigma_{\text{int}}$ similar to that of the J15 relation, demonstrating that the J15 calibrations are useful even for extremely massive AGNs. We note that the extremely massive AGNs are mostly from this work and they distribute similarly in luminosity space to other luminous quasars, but have FWHM values higher than the latter. This suggests that the main factor that gives rise to EMBH estimates is their wide velocity widths.

Also, we check in Figure 5 whether the rest-UV to rest-optical $M_{\text{BH}}$ values are mutually consistent at the massive end, using the J15 and S12 relations. The Hβ and Hα $M_{\text{BH}}$ values of luminous, massive AGNs are consistent with each other irrespective of using the S12 or J15 estimators, albeit with a smaller intrinsic scatter for the J15 estimator due to the inclusion of the measurement uncertainties in the $f$-factor, $R_{\text{BLR}}$–$L$ relation, and luminosity/line width correlations. The rest-UV to Balmer $M_{\text{BH}}$ values for EMBHs are mutually consistent using the J15 estimators, whereas the S12 estimators lead to systematically underestimated $M_{\text{BH}}$ ratios (~0.21 and 0.40 dex underestimation in Mg II and C IV $M_{\text{BH}}$ values respectively at $M_{\text{BH},H_α} = 10^{10} M_\odot$, and more deviations at higher $M_{\text{BH}}$). The existing estimators determined from a relatively limited dynamic range in rest-UV FWHM tend to have shallower scaling of the FWHM into the mass estimator compared to the J15, underestimating the rest-UV $M_{\text{BH}}$ values at the massive end. Therefore, we keep the J15 estimator as a relatively more reliable $M_{\text{BH}}$ indicator for the rest of the paper.

4.2. Mass Biasing Factors in the Spectra

4.2.1. Double-peaked Broad Emission

We find seven out of 26 broad Hα profiles classified as double-peaked emitters in Section 3 (J0203+13, J0257+00,
J0741 + 32, J1010 + 05, J1053 + 34, J1055 + 28, J1057 + 31, best fit as triple Gaussians with clear blue- and redshifted components comparable in strength or dominating over the central broad component. In Figure 6, we plot the H\(\alpha\) fit and the noise spectrum of the double-peaked emitters, and find that the double-peaked features are stronger than the noise levels. We follow Baskin & Laor (2005) to place these objects along various parameters describing their profile: the shape, (FW1/4M + FW3/4M)/(2FWHM); the asymmetry, (\(\lambda_{3/4} - \lambda_{1/4}\))/FWHM; and the shift, (\(\lambda_{3/4} - \lambda_{4/4}\))/FWHM, where FWN/4M and \(\lambda_{N/4}\) (\(N = 1–4\)) are the width and centroid of the Nth-quarter maximum of the line. The shape parameter for the seven double-peaked objects ranges within 0.89–1.16 (1.03 on average), shifted to the distribution of 1.02–1.37 (1.16 on average) for the non-double-peaked objects and lying on the smaller end of the H\(\beta\) distribution from Baskin & Laor (2005).
The distribution of asymmetry and shift parameters are indistinguishable between the double-peaked and ordinary profiles. Overall, our selected double-peaked profiles are systematically different to ordinary profiles as being wider toward the peak or the wings. However, we still caution against directly comparing our double-peaked profiles to those in the literature, as some examples (J1010+05, J1055+28) look marginal in appearance.

From Figure 4, we find the double-peaked emitters are slightly above the J15–L_{5100}–L_{Hα} relation by 0.068 dex on average, though within σ_{int} = 0.095 dex from the J15 relation. Also, the double-peaked emitters lie below the FWHM_{Hα}–FWHM_{C IV} relation by −0.24 dex on average, slightly larger than σ_{int} = 0.21 dex from the J15 relation. We further estimate the differences in the Hα and C IV M_{BH} estimates for the double-peaked emitters, to find log M_{BH, Hα}/M_{BH,C IV} = −0.01–1.15 (0.45 on average). The C IV spectra of double-peaked Hα emitters appear to show weaker double-peaks (e.g., Eracleous et al. 2004), which is consistent with the larger FWHM_{Hα}, to FWHM_{C IV} ratios for our double-peaked emitters, 0.01–0.44 dex (0.16 dex on average).

We independently check whether using the line widths for double-peaked Hα emitters lead to overestimated M_{BH} values (e.g., Wu & Liu 2004; Zhang et al. 2007), from the stellar velocity dispersion (σ_{s}) and FWHM_{Hα} measurements of 10 double-peaked emitters from Lewis & Eracleous (2006), where we find nine objects having both σ_{s} and FWHM_{Hα} compiled from the literature (Eracleous & Halpern 1993, 1994; Barth et al. 2002; Sergeev et al. 2002; Nelson et al. 2004; Lewis & Eracleous 2006; Lewis et al. 2010). Applying the M_{BH}–σ_{s} relations from Kormendy & Ho (2013) and McConnell & Ma (2013) gives a range of M_{BH}(σ_{s}) values, considering that the slope of the relation is different between the references. Meanwhile, we converted the bolometric luminosities in Lewis & Eracleous (2006) to L_{5100} using the bolometric correction 10.33 from Richards et al. (2006a), to estimate the M_{BH,Hα} using the J15 estimator. We use only objects with L_{5100} > 10^{41.5} erg s^{-1} where the mass calibration is defined, yielding six M_{BH} estimates. To minimize the time-dependent changes in FWHM_{Hα}, we use the averaged value through monitored observations available for four objects. Assuming that the double-peaked emitters are lying on the M_{BH}–σ_{s} relation, we find the M_{BH,Hα} values are larger than the M_{BH}(σ_{s}) values by 0.32–1.14 dex (0.85 dex on average), and 0.32–2.06 dex (1.01 dex on average), out of the Kormendy & Ho (2013) and McConnell & Ma (2013) relations respectively. This is in agreement with the Zhang et al. (2007) result.

We make a cautionary note that the M_{BH} estimates thought to be less affected by the double-peaked features involve large intrinsic scatter (~0.4 dex for the M_{BH,C IV} from J15, ~0.3–0.4 dex for the M_{BH}(σ_{s}) from Kormendy & Ho 2013; McConnell & Ma 2013), and the bolometric luminosities in Lewis & Eracleous (2006) suffer from incomplete wavelength coverage. Still, the overestimation in M_{BH}, comparable to or even more sizable than the uncertainties, suggests that the M_{BH} values of double-peaked emitters using the full broad Balmer emission profile are possibly overestimated. We find that four objects out of the seven double-peaked Hα emitters with Hβ S/N > 5 have relatively broad FWHM_{Hβ} values of 7600–14,000 km s^{-1} (10,300 km s^{-1}on average) compared to 4430–8500 km s^{-1} (6580 km s^{-1}on average) for the rest of the sample. Our Hβ observations have poorer sensitivities than the Hα to identify double-peaked emission, but the FWHMs are consistent with the expected broadening of the line profile from a rotating accretion disk.

4.2.2. Extremely Wide Fe II Solution Near Mg II

Next, we investigate the effect of Fe II subtraction on the systematic uncertainty of the M_{BH} estimates. Whereas most of the H/β spectral fits in Section 3 yielded a least-squares solution for the Fe II complex, four out of 25 Mg II spectra (J0416-10, J0203+13, J1053+34, J1057+31) did not converge until the FWHM_{Fe II} reached its maximum limit of 20,000 km s^{-1}, with the first three classified as double-peaked emitters from the Hα spectra. We note that the automated fitting of SDSS spectra from Shen et al. (2011) also identifies extremely broad Fe II solutions within our sample (J1010+05, J1053+34, J1057+31, J1522+52), with the first three double-peaked in our Hα. To improve the Mg II fit of these sources we attempted to include a Balmer continuum emission component that is usually degenerate with the power-law continuum and the Fe II complex (e.g., Maoz et al. 1993; Wang et al. 2009), following the functional form and parameter boundaries of S12. Fitting both the power-law and Balmer continua does not reduce the extremely wide Fe II widths to convergence for all four of our sources, however, such that either the standard Fe II template does not fit these quasar spectra, or the broad Gaussian model is insufficient to model these Mg II profiles. In any case, the M_{BH} measurements associated with extremely broad Fe II solutions require careful interpretation as they correlate with sources showing double-peaked Hα emission.

4.2.3. blueshifted C IV

Third, though it is typical to find C IV emission in quasar spectra blueshifted relative to the rest-optical or Mg II redshifts by ~1000 km s^{-1} (e.g., Richards et al. 2002; Shen et al. 2008, 2011), we find stronger blueshifts in our sample. For comparison, the mean and rms scatter of the C IV to Mg II blueshift from SDSS DR7 quasars at 1.6 < z < 2.0 with S/N > 20 in both Mg II and C IV is 844 ± 916 km s^{-1} (Shen et al. 2011). Seven out of 12 (58%) of the objects in our sample that are not double-peaked emitters and have fits to both Mg II and C IV show C IV to Mg II blueshifts exceeding the 1–σ limits of the SDSS sample distribution (>1760 km s^{-1}). This fraction for the SDSS comparison sample is only 107/728 (15%). In Figure 7 top panels, we show the best-fit broad line models of the five objects in our sample with the largest C IV to Balmer blueshifts. The H/β, Hα, Mg II, and C IV fits are plotted on top of each other, normalized in height and shown relative to the Hα redshift. Interestingly, the spectra showing the largest C IV blueshifts (~5000–6000 km s^{-1}, J0946+28, J1522+52) have sequentially decreasing, but measurable, blueshifts toward Mg II and H/β. The blueshifted C IV profiles often appear asymmetric, skewed toward extreme blueshifts (~10,000 km s^{-1}), and the asymmetry continues to appear in some of the Mg II and Balmer lines.

We follow Baskin & Laor (2005) to place these blueshifted C IV quasars along the shape, asymmetry, and shift parameters describing their profiles. The shape parameter ranges within 1.05–1.46 (1.16 on average) for the 11 objects with C IV blueshift smaller than 2000 km s^{-1}, and 1.05–1.49 (1.16 on...
average) for the five objects with C IV blueshift larger than 2000 km s\(^{-1}\). The indistinguishable distribution of the shape parameter indicates that the FWHM is a good indicator of the overall line shape, irrespective of the C IV blueshift (but see also Coutman et al. 2016 for the changing ratios between FWHM and \(\sigma\) along the C IV blueshift). On the other hand, the asymmetry parameter is preferentially distributed toward excess blue wings at highly blueshifted C IV, \(-0.10\) to \(-0.12\) (0.02 on average) and \(-0.04\) to \(-0.35\) (0.20 on average) for objects with C IV blueshift smaller and larger than 2000 km s\(^{-1}\), respectively. Furthermore, the shift parameter goes more negative at highly blueshifted C IV, \(-0.32\) to \(-0.10\) (\(-0.21\) on average) and \(-0.67\) to \(-0.31\) (\(-0.41\) on average) for objects with C IV blueshift smaller and larger than 2000 km s\(^{-1}\), respectively. Having seen the asymmetric, blueshifted nature of the C IV profiles that are suggestive of obscuration or outflows in Baskin & Laor (2005), we investigate whether the C IV \(M_{\text{BH}}\) values of the five objects showing C IV to H\(\alpha\) blueshifts >2000 km s\(^{-1}\) (J0400−07, J0651+38, J0946+28, J1523+52, J2123−01), are positively offset with respect to the H\(\alpha\) \(M_{\text{BH}}\) values by 0.26–0.68 dex (0.41 dex on average).

4.2.4. Ionized Outflows

Finally, we find a handful of blueshifted narrow [O III] 5007 emissions that are wider than the typical narrow lines. Nine out of the 21 objects with an H\(\beta\) region fit have unambiguous [O III] profiles and peak S/N > 5, where five of them meet FWHM [O III] > 1000 km s\(^{-1}\) (J0146−10, J0319−07, J0905+24, J1035+45, J1055+28). In Figure 7, bottom panels, we plot the best-fit model for the [O III] and broad emission lines of these five objects. We find that the [O III] profiles are typically blueshifted by a few hundred km s\(^{-1}\) relative to the broad Balmer redshift, and the FWHMs reach up to 1600–1900 km s\(^{-1}\) (J0146−10, J0319−07, J1035+45). These [O III] line widths are too broad to be explained by even the most massive galaxy’s gravitational potential (FWHM \(\sim\) 1000 km s\(^{-1}\)), and are broad relative to quasars at comparable luminosity or redshift (e.g., Netzer et al. 2004; Brusa et al. 2015; Shen 2016). Previous work on broad [O III] emission in quasars shows that the width correlates with its blueshift, indicative of strong outflows (e.g., Liu et al. 2014; Zakamska & Greene 2014). We therefore investigate the effect of fixing the width of narrow lines around the H\(\alpha\) for the objects with [O III] profiles broader than FWHM = 1000 km s\(^{-1}\), bearing in mind they were fixed to 1000 km s\(^{-1}\) in Section 3. We fit the H\(\alpha\) region by first fixing the narrow line FWHM to that of the [O III] assuming all the narrow lines are fully broadened as the [O III], and to 400 km s\(^{-1}\) (the mean FWHM of local quasars used in Section 3) assuming they are completely absent of outflows, respectively, where the FWHM of quasars with broad [O III] for example, seem to lie in between (Zakamska & Greene 2014). When the narrow line widths are fixed to that of the [O III] instead of 1000 km s\(^{-1}\) the H\(\alpha\) \(M_{\text{BH}}\) values vary by \(-0.01\) to 0.12 dex (0.03 dex on average), and by \(-0.07\) to 0.02 dex (\(-0.02\) dex on average) when fixed to 400 km s\(^{-1}\). The limited differences in the \(M_{\text{BH}}\) values indicate that the effect of narrow line outflows, whether or not present at the H\(\alpha\) region, is negligible in determining the broad line widths of extremely massive quasars.

4.2.5. Summary of Biases from Spectra

In Figure 8, we compare the rest-optical and rest-UV \(M_{\text{BH}}\) values determined from Section 3, marking the sources with unusual spectral features addressed here. We calculate how much the \(\sigma_{\text{int}}\) values between the rest-optical and rest-UV \(M_{\text{BH}}\) values decrease as we remove each class of unusual spectra. There is a general agreement between the Balmer and rest-UV line-based masses up to \(\sim 10^{10}\ M_{\odot}\), with a much smaller scatter between the Balmer and Mg II-based masses (\(\sigma_{\text{int}} < 0\)) than between the Balmer and C IV-based masses (\(\sigma_{\text{int}} = 0.33\) dex). This is in accord with earlier results from relatively less massive regimes (e.g., Shen et al. 2008; J15). The \(\sigma_{\text{int}}\) between the Balmer and C IV \(M_{\text{BH}}\) values drops from \(\sigma_{\text{int}} = 0.33\) dex to 0.23 dex when the double-peaked emitters are excluded, and down to \(\sigma_{\text{int}} = 0.16\) dex when objects with C IV
blueshifts $>2000$ km s$^{-1}$ are further omitted. The number of $M_{\text{BH}} > 10^{10} M_\odot$ AGNs drops from 10, 7, 8 based on Balmer-, Mg II-, and C IV-based measurements, to 5, 4, 5 after removing the double-peaked Hα emitters, extremely broad Fe II around the Mg II, and highly blueshifted C IV sources, respectively. This suggests that $M_{\text{BH}}$ values $\gtrsim 10^{10} M_\odot$ from any line should be carefully inspected for unusual features appearing in or on top of the broad lines.

### 4.3. Mass Biasing Factors in Using the Estimator

#### 4.3.1. f-factor

When bringing the spectral measurements into the single-epoch $M_{\text{BH}}$ estimators, we consider the variations in the constant of the $M_{\text{BH}}$ equation for AGNs ($f$-factor) that gives an overall normalization but is inaccurate for individual mass measurements. Because this constant is obtained from normalizing the zeropoint of the $M_{\text{BH}}$–$\sigma_*$ relation, it has a systematic uncertainty of 0.3–0.4 dex (e.g., Kormendy & Ho 2013; McConnell & Ma 2013). Using a constant $f$-factor as a representative value could overestimate the $M_{\text{BH}}$ values for objects with anisotropic radiation or velocity dispersion (e.g., Peterson et al. 2004), when the line-of-sight values of these quantities are observed to be larger than geometrically averaged. To check whether the $M_{\text{BH}} \sim 10^{10} M_\odot$ estimates can be explained by large line-of-sight spectral quantities of less massive BHs, we compared the average and rms scatter of the $L_{\text{H}\alpha}$ and FWHM$_{\text{H}\alpha}$ from our sample excluding the double-peaked emitters, divided by groups with $M_{\text{BH,H\alpha}}$ values smaller and larger than the median, $10^{9.5} M_\odot$. The averaged luminosities are $\log(L_{\text{H}\alpha}/\text{erg s}^{-1}) = 46.38 \pm 0.32$ and $46.55 \pm 0.38$ respectively, where the average difference in the luminosities correspond to a 0.08 dex difference in $M_{\text{BH}}$ much smaller than the difference in the average $M_{\text{BH}}$ between the two groups, 0.52 dex. This suggests that EMBH masses are not caused by the continuum luminosities that are boosted to unusually large values due to mechanisms like anisotropic accretion or gravitational lensing. Meanwhile, the averaged line widths are FWHM$_{\text{H}\alpha} = 3920 \pm 960$ and $6210 \pm 1390$ km s$^{-1}$, respectively, showing that $\gtrsim 10^{10} M_\odot$ estimates are influenced by large FWHM values that could be caused by anisotropic velocity field. However, this does not rule out the case where the line widths of extremely massive AGNs are intrinsically wide due to the stronger gravitational potential from the BH.

There are issues of whether the $f$-factor is systematically different (up to $\sim 0.3$ dex) between AGN subsamples grouped by host galaxy and BH properties, and also the limited statistical significance and dynamic range in the constraints to the $f$-factor (e.g., McConnell & Ma 2013; Woo et al. 2013; Ho & Kim 2014). The local $M_{\text{BH}}$–$\sigma_*$ relation for AGNs at least, which covers up to $\sim 10^{9.5} M_\odot$, BHs, does not differ in $\sigma_{\text{int}}$, with respect to inactive galaxies (e.g., Woo et al. 2013). The spatially resolved direct dynamical $M_{\text{BH}}$ measurement for inactive galaxies is thought to be much more accurate than the $M_{\text{BH}}$ estimate for AGNs using a constant $f$-factor, and the $\sigma_{\text{int}}$ for AGNs is expected to be significantly larger than that for inactive galaxies if there was a large intrinsic dispersion in the $f$-factor. The indistinguishable $\sigma_{\text{int}}$ values for AGNs support that the $M_{\text{BH}}$–$\sigma_*$ relation itself is intrinsically scattered rather than the $f$-factor, which hints that the EMBHs in luminous quasars are intrinsically massive rather than positively biased in mass. Alternatively, the widespread distribution of FWHM$_{\text{H}\alpha}$/Fe II strengths for type-1 quasars are interpreted as the geometric orientation playing a significant role in the observed dispersion of the FWHM$_{\text{H}\alpha}$ values (e.g., Shen & Ho 2014). Still, the luminous, intermediate-redshift type-1 quasar samples of S12 and Shen (2016) reaching up to EMBH masses show broader FWHM$_{\text{H}\alpha}$ values than the less luminous, local quasars in Shen et al. (2011), which they claim as due to intrinsically broader line width or more massive BHs for the S12 and Shen (2016) samples. Further study of the $M_{\text{BH}}$–$\sigma_*$ relation at the...
massive end, especially for active galaxies, and detailed modeling of the velocity structure of the BLR (e.g., Brewer et al. 2011; Pancoast et al. 2014) are crucially required to better understand whether EMBH masses are either a geometric selection or intrinsic property.

4.3.2. Variability

Second, the $M_{\text{BH}}$ estimators could suffer from variability such that the single-epoch measurements may not be representative values. Also, the time lag of the continuum to reach the BLR hinders obtaining coherent continuum luminosity and broad emission width from a given epoch. To probe the extent of continuum variability, we compiled the Catalina Real-time Transient Survey (Drake et al. 2009) optical light curves of our sample spanning eight years on average. We calculated the variability amplitude $\sigma_{\text{var}}$ where $\sigma_{\text{var}} = \sqrt{\sum_{i=1}^{N} (m_i - \bar{m})^2 - \Delta m_i^2} / (N - 1)$ for the mean magnitude $\bar{m}$ and $N$ magnitude and error measurements ($m_i, \Delta m_i$), and find the $\sigma_{\text{var}}$ value to range within 0.27 (median of 0.08) mag. This level of intrinsic variability in the optical continua is small, and even the object with the largest magnitude variation has a corresponding luminosity variation of 0.11 dex, or an $M_{\text{BH}}$ variation of 0.05 dex. To further investigate the emission line variability, we plot in Figure 9 the single-epoch $M_{\text{BH}}$ values from multi-epoch SDSS spectroscopy with connected symbols. We do not perform secondary flux calibration to the spectra (e.g., Section 2.2) so that the variations in the spectral continuum includes the contribution from imperfect spectral flux calibration. Excluding the single object without a converging Fe II solution around the Mg II region (J0146−10), we have 1, 6, 10 objects with multi-epoch (2–5 visits) $M_{\text{BH}}$ measurements in H/β, Mg II, and C IV, respectively. We find that the $M_{\text{BH}}$ values fall within their errors throughout the sparsely covered epochs. Overall, the mean level and effect of variability on the single-epoch $M_{\text{BH}}$ estimates for extremely massive AGNs, is consistent with the trends at lower masses (e.g., Park et al. 2012; Jun & Im 2013).

4.3.3. Overestimated Ionizing Continuum

Third, we investigate cases where the observed AGN luminosities and broad line widths may not be applied to the standard $M_{\text{BH}}$ equation. J15 report that the rest-optical continuum luminosity of extremely luminous AGNs ($L_{5100} \sim 10^{47}$ erg s$^{-1}$) marginally overestimates the ionizing luminosity as traced by the Hα line luminosity, perhaps hinting that the accretion disk of extremely massive and low-spin BHs does not produce sufficient ionizing radiation (e.g., Laor & Davis 2011; Wang et al. 2014). In Figure 10 we examine the luminous end $L_{5100}$-$L_{\alpha}$ relation, including our IRTF data points. We find that the IRTF data are mildly below the J15 relation, but do not show a systematic trend with $L_{5100}$. Further imposing a 20% uncertainty limit to the combined data, most of the negatively offset outliers from J15 are removed so that the downward trend of the relation at the highest luminosities is less likely with higher-sensitivity data. We also find that the IRTF data improve the completeness of the relation at $L_{5100} \sim 10^{46}$ erg s$^{-1}$, filling the weaker emission line AGNs less covered by S12. The combined, sensitivity cut data in Figure 10 show a 0.03 ± 0.13 dex offset and scatter to the J15 relation, supporting that the slope of the $L_{5100}$-$L_{\alpha}$ relation stays universal across $L_{5100} \sim 10^{47}$ erg s$^{-1}$ and that cold accretion disks in low-spin EMBHs, if any, have a minor effect ($\leq 0.1$ dex) in positively biasing the $M_{\text{BH}}$ estimates derived using $L_{5100}$ instead of $L_{\alpha}$.

4.3.4. FWHM versus $\sigma$

Finally, we further look into the possible bias of using the broad line FWHM rather than the $\sigma$. Although the FWHM is technically simple to measure and is less affected than $\sigma$ by...
weakened lines at poor sensitivity, it could be
relatively inaccurate when the line profiles are far from a
universal shape (e.g., Peterson et al. 2004; Collin et al. 2006).

The $M_{BH}$ estimates in J15 assume a constant FWHM = 2$\sigma$
condition for the broad H$\alpha$ line widths, but any deviation
from this constant could bias the $M_{BH}$ estimates derived using
FWHM. We checked whether our sample exhibits this constant
relation between the H$\alpha$ FWHM and $\sigma$ values determined from
Section 3. We find that the mean and rms scatter of the FWHM
to $\sigma$ ratios of the 21 objects without double-peaked emitters are
mildly smaller than 2 (FWHM/$\sigma$ = 1.5 $\pm$ 0.3) and thus the
EMBH masses are less likely to be spuriously overestimated by
using FWHM instead of $\sigma$. In fact, when assuming that the
$M_{BH,1/2}$ scales proportional to $\sigma_{1/2}^2$ and FWHM$_{H\alpha}$ = 2 $\sigma_{1/2}$, the
$\sigma_{1/2}$-based $M_{BH,1/2}$ values from Equations (1) and (2) would
change from the FWHM-based values by $\approx$ 0.30 dex (0.30 dex on average), nearly doubling the non-double-peaked, $M_{BH,1/2}$ > $10^{10}$ M$_\odot$ objects from 7 to 13. Interestingly, the FWHM to $\sigma$ ratios for the double-peaked emitters are
somewhat larger than the rest of the sample (average and rms scatter of 2.2 $\pm$ 0.4) so that they will be better noticed by
extremely wide FWHMs rather than $\sigma$ values.

5. Discussion

5.1. $M_{BH}$ Bias Due to Double-peaked Lines

In the previous section, we considered cases where the $M_{BH}$
estimates of AGNs, including those in the EMBH regime,
could be systematically biased. Here, we investigate whether
the two largest factors associated with possibly overestimated
$M_{BH}$ values, double-peaked broad emission, and blueshifted
C IV, are preferentially selected toward EMBH masses, or if
they are conditionally appearing in general type-1 quasar
spectra. We begin by comparing the double-peaked emitter fraction
to those from the literature with larger samples at $z \leq 0.4$. Our double-peaked emitter fraction, $(5/7)/26$ (19%–
27%),$ ^{12}$ is comparable to or higher than 20% among 106 radio-
loud AGNs (Eragaleous & Halpern 2003), and much higher than
3% out of 3216 optically selected quasars (Strateva et al. 2003),
although the fraction is dependent on the parameter space
where the double-peaked emitters are examined and the definition
of being double-peaked. The double-peaked emitters show broader FWHM$_{H\alpha}$ than typical AGNs, distributed mostly
above 5000 km s$^{-1}$ and comparable in number to the non-
double-peaked at above 8000 km s$^{-1}$ (Eragaleous & Hal-
pern 2003; Strateva et al. 2003). Our study is in agreement with the expectation that 5/7 double-peaked emitters reach

$^{12}$ We consider J1010+05 and J1055+28 marginally double-peaked and provide the range of fractions depending on the inclusion of these objects.

| log L$_{5100}$ | <2000 | 2000–4000 | FWHM$_{H\alpha}$ | 4000–6000 | 6000–8000 | >8000 |
|-------------|-------|-----------|----------------|-----------|-----------|------|
| 44.6–44.9   | 0.00–0.02 | 0.02–0.12  | 0.14–0.36      | 0.22–0.59  | 0.78–0.83  |
| 44.3–44.6   | 0.00–0.00 | 0.01–0.13  | 0.12–0.31      | 0.14–0.52  | 0.23–0.48  |
| 44.0–44.3   | 0.00–0.00 | 0.02–0.12  | 0.05–0.23      | 0.17–0.38  | 0.27–0.44  |

Note. The fraction of $z < 0.37$, S/N > 10, type-1 quasars in Shen et al. (2011) that are classified as highly double-peaked, and highly/weakly double-peaked are shown in ranged values. The L$_{5100}$ and FWHM$_{H\alpha}$ are in units of erg s$^{-1}$ and km s$^{-1}$, respectively.
that the FWHMs of the highly blueshifted (>2000 km s\(^{-1}\)) C IV profiles are 5400–11,100 km s\(^{-1}\) (8200 km s\(^{-1}\) on average), near the broad end of the FWHM distribution.

To summarize, we caution against blindly adopting \(M_{\text{BH}}\) estimates based on any line with FWHM \(\gtrsim 8000\) km s\(^{-1}\). For example, searching for quasars in Shen et al. (2011) with S/N > 10 and flagged not to be double-peaked emitters, there are 14 \(\text{H}\alpha\)-based and 213 \(\text{H}\beta\)-based masses with \(M_{\text{BH}} > 10^{5.5} M_\odot\) at \(z < 0.37\) and \(z < 0.7\), respectively. However, 14/14 \(\text{H}\alpha\)-based and 212/213 \(\text{H}\beta\)-based objects have broad line FWHM > 8000 km s\(^{-1}\) and the spectra of these objects need to be carefully checked. Indeed, through visual inspection of the spectra, we find that 12 out of the 14 \(\text{H}\alpha\) spectra indicating \(M_{\text{BH}} > 10^{5.5} M_\odot\) and FWHM > 8000 km s\(^{-1}\) show moderate to strong double-peaked line profiles, raising caution about their \(M_{\text{BH}}\) values.

5.2. \(M_{\text{BH}}\) Bias Due to C IV Blueshift

Next, we consider the general effect of blueshifted C IV on \(M_{\text{BH}}\) estimation, thought to be a combined effect of outflows and obscuration in high ionization lines (e.g., Baskin & Laor 2005). Though it is expected that optically bright type-1 AGNs are seen through minimal obscuring material, they display a moderate range of UV/optical through infrared colors (e.g., Richards et al. 2003; Jun & Im 2013). This hints that not only can the UV continuum emission be absorbed, but likewise for the broad line emission, so that the reliability of UV line widths should be checked, especially at higher levels of obscuration. We follow S12 to plot in Figure 11(a) the ratio between the C IV and Balmer broad line FWHMs against rest-frame 1350–5100 Å continuum color, using compiled references and this work. We checked that the plotted objects are luminous enough to have an estimated host galaxy contamination of less than 20% at 5100 Å (Shen et al. 2011), or have Hubble Space Telescope imaging so that the spatially resolved host galaxy contamination is below 20% at optical wavelengths. We do not find any correlation between the quantities (linear Pearson correlation coefficient \(r = 0.18\), implying the C IV line width does not suffer any more systematic biases than the Balmer lines. Instead, having checked that the IRTF sources with blueshifted C IV emission show broader C IV than the Balmer line widths (Section 4.2), we plot in Figures 11(b) and (c) the C IV to Balmer broad line FWHM and \(M_{\text{BH}}\) ratios against the Balmer to C IV broad line shift from compiled references and from this work. We find that the quantities are positively correlated (\(r = 0.66\) and 0.70 respectively), in accord with the trends between the C IV and Mg II (e.g., Shen et al. 2008). The linear fit to the data based on the FITEXY and BCES methods (Press et al. 1992; Akritas & Bershady 1996) respectively yield

\[
\log(\text{FWHM}_{\text{C IV}} / \text{FWHM}_{\text{H}\alpha}) = -(0.201 \pm 0.003) - (0.161 \pm 0.002) (v_{\text{C IV}} - v_{\text{H}\alpha}/\text{H}\beta) (10^3 \text{ km s}^{-1}),
\]

\[
\log(\text{FWHM}_{\text{C IV}} / \text{FWHM}_{\text{H}\beta}) = -(0.190 \pm 0.015) - (0.161 \pm 0.010) (v_{\text{C IV}} - v_{\text{H}\beta}/\text{H}\beta) (10^3 \text{ km s}^{-1}),
\]

\[
\log(\frac{M_{\text{BH,C IV}}}{M_{\text{BH,H}\beta}}) = -(0.457 \pm 0.006) - (0.382 \pm 0.003) (v_{\text{C IV}} - v_{\text{H}\beta}/\text{H}\beta) (10^3 \text{ km s}^{-1}),
\]

\[
\log(\frac{M_{\text{BH,C IV}}}{M_{\text{BH,H}\beta}}) = -(0.371 \pm 0.035) - (0.335 \pm 0.022) (v_{\text{C IV}} - v_{\text{H}\beta}/\text{H}\beta) (10^3 \text{ km s}^{-1}).
\]

Because of the tighter linear correlation for the \(M_{\text{BH}}\) ratios than the FWHM ratios, we recommend using Equation (4) when correcting the C IV \(M_{\text{BH}}\) values. Equations (3) and (4) imply that C IV to Balmer FWHM ratios systematically increase with C IV blueshift (e.g., Coatman et al. 2016, 2017, hereafter C17), for instance, by 0.32 dex between 0 and 2000 km s\(^{-1}\) C IV blueshift, or by 0.67–0.76 dex in \(M_{\text{BH,C IV}}/M_{\text{BH,H}\beta}\) values.

The blueshift of the C IV line has been considered as one of the causes for the scatter in the broad line width ratios against Mg II or Balmer lines. At the time of writing, we find the C17 relation well points out for the systematic overestimation in C IV to Balmer line width ratios along C IV blueshift, drawing similar conclusions although linear in the correction method as

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**Figure 11.** Ratio between C IV and Balmer broad line FWHMs plotted against rest-frame 1350–5100 Å continuum luminosity ratio (left) and Balmer to C IV broad line shift (center), and the \(M_{\text{BH}}\) ratio against C IV blueshift (right). Negative velocities indicate blueshift. The Balmer to C IV shifts are averaged when both the H\(\alpha\) and H\(\beta\) lines are observed, and the FWHM\(_{H\alpha}\) is converted from FWHM\(_{H\beta}\) whenever available using the J15 relation, in order to benefit from the enhanced sensitivity of the H\(\alpha\) line. We plot the data points from the literature (Netzer et al. 2007; Shang et al. 2007; Dietrich et al. 2009; Assef et al. 2011; Ho et al. 2012; S12; Bentz et al. 2013; Park et al. 2013; J15; Mejía-Restrepo et al. 2016; C17 and references within) converted to our adopted cosmology in black, and from this work in red. We limit the line width ratios and luminosity ratios to sources with <0.15 dex uncertainties, and the line shifts to sources with <1000 km s\(^{-1}\) uncertainties. Objects with broad absorption lines near the C IV line are rejected, while objects with FWHM\(_{H\beta} > 8000\) km s\(^{-1}\) among the literature or those classified as double-peaked emitters from this work are shown as open circles. The two objects in Shang et al. (2007) that overlap with Park et al. (2013) are removed, while the \(L_{\text{IR,T}}\) and FWHM\(_{C IV}\) from Netzer et al. (2007) are updated to the values from Shen et al. (2011). On panel (b) the FITEXY and BCES fit to the filled data are shown in solid and dotted lines, respectively, while the C17 relation (corrected as \(M_{\text{BH}} \propto \text{FWHM}^2\) for panel (c)) is overplotted (dashed line).
opposed to our log-linear correction. We compare the reduction in the intrinsic scatter between the C IV to Hβ M_{BH} ratios when applying either correction to the data in Figure 11(c), for the C IV blueshifted bounded within −1000 and 5000 km s^{-1} in order to compare well sampled data and to reject data where the C17 relation diverges. We find that σ_{int} decreases merely from 0.38 to 0.27 dex (this work, FITEXY), 0.25 dex (this work, BCES), and 0.30 dex (C17 relation). The C17 relation performs as much as ours (or perhaps better at C IV blueshifts larger than 5000 km s^{-1}) to reduce the σ_{int} values, considering that we are correcting for the M_{BH} ratios while using the FWHM^2 ratios from C17, although the linear correlation coefficients are slightly larger between the C IV blueshift and log M_{BH} ratio (r = 0.70) than against M_{BH} ratio (r = 0.66). In any case, the relatively minor change in σ_{int} values (0.08–0.13 out of 0.38 dex) imply that the broad line outflows, although effectively explaining the bias in the C IV to Balmer M_{BH} ratios, are not fully responsible for the scatter.

Among other mutually correlated observables (Eigenvector 1, Boroson & Green 1992) that scale with the broad line width ratios or the residuals of the ratios are the C IV luminosity, equivalent width of the C IV line, and shape parameters (e.g., Baskin & Laor 2005; Runnoe et al. 2013), reducing the intrinsic scatter between the C IV- and Balmer-based M_{BH} values from 0.43–0.51 dex by merely 0.10–0.13 dex. Many Eigenvector 1 properties are correlated with the Eddington ratio, perhaps hinting that the C IV line width bias could be driven by a physical mechanism such as strong outflowing winds at high Eddington ratios, although the high Eddington ratio is a necessary rather than sufficient condition for C IV outflows (Baskin & Laor 2005). We further note that studies reporting the reduction of the σ_{int} value between the C IV- and Balmer-based M_{BH} values by adding an obscuration correction term or adopting a shallower scaling of the FWHM_{CIV} term (e.g., Assef et al. 2011; S12) are not as effective when the dynamic range and sampling of the parameter space are improved (e.g., Figure 11(a) in this work, J15). Overall, the intrinsic scatter between C IV- to Balmer-based M_{BH} values (~0.4 dex, J15) is not yet fully explained by either empirical or physical approaches, leaving the possibility that the C IV mass estimator is less reliable than the Balmer- or Mg II-based estimators for more fundamental reasons, e.g., non-virialized or non-reverberating velocity structure within the C IV line region (Denney 2012).

5.3. EMBH–Host Galaxy Coevolution

We probe how the observed EMBH masses in AGNs constrain models for galaxy evolution in Figure 12, showing Balmer M_{BH} values at the massive end as a function of redshift from compiled references and from this work. The most massive BHs seen in local inactive galaxies appear similarly massive to AGNs at z ∼ 1 and beyond. Assuming that the EMBH hosting AGNs at z = 2.5 will become inactive bulge galaxies falling on the local M_{BH}–M_{bulge} relation, we draw in Figure 12 the expected evolutionary tracks of the M_{bulge} adopting the consensus of observed and simulated evolution of σ_{b} and effective radius (R_e) for massive galaxies, i.e., 20%–40% decrease in σ_{b} and 3–5 times increase in R_e from z = 2 to 0, and the proportionality M_{bulge} ∝ R_e σ_{b}^2 (e.g., Trujillo et al. 2006; Toft et al. 2007; Cenarro & Trujillo 2009; Naab et al. 2009; van Dokkum et al. 2010; Oser et al. 2012; Tripe 2016). The estimated M_{bulge} values at z ∼ 2 are factors of a few smaller than the most massive local galaxies, leaving the possibility for M_{bulge} to grow after the BH has reached EMBH mass. Therefore, the observed EMBH masses in z = 1–2 AGNs require them to be overmassive to their host bulges. On the other hand, we consider the effect of relaxing the assumption that the most massive BHs are hosted in the most massive early-type galaxies shaping the present day BH–galaxy scaling relations. First, the host galaxies of z = 1–2 EMBHs may not end up being the most massive galaxies due to galaxy environment. If the EMBH hosts are not the central galaxies in moderately dense environments (e.g., Brown et al. 2008; Wellons et al. 2016), they will not encounter minor mergers as frequently, which would imply more limited size growth. Indeed, local examples of overmassive BHs are often in compact galaxies (e.g., Rusli et al. 2011; van den Bosch et al. 2012; Ferré-Mateu et al. 2015; Walsh et al. 2016). Second, it could be that the host galaxy evolves to be massive in stellar content, but not bulge-dominated in morphology. Gas-rich major mergers that could trigger the observed AGN luminosity traced by our sample (e.g., Hong et al. 2015) and form a bulge may still leave a disk, and transformation into the bulge through secular processes or repeated minor mergers could have somehow been prevented (e.g., Springel & Hernquist 2005; Robertson et al. 2006; van der Wel et al. 2011). This scenario is consistent with most of the overmassive BHs on the M_{BH}–M_{bulge} relation (e.g., Walsh et al. 2016) being lenticular galaxies, with bulge to total mass (or luminosity) ratios typically ranging below unity (0.1–0.6, e.g., Cretton & van den Bosch 1999; Rusli et al. 2011; van den Bosch et al. 2012; Strader et al. 2013; Walsh et al. 2015).
We have discussed that the relative growth modes for extremely massive BHs and their host galaxies can not only depend on the galaxy mass, but also environment or morphology. Galaxy environment studies of EMBH hosts will help probe the contribution of mergers shaping the BH–galaxy scaling relations (e.g., Jahnke & Macciò 2011), and spatially resolved imaging of the host will tell if a two-parameter relation (e.g., M_{BH}–σ) is sufficient to explain BH–galaxy coevolution. Luminous AGN activity is rare in the present-day universe and EMBHs have mostly been found in quiescent early-type galaxies. Further discoveries of EMBHs (e.g., van den Bosch et al. 2015) in lower bulge masses will constrain how tight the BH–galaxy scaling relations are at their massive end, and how often EMBHs in distant AGNs remain in the most massive galaxies at present.

6. Summary

We performed followup rest-optical spectroscopy of a sample of 26 extremely massive quasars at 0.7 < z < 2.5 in order to cross-check their rest-UV M_{BH} values, and to examine possible biases affecting the measured M_{BH} values. We summarize the results as follows.

1. The rest-UV M_{BH} estimates of \( \lesssim 10^{10} M_{\odot} \) in luminous AGNs, are generally consistent with the Balmer-based estimates. However, double-peaked emitters strongest in the Hα, extremely broad Fe II around Mg II, and highly blueshifted (>2000 km s^{-1}) C IV profiles are frequently associated with M_{BH} \( \gtrsim 10^{10} M_{\odot} \) estimates, easily boosting reported masses by a factor of a few. We find these cases mostly at broad line FWHM > 8000 km s^{-1}, and make cautionary remarks for estimating M_{BH} values based on any line width over this limit. The presence of broadened (FWHM > 1000 km s^{-1}) narrow emission (e.g., [O III]), however, does not appear to significantly bias EMBH mass measurements.

2. We checked for systematic biases in single-epoch M_{BH} estimators for AGNs with EMBH masses and general AGNs. Anisotropic radiation and the use of broad line FWHM in place of \( \sigma \) are not the major cause of producing false EMBH M_{BH} estimates for our sample. Furthermore, variability, overestimated line equivalent width from cold accretion disks, and obscuration do not bias the M_{BH} estimates for general type-1 quasars by more than \( \sim 0.1 \) dex. Instead, correcting the C IV M_{BH} estimator based on its blueshift relative to the Balmer line redshift, the C IV M_{BH} values decrease by 0.67–0.76 dex from a zero to 2000 km s^{-1} blueshift, with sizable scatter.

3. Removing the systematically uncertain M_{BH} values arising from the spectra or mass estimators, there is still a chance that EMBH masses are boosted by anisotropic motion of the broad line region from \( \sim 10^{5.5} M_{\odot} \) BHs, but this is contradictory to the current \( \sigma_{\text{int}} \) values of the local M_{BH}–\( \sigma \) relation for AGNs. The observed and simulated growth of M_{bulge} in massive galaxies support that EMBH hosting AGNs at \( z = 1–2 \) are growing predominantly by minor dry mergers, with their BHs overmassive to the host’s bulge mass. Depending on the galaxy environment on galactic and intergalactic scales, we expect that either the EMBH host will catch up the BH growth or the BH will stay overmassive to the bulge.

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