Systematic Redshift of the FeIII UV Lines in Quasars: Measuring Supermassive Black Hole Masses under the Gravitational Redshift Hypothesis

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Abstract

We find that the Fe III λ2039–2113 spectral feature in quasars appears systematically redshifted by amounts accountable under the hypothesis of gravitational redshift induced by the central supermassive black hole (BH). Our analysis of 27 composite spectra from the BOSS survey indicates that the redshift and the broadening of the lines in the Fe III λ2039–2113 blend roughly follow the expected correlation in the weak limit of Schwarzschild geometry for virialized kinematics. Assuming that the Fe III UV redshift provides a measure of \( M_{\text{BH}} \),

\[
\left( \frac{\Delta \lambda}{\lambda} \right) \simeq \frac{3}{2} \frac{G M_{\text{BH}}}{c^2 R}
\]

and using different estimates of the emitting region size, \( R \) (either from gravitational microlensing, reverberation mapping, or from the scaling of size with intrinsic quasar luminosity), we obtain masses for ten objects that are in agreement within uncertainties with previous mass estimates based on the virial theorem. Reverberation mapping estimates of the size of the Fe III λ2039–2113 emitting region in a sample of objects would be needed to confirm the gravitational origin of the measured redshifts. Meanwhile, we present a tentative BH mass scaling relationship based on the Fe III λ2039–2113 redshift useful to measure the BH mass of one individual object from a single spectrum.

Key words: black hole physics – gravitational lensing: micro

1. Introduction

In the classical picture of quasars, a central supermassive black hole (BH) is surrounded by an inspiraling disk that transports matter into the depth of the gravitational well of the BH, releasing huge quantities of energy (Salpeter 1964; Zel’dovich 1964). This central engine illuminates gas clouds located in a larger region (Broad Line Region, BLR) giving rise to very broad emission lines (BEL) whose width and shape are determined by the kinematics of the gas clouds, ultimately ruled by the central BH. Thus, the kinematics of the BLR potentially provides a means of measuring the central masses of supermassive BHs and of studying the structure of the accretion disk.

Specifically, the methods for estimating BH masses in distant quasars are mainly based on the measure of the broadening of the BLR in combination with the virial theorem (see, e.g., Peterson 2014). According to this theorem, the square of the line broadening, \((\Delta \nu)^2\), is a proxy for \( M/R \) that, in combination with a determination of the size, \( R \), can provide an estimate of the mass,

\[
M = f (\Delta \nu)^2 R / c^2
\]

(1)

The dimensionless factor, \( f \), includes the effects of the unknown BLR geometry, kinematics and inclination. Without more information, it is a common practice to use an average value for \( f \) obtained by calibrating with other methods,11 even when \( f \) is different for each object. This virial factor, by itself, limits the accuracy of individual estimates of mass to \( \sim 0.4 \) dex (Peterson 2014). The size can be determined from reverberation mapping (see, e.g., the reviews by Peterson 1993, 2006), which is an observationally expensive technique, or alternatively using the size–luminosity, \( R-L \), relationship for AGNs, a shortcut inferred from reverberation mapping results (Kaspi et al. 2000, 2005; Bentz et al. 2009; Zu et al. 2011). Both techniques are relatively accurate and the main experimental problem of Equation (1) (in addition to the unknown factor \( f \)), arises from the determination of the line widths (Peterson 2014), due to both, the ambiguity in the definition of \( \Delta \nu \) (FWHM, \( \sigma \), use of the variable or constant part of the spectra, etc.), and the presence of contaminating features (extra components, blended lines, pseudo-continuum, etc.).

An alternative path to BH masses is the gravitational redshift of the BEL. If we consider the width of the BEL as caused by motion in the gravitational field of a central mass, a simple calculation shows that we should expect measurable gravitational

11 The \( M_{\text{BH}}/R^2 \) relationship, for instance (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002).
and transverse Doppler redshifts (see, e.g., Netzer 1977; Anderson 1981; Mediavilla & Insertis 1989). Indeed, in the weak limit of the Schwarzschild metric, the velocity of the emitters is proportional to $\sqrt{GM/R}$, and the gravitational plus transverse Doppler redshift$^{12}$ will tend to $\frac{3G M}{c^2 R}$. Thus, line broadenings typical of the BEL, $\Delta \nu \gtrsim 10^4$ km s$^{-1}$, will result in redshifts $\lambda_{grav} = \frac{\Delta \lambda}{\lambda} \gtrsim 0.003$, which for UV lines corresponds to displacements $\Delta \lambda \gtrsim 6$ Å, which should be very easy to measure.

However, experimental results do not satisfy these theoretical expectations. According to massive analyses of quasar spectra like SDSS (Vanden Berk et al. 2001) and BOSS (Harris et al. 2016), the peaks of the brightest permitted and semi-forbidden lines can appear shifted either toward the red or the blue, but with blueshifts being more frequent and strong, the opposite of what is expected. This indicates that the shifts of the BEL peaks are probably of kinematic origin. Nevertheless, the profiles of some BEL (H/$\beta$ in many cases) can show redward asymmetries (Peterson et al. 1985; Sulentic 1989, Zheng & Sulentic 1990, Popovic et al. 1995; Corbin 1997), that have been sometimes interpreted as the result of gravitational redshift (Jonic et al. 2016), although the presence of an extra component redshifted due to inflow is, perhaps, a more accepted explanation for the line asymmetry. In a few cases in which spectroscopic monitoring is available, the redshift between the mean and rms profiles of Balmer lines has been associated with gravitational redshift (Kollatschny 2003; Liu et al. 2017).$^{13}$ There has also been continued controversy about the existence of redshifts in FeII emission. Hu et al. (2008) interpreted the redshift measured in the FeII optical lines of a sample of SDSS spectra in terms of kinematics dominated by infall. In this scenario, to prevent the gas from being accelerated away from the central source by the radiation force, Ferland et al. (2009) propose that we only observe the shielded face of near-side infalling clouds. However, Kovačević et al. (2010) report only a slight redshift of the FeII optical lines. The same result is reached by Sulentic et al. (2012) who find that the FeII optical lines follow the same kinematics as the Balmer lines. Finally, Kovačević-Dojićinović & Popović (2015) find a significant average redshift in the UV lines that, however, is not present in the optical lines. In any case, the FeII redshifts were interpreted as inflow of gas clouds located at the outer parts of the BLR, leaving aside the gravitational redshift scenario.

The main cause of the scarcity of unquestionable identifications of gravitational redshift is likely the complex morphology of the lines, with several kinematic components arising from different regions, and often blended with lines from other species that may significantly distort the shape and change the width of the line profile. To achieve a robust detection of gravitational redshift, we need a feature associated with one single ion, not blended with emission lines of other species, and that presumably originates from an inner region of the BLR.

The size of the region giving rise to an emission line in the quasar spectrum can be estimated from the changes in magnification of the emission line induced by gravitational microlensing,$^{14}$ so that the larger the changes are the smaller the size. According to previous studies (Guerras et al. 2013a, 2013b; Fian et al. 2018), the FeIII$\lambda\lambda2039–2113$ blend is a relatively isolated feature strongly affected by microlensing and hence must originate in a small region (a few light-days across) where gravitational redshift is significant. The objective of this work is, then, to measure the shifts of the FeIII lines of this blend, to explore their consistency with the gravitational redshift hypothesis, and to discuss their possible use in the determination of SMBH masses and in the study of the physics of accretion disks.

The paper is organized as follows: In Section 2, we fit the FeIII$\lambda\lambda2039–2113$ blend in a sample of high S/N spectra collected from several data sources. Section 3 is devoted to deriving a scaling relationship of mass with redshift and luminosity. Finally, in Section 4, we summarize the main conclusions.

2. Results: FeIII$\lambda\lambda2039–2113$ Redshift Measurements

2.1. Data

The data analyzed in this work have different origins. The 14 lensed quasar spectra fitted in Section 2.2 have been compiled from many sources in the literature (see details in Fian et al. 2018). In Section 2.2, we also analyze the publicly available SDSS composite spectrum (Vanden Berk et al. 2001) and the 27 BOSS quasar composite spectra (Jensen et al. 2016). Finally, in Section 3.1, the monitoring series of spectra of NGC 5548 (Korista et al. 1995) and the spectrum from NGC 7469 (Kriss et al. 2000) are used to determine the BH masses. All the spectra are corrected from cosmological redshift.

2.2. Analysis and Results

We model the FeIII$\lambda\lambda2039–2113$ spectral feature in 14 lensed quasars (Fian et al. 2018). First, we fit the continuum to a straight line defined in two windows at the blue (2013.3 Å, 2017.9 Å) and red (2195.3 Å, 2205.0 Å) sides of the blend. Then we subtract the continuum and fit the feature using a template of 19 single FeIII lines between 2038.5 and 2113.2 Å of fixed relative amplitudes as provided by Vestergaard & Wilkes (2001). The (Gaussian) lines are broadened, shifted, and scaled with the same width, $\sigma$ ($=\text{FWHM}/2.35$, wavelength shift, $\Delta \lambda$, and scale factor. In Figure 1, we can see that this template is able to reproduce very well the shape of the FeIII$\lambda\lambda2039–2113$ feature in the spectra of the objects in our sample,$^{15}$ but the fitted features are redshifted in all the objects except one (SDSS 1004+4112, which is strongly affected by microlensing). Leaving aside this object, we find that the average of this systematic redshift is $\langle \Delta \lambda \rangle = 10.3$ Å with a scatter between objects of $\pm 5.9$ Å. If we take the microlensing based size inferred by Fian et al. (2018) for the FeIII UV lines,$^{16}$ $R = 1.18 \times 11.3^{+2.5}_{-3}$ lt-day, we can estimate the

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$^{12}$ Hereafter, we refer to the combined gravitational and transverse Doppler effects as gravitational redshift.

$^{13}$ In any case, the presence of gas cold enough to generate the Balmer lines so close to the BH as to justify the redshift needs to be explained (Bon et al. 2015).

$^{14}$ When a distant quasar is lensed by the gravitational potential of an intervening (lens) galaxy, the relative movement between the quasar and the distribution of stars in the lens galaxy can change the brightnesses of the images, an effect called quasar gravitational microlensing (Chang &Refsdal 1979, 1984, see also the review by Wambsganss 2006).

$^{15}$ See also other fits in the upper panels of Figures 2 and 3.

$^{16}$ Fian et al. (2018) consider a disk with a Gaussian radial profile, for which the half-light radius, $R$, is obtained from the reported Gaussian sigma, $\sigma_r$, through $R = 1.18\sigma_r$. 
average mass of the supermassive BHs of the lensed quasars under the hypothesis of a gravitational origin for the redshift. If we assume that gravitational and transverse Doppler are the physical phenomena giving rise to the redshift, we have (see, e.g., Mediavilla & Insertis 1989),

$$\nu = \left(\frac{v_0}{\gamma}\right) \sqrt{1 - 2G M_{\text{BH}}/Rc^2}$$

with \(\gamma = \left(1 - (v/c)^2\right)^{-1/2}\). In the weak limit of the Schwarzschild metric, \(\nu \simeq GM_{\text{BH}}/R\), and we have,

$$z_{\text{grav}} = \frac{\Delta \lambda}{\lambda} \simeq \frac{3}{2} \frac{G M_{\text{BH}}}{c^2 R}.$$  

(2)

and,

$$M_{\text{BH}} \simeq \frac{2c^2 \Delta \lambda}{3G} R = \left(\frac{z_{\text{grav}}}{0.005}\right) \left(\frac{R}{10 \text{ lt-day}}\right) \times (0.58 \times 10^9 M_\odot).$$  

(3)

Substituting in Equation (3) the mean redshift of the iron lines and the microlensing based size, we obtain for the average mass of the supermassive BHs, \(\langle M_{\text{BH}} \rangle \simeq (0.83 \pm 0.47) \times 10^9 M_\odot\), where the uncertainty arises partly from the method and partly from the intrinsic scatter between objects. This value is in good agreement, in mean and scatter, with virial based estimates for lensed quasars (see, e.g., Figure 8 of Mosquera et al. 2013). In fact, if we consider the eight lensed quasars in our sample (HE 0047–1756, SDSS 0246–0285, SDSS 0924+0219, FBQ 0951+2635, Q 0957+561, HE 1104–1805, SDSS 1335+0118, and HE 2149–2745) that have virial mass estimates by Peng et al. (2006) and Assef et al. (2011), we obtain from Equation (3), \(\langle M_{\text{BH}}^{\text{micro}} \rangle \simeq (0.9 \pm 0.5) \times 10^9 M_\odot\), in very good agreement with the average of their virial masses, \(\langle M_{\text{BH}}^{\text{virial}} \rangle \simeq 0.93 \times 10^9 M_\odot\).

Because of the interesting implications of these results, and to exclude any systematic issue in our sample of lensed quasars, we fit the Fe III λ2039–2113 blend in 14 lensed quasars. The broadening, \(\sigma\), and shift, \(d = \Delta \lambda\), of the iron lines are indicated for each spectrum (in Å). The continuous (dashed) curve corresponds to the data (fit). Vertical dashed lines are located at the wavelengths corresponding to the Fe III lines of the Vestergaard \& Wilkes (2001) template at rest. The spectra have been shifted by an amount \(-d\) to match the template rest frame.
UV features of Fe III that, in spite of their lower intensity, can be modeled in this high S/N composite spectrum: the Fe III λ2419 line and the Fe III λ1970–2039 blend. The Fe III λ2419 line (Figure 2) appears blended with a narrow line identified as Ne IV λ2424 (Vanden Berk et al. 2001). Figure 2 shows that, while the Ne IV narrow line can be well fitted at its nominal wavelength (Vanden Berk et al. 2001), the Fe III line has a clear redshift with respect to it. Finally, the redshift is also observed in the (noisier) Fe III λ1970–2039 blend. The best-fit estimates of the redshift, \( z = \Delta \lambda / \lambda \), of these features are: 0.0034 ± 0.0002 (Fe III λ2039–2113), 0.0037 ± 0.0001 (Fe III λ2419), and 0.0034 ± 0.0007 (Fe III λ1970–2039). For the widths, \( \sigma / \lambda \), we obtain: 0.0057 ± 0.0003 (Fe III λ2039–2113), 0.0059 ± 0.0002 (Fe III λ2419), and 0.0055 ± 0.0006 (Fe III λ1970–2039). The good agreement between the fitted parameters of the three Fe III features confirms that the redshift is intrinsic to the Fe III emitters.

Going a step further, to study the incidence and meaning of the observed redshift using high S/N spectra, we fit (see Figures 3) the Fe III λ2039–2113 feature in the 27 composite spectra of the BOSS survey (Jensen et al. 2016). The fits are very good with \( \chi^2 \) of 2, although some of the spectra have a low S/N. We can use BOSS composites to discuss virialization. If the kinematics is virialized (Equation (1)), we should have,

\[
G \frac{M_{BH}}{R} = f (\Delta \nu)^2 = f \left( \frac{\sigma}{\lambda} \right)^2 c^2,
\]

where we have taken \( \sigma c / \lambda \) as representative of the line broadening, \( \Delta \nu \). Combining Equation (4) with the expression for the mass in terms of the redshift (Equation (2)), we obtain,

\[
\frac{\Delta \lambda}{\lambda} = \frac{3}{2} f \left( \frac{\sigma}{\lambda} \right)^2.
\]

Taking logarithms, we can write this condition of virialized kinematics in a linear shape convenient for quantitative fitting,

\[
\log \left( \frac{\sigma}{\lambda} \right)^2 = - \log \left( \frac{3f^2}{2} \right) + \log \left( \frac{\Delta \lambda}{\lambda} \right).
\]

The measured redshifts, \( z = \Delta \lambda / \lambda \), and widths of the Fe III lines, \( \left( \frac{\sigma}{\lambda} \right)^2 \), obtained from the BOSS composite spectra (excluding the cases with S/N < 3.0) follow this correlation though with a relatively high scatter (Figure 4). Fitting Equation (6) to the data, we obtain (R-squared \( \approx 0.75 \)),

\[
\log \left( \frac{\sigma}{\lambda} \right)^2 = -2.09 \pm 0.64 + (0.99 \pm 0.26) \log \left( \frac{\Delta \lambda}{\lambda} \right).
\]

The large uncertainties in the fit parameters (Equation (7)) can have an intrinsic origin, for the virial factors, \( f \), can be significantly different from system to system depending on physical unknowns like the flatness of the emitter’s distribution, its orientation, or the presence of nongravitational forces (e.g., radiation pressure). It is likely that the criteria to form the BOSS composites may be biased with respect to any of these unknowns giving rise to an intrinsic scatter in \( f \). On the other hand, radial motions may also contribute to the redshift in a variable way from object to object, increasing the scatter. In any case, alternative explanations (inflow, for instance, may be another mechanism giving rise to the redshifts) would need additional physics to explain the observed trend between broadening and redshift. Thus, while a tight correlation between \( \Delta \lambda / \lambda \) and \( \left( \frac{\sigma}{\lambda} \right)^2 \) is not generally expected, the trend found between these two quantities among the composite spectra of BOSS supports the gravitational interpretation of the Fe III λ2039–2113 redshifts and indicates that the kinematics is not far from virialized.

Although the fits of the Vestergaard & Wilkes (2001) template to the Fe III λ2039–2113 feature of BOSS composites are very good, it is true that this template is based on one particular object. To eliminate any possible bias related to the use of the template, we have performed an alternative study based on the centroid of the blend, \( \lambda_c = \langle \lambda \rangle \), in each composite spectrum. The standard deviation between the redshift measurements based on either the fit of the template or the centroid of the blend is \( \approx 0.5 \) Å. This result confirms the redshift estimates irrespective of the choice of template. Another possible source of uncertainty in the measurement of the redshifts is the difficulty to determine the systemic velocity of the quasars, which may depend on the choice of the

\[\text{Equation (2)}\]

\[\text{Equation (6)}\]

\[\text{Equation (7)}\]

For our Gaussian based fits, \( \sigma = \text{FWHM}/2.35 \) but in many applications of the virial theorem based on emission-line profiles, \( \sigma \) is the second moment of the experimental line profile, and FWHM/\( \sigma \) depends on the profile shape (Collin et al. 2006).
spectral features. However, this indetermination can account for shifts of roughly a few hundred km s$^{-1}$, randomly distributed between blue- and redshifts while we are measuring exclusively redshifts of about 1000 km s$^{-1}$. In addition, this problem should be mitigated in the case of BOSS composites resulting from the average of many spectra.

3. Discussion: BH Mass Estimates Based on Fe III $\lambda\lambda 2039–2113$ Redshift

Under the hypothesis that the redshift of the Fe III $\lambda\lambda 2039–2113$ is of gravitational origin, we can invert Equation (2) to derive the central BH mass corresponding to any object for which an estimate of $R_{\text{Fe III}}$ can be obtained (see Equation (3)). We are going to consider three different methods for computing sizes: reverberation mapping, scaling of the size of the BLR with luminosity and gravitational microlensing.

3.1. Mass Estimates of the Central BHs in NGC 5548 and NGC 7469 Based on Fe III $\lambda\lambda 2039–2113$ Redshift and Reverberation Mapping

NGC 5548 is a widely studied AGN$^{18}$ for which reverberation mapping has yielded estimates of the size for the BLR with luminosity and gravitational microlensing.

$^{18}$ Notice, however, that some common conceptions about this AGN could change if the suspected existence of a supermassive BH binary in the center of this galaxy (Li et al. 2016) is confirmed.
continuum and several strong emission lines (see, e.g., Clavel et al. 1991; Korista et al. 1995; Peterson et al. 2002; see also Pei et al. 2017 and references therein).

We fit the Fe III $\lambda\lambda$2039–2113 blend in each of the spectra of the monitoring series (Korista et al. 1995), deriving the light curve of the Fe III amplitude (Figure 5). We infer a lag of the Fe III relative to the UV$\lambda\lambda$1970 continuum of $3.3 \pm 0.8$ (2.8 ± 1.4) days when the centroid (peak) of the cross-correlation centroid (peak) distribution CCCD (CCPD) is taken as a reference. The errors have been estimated applying flux randomization Monte Carlo methods. Adopting these lags as estimates of $R_{\text{Fe III}}$ and using the measurement of the redshift from the fit to the average spectra, $z_{\text{grav}}(\text{Fe III}) = (\Delta \lambda / \lambda)_{\text{Fe III}} = 0.0056 \pm 0.0010$, we obtain, $M_{\text{BH}} = 2.2_{-0.4}^{+0.6} \times 10^8 M_\odot$ ($M_{\text{BH}} = 1.8_{-0.9}^{+1.0} \times 10^8 M_\odot$) for the centroid (peak). These values are relatively large but in agreement within uncertainties with recent estimates of the BH mass derived from the virial theorem ($M = 1.2_{-0.3}^{+0.4} \times 10^8 M_\odot$, Ho & Kim 2015; $M = 6.7_{-1.7}^{+2.7} \times 10^7 M_\odot$, Pei et al. 2017), taking into account a 30% uncertainty in the average virial factor $f$ (Woo et al. 2015), and the intrinsic scatter between objects (0.35 dex according to Ho & Kim 2015).

We also fit the Fe III $\lambda\lambda$2039–2113 feature in another well studied galaxy, NGC 7469 (Kriss et al. 2000). We measure $z_{\text{grav}}(\text{Fe III}) = 0.0026 \pm 0.0005$. In this case, there is no UV spectroscopic monitoring to obtain the light curve of the Fe III

Figure 3. (Continued.)
blend, but we can set an upper limit to the size of $\sim 0.7$ lt-day. This value corresponds to the reverberation lag of He II. This is a high ionization line, known from the impact of microlensing (Fian et al. 2018) to arise from a region of size comparable or somewhat greater than that corresponding to Fe III. Taking this upper limit, we infer $M_{\text{BH}} \lesssim 2.1^{+0.4}_{-0.3} \times 10^7 M_\odot$, compatible with previous virial estimates ($M = 1.5^{+0.4}_{-0.3} \times 10^7 M_\odot$, Ho & Kim 2015, (1–6) $\times 10^7 M_\odot$, Shapovalova et al. 2017).

Finally, it is also important to stress that once the size is known via reverberation mapping the mass of the object is directly obtained from the redshift without using any previous calibration, i.e., in combination with reverberation mapping, the gravitational redshift of the FeIII$\lambda\lambda2039$–$2113$ feature is a primary method to determine masses. In fact, because gravitational redshift does not depend on geometrical considerations, it may become the primary calibrator of all the other methods used to measure the mass of the BH.

### 3.2. BH Mass Estimates Based on Fe IIIλ2039–2113 Redshift and Quasar Luminosity.

Reverberation mapping is an observationally expensive technique to estimate sizes. An alternative is to use the scaling of the size of the BLR with luminosity, $R \propto (L_\lambda)^{0.59}$ (Kaspi et al. 2000, 2005). In combination with the line width of the BLR lines as an estimator of the virial velocity, empirical BH mass calibrations, $M_{\text{BH}} \propto \text{FWHM}^2(L_\lambda)^{0.59}$, can be obtained. The most reliable $R$–$L_\lambda$ relationship is based on H/β and L$^5100$. Other determinations, related to Hα, Mg II, or C IV, are recalibrated from the $R(H/\beta)$–Hα relationship. In spite of some problems associated with it (see, e.g., Mejía-Restrepo et al. 2016), the calibration using the C IV line is important because it is the only prominent BEL that lies within the optical window at high-$z$ as is the case in many of the objects we studied.

Specifically, for high-redshift quasars, BH masses can be estimated from the C IV$\lambda\lambda1549$ broadening using

$$M_{\text{BH}}(\text{C IV}) = 10^{7.69^{+0.06}_{-0.06}} \left( \frac{\text{FWHM}_{\text{C IV}}}{10^3 \text{ km s}^{-1}} \right)^2 \times \left( \frac{\lambda_{\lambda}(1350 \text{ Å})}{10^{44} \text{ erg s}^{-1}} \right)^{0.599^{+0.001}_{-0.001}} M_\odot. \quad (8)$$

Thus, we can use the FWHM$_{\text{C IV}}$ measurements available for the BOSS composites (Jensen et al. 2016) to recalibrate Equation (8) in terms of the Fe III gravitational redshift.\(^{20}\) On average, we find for the BOSS composite spectra:

$$M_{\text{BH}}(\text{Fe III}) = 10^{7.69^{+0.06}_{-0.06}} \left( \frac{\text{FWHM}_{\text{Fe III}}}{10^3 \text{ km s}^{-1}} \right)^2 \times \left( \frac{\lambda_{\lambda}(1350 \text{ Å})}{10^{44} \text{ erg s}^{-1}} \right)^{0.599^{+0.001}_{-0.001}} M_\odot. \quad (9)$$

To check the validity of this relationship, we compare in Figure 6 the mass estimates obtained applying Equation (9) to the measured Fe III gravitational redshifts of the lensed quasars in our sample (Fian et al. 2018) with the virial based masses obtained by Peng et al. (2006) and Assef et al. (2011). We have eight objects in common: HE 0047–1756, SDSS 0246–0285, SDSS 0924+0219, FBQ 0951+2635, Q 0957+561, HE 1104–1805, SDSS 1335+0118, and HE 2149–2745. We have also included NGC 5548 and NGC 7469 in the plot (gravitational redshift masses obtained from Equation (9) and virial masses from Vestergaard & Peterson 2006). The global agreement over two orders of magnitude in mass is very noticeable, showing that the Fe III$\lambda\lambda2039$–2113 gravitational redshift can be used to measure the BH mass.

The intercept of the best fit with slope unity (dashed line in Figure 6) corresponds to the shift in the calibration that we would obtain following the usual steps to derive the mass scaling relationships (see, e.g., Peterson et al. 2004; Vestergaard & Peterson 2006): (i) adopt a R–L relationship, $R \propto L^{0.59}$, and (ii) use the available virial based mass estimates to calibrate our unscaled masses, $\mu = (\text{FWHM} (\text{Fe III}) c / 10^3 \text{ km s}^{-1}) (\lambda_{\lambda}(1350 \text{ Å}) / 10^{44} \text{ erg s}^{-1})^{0.599} M_\odot$. The relatively small value of the shift in the calibration, 0.04 dex, as compared with the 1σ scatter of the masses with respect to the best fit, 0.26 dex, indicates that there is a good agreement between the BOSS composite spectra based calibration and the independent calibration that would be obtained fitting the virial masses. The 0.26 dex scatter of the masses relative to the fit, also indicates that Equation (9) is reliable taking into account that virial masses are themselves uncertain typically by $\sim 0.3$ dex (Vestergaard & Peterson 2006).

Notice that the R–L relationship is very tight (with errors comparable to the lags inferred from reverberation mapping, Peterson 2014). Thanks to this and because the Fe III gravitational redshift is easy to measure from a single spectrum, Equation (9) provides a robust estimate of the mass of a quasar or AGN. An attempt to fit the Fe IIIλ2039–2113 blend in a

\(^{19}\) The use of other standard calibrations (e.g., Vestergaard & Peterson 2006; Assef et al. 2011) do not substantially affect the results.

\(^{20}\) This is supported by Equation (5), which relates broadenings and redshifts.
include a mass estimates based calibration and the calibration that would be obtained using the virial relationship: the best linear fit to the data with slope unity. The small separation between both lines indicates the good agreement between the BOSS composite spectra. Figure 6 shows the good agreement, 0.27 dex of error, between the mass estimates obtained using the virial based mass estimates (see the text). Errors in $M_{\text{vir}}$ are from Assef et al. (2011) or correspond to the dispersions of the virial relationships (Peng et al. 2006; Vestergaard & Peterson 2006). Errors in $M_{\text{grav}}$ include a (conservative) error of $\pm 1.5 \, \AA$ in the gravitational redshift estimate, and 0.13 dex of intrinsic scatter in the R–L relationship (Peterson 2014).

A change of scale, $R \propto \lambda^{0.5}$, used by these authors to infer (R), can write,

$$M_{\text{BH}} \simeq \frac{2c^2 \Delta \lambda (R)}{3G} \frac{\lambda L_{\lambda}}{\langle \lambda L_{\lambda} \rangle}. \quad (10)$$

This equation is, indeed, very similar to Equation (9) but has been differentiated on different grounds. Inserting the value of $\langle R \rangle$ from Fian et al. (2018) and the average of the square root of the luminosities of the quasars, $\langle \lambda L_{\lambda} \rangle$, used by these authors to infer $\langle R \rangle$, we can write,

$$M_{\text{BH}} \simeq \frac{\Delta \lambda}{10.3 \, \AA} \lambda L_{\lambda} \frac{10^{58.75} \text{ erg s}^{-1}}{10^{14} \text{ erg s}^{-1}} \times (0.83 \pm 0.47) \times 10^9 M_\odot. \quad (11)$$

It is convenient to rewrite this equation to compare it with the equivalent expression (Equation (9)) based on the BOSS composite spectra calibration,

$$M_{\text{BH}}^{\text{micro}} (\text{Fe III}) = 10^{7.85^{+0.10}_{-0.19}} \left( \frac{c_{\text{grav}} (\text{Fe III}) c}{10^3 \text{ km s}^{-1}} \right) \lambda L_{\lambda} (1350 \, \AA) ^{0.5} M_\odot. \quad (12)$$

Thus, Equations (9) and (12) agree within uncertainties. This agreement is noteworthy taking into account that the calibration of Equation (11) (and hence Equation (12)) resides on gravitational microlensing while Equation (9) has been calibrated from the widths of the C IV lines of BOSS composites. Figure 7 shows the good agreement, 0.27 dex of scatter (1σ), between the mass estimates obtained using Equation (11) and the virial masses.

3.4. Best Fit of the Mass Scaling Relationship to the Virial Masses Leaving Free the $R \propto \lambda^{p}$ Law.

Finally, it is also interesting to perform a fit of Equation (10) to the virial masses of our 10 objects but now leaving free the exponent of the R–L relationship, $R \propto \lambda L_{\lambda}^{p}$. A change of scale,
Figure 8. Best fit of the mass scaling relationship based on the redshift to the virial masses leaving free the $R \propto L^a$ law. The continuous line corresponds to $M_{\text{best fit}} = M_{\text{virial}}$. The best linear fit to the data with slope unity is indistinguishable from this line. Errors in $M_{\text{best fit}}$ are from Assef et al. (2011) or correspond to the dispersions of the virial relationships (Peng et al. 2006; Vestergaard & Peterson 2006). Errors in $M_{\text{best fit}}$ include the error in the parameters of the fit and 0.13 dex of intrinsic scatter in the R–L relationship (Peterson 2014).

We have studied the FeIII $\lambda$2039–2113 emission line blend in 14 spectra of lensed quasars, in two well known AGN (NGC 5548 and NGC 7469), in the SDSS quasar composite spectrum and in 27 BOSS quasar spectra composites. This feature is relatively free of contamination from lines of other species and, according to the impact of microlensing magnification on it, arises from an inner region of the BLR. The main results are as follows:

1. The FeIII $\lambda$2039–2113 feature appears systematically redshifted. In the high S/N SDSS composite spectrum, this redshift is also consistently measured in the FeIII $\lambda$2419 line and the FeIII $\lambda$1970–2039 blend.
2. There is a correlation, though, with a large scatter between the observed redshift and the broadening of the FeIII $\lambda$2039–2113 lines. This dependence is expected in the case of virialized kinematics if the redshift is gravitational. The scatter may reflect the differences in geometry, kinematics, and impact of nongravitational forces, among the quasars.
3. In combination with microlensing based estimates of the FeIII UV emitting region size, the measured redshifts for gravitational lenses lead, under the gravitational redshift hypothesis, to values for the central BH mass, $\langle M_{\text{BH}} \rangle \simeq (0.9 \pm 0.5) \times 10^9 M_\odot$, in good agreement with previous virial based estimates.
4. We present a scaling relationship of mass with redshift and luminosity useful to measure the BH mass of one individual object from a single spectrum. This relationship can be formally derived from the Schwarzschild metric and is consistently calibrated using three different methods: the broadening of the CIV lines of the BOSS composite spectra, the strength of gravitational microlensing in the FeIII UV lines, and the best fit to the available virial masses. The two first methods are completely independent and the estimated masses using any of them are in statistical agreement with virial masses over two orders of magnitude (1 $\sigma$ scatter of 0.27 dex comparable to the intrinsic scatter of the virial masses).
5. If the gravitational redshift hypothesis is correct, the application of the scaling relationship to spectra of available quasar surveys will provide thousands of estimates of supermassive BH masses. Future mass estimates based on the FeIII redshift and reverberation mapping may become the primary calibrators for all BH mass measurement methods.

Although the good matching between the masses derived from the measured redshifts of the FeIII $\lambda$2039–2113 feature and the virial masses makes gravitational redshift a compelling explanation, the potential importance of the confirmation of this hypothesis is worthy of additional study. However, this is not straightforward. Because of the large intrinsic uncertainties of the virial method applied to individual objects, a direct confirmation based on the comparison with virial masses, can be firmly established only from a large enough sample. In addition, as virial masses are not exempt of biases arising from the geometry of the emitters distribution or by the presence of nongravitational forces, this comparison will actually be two-way, testing both the conditions of applicability of the virial theorem and the gravitational redshift hypothesis. For these reasons, the most convincing support likely will be based on
high S/N reverberation mapping studies of the Fe IIIλλ2039–2113 blend in several objects, which can confirm the small size of the region emitting this spectral feature and provide an accurate R–L relationship for it.

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