REVERBERATION AND PHOTOIONIZATION ESTIMATES OF THE BROAD-LINE REGION RADIUS IN LOW-\(z\) QUASARS

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ABSTRACT

Black hole mass estimation in quasars, especially at high redshift, involves the use of single-epoch spectra with signal-to-noise ratio and resolution that permit accurate measurement of the width of a broad line assumed to be a reliable virial estimator. Coupled with an estimate of the radius of the broad-line region (BLR) this yields the black hole mass \(M_{\text{BH}}\). The radius of the BLR may be inferred from an extrapolation of the correlation between source luminosity and reverberation-derived \(r_{\text{BLR}}\) measures (the so-called Kaspi relation involving about 60 low-\(z\) sources). We are exploring a different method for estimating \(r_{\text{BLR}}\) directly from inferred physical conditions in each source. We report here on a comparison of \(r_{\text{BLR}}\) estimates that come from our method and from reverberation mapping. Our “photoionization” method employs diagnostic line intensity ratios in the rest-frame range 1400–2000 Å (\([\text{Al}\,\text{iii}\,1860/\text{Si}\,\text{iii}\,1892, \text{C}\,\text{iv}\,1549/\text{Al}\,\text{iii}\,1860]\)) that enable derivation of the product of density and ionization parameter with the BLR distance derived from the definition of the ionization parameter. We find good agreement between our estimates of the density, ionization parameter, and \(r_{\text{BLR}}\) and those from reverberation mapping. We suggest empirical corrections to improve the agreement between individual photoionization-derived \(r_{\text{BLR}}\) values and those obtained from reverberation mapping. The results in this paper can be exploited to estimate \(M_{\text{BH}}\) for large samples of high-\(z\) quasars using an appropriate virial broadening estimator. We show that the width of the UV intermediate emission lines are consistent with the width of H\(\beta\), thereby providing a reliable virial broadening estimator that can be measured in large samples of high-\(z\) quasars.

Key words: black hole physics – galaxies: active – quasars: emission lines – quasars: general

Online-only material: color figures

1. INTRODUCTION

Quasars are intriguing objects whose intense activity arises in a small volume (fraction-of-parsec radius) whose widely accepted interpretation involves accretion onto a central black hole (e.g., D’Onofrio et al. 2012, and references therein). An important signature of the majority of quasars involves the presence of broad emission lines in the UV–optical–IR spectrum. A major challenge involves estimation of the distance \(r_{\text{BLR}}\) from the central continuum source of the line emitting region (the broad-line region, BLR). The BLR cannot be resolved with direct imaging even in the nearest sources. The most direct method for estimating \(r_{\text{BLR}}\) (hereafter also referred to as the “radius” for brevity) is through reverberation mapping (RM; Peterson 1998; Horne et al. 2004). This technique measures the time delay \(\tau\) in the response of the broad emission lines to changes in the ionizing continuum. The rest-frame distance is then defined as

\[
\text{\(r_{\text{BLR}} = \frac{c \cdot \tau}{(1+z)} = c \tau_{rf}.\)}
\]

where \(\tau_{rf}\) is the time delay in the quasar rest frame. For brevity we shall use only \(\tau\) to refer to this rest-frame distance. \(r_{\text{BLR}}\) estimates from RM require a significant observational effort and have been obtained for only \(\approx 50\) nearby objects (\(z < 0.4\); Kaspi et al. 2000, 2005; Peterson et al. 2004; Bentz et al. 2009, 2010; Denney et al. 2010). An indirect method for measuring \(r_{\text{BLR}}\) was proposed by Kaspi et al. (2000, 2005) who found a correlation between \(r_{\text{BLR}}\) and the optical continuum luminosity at 5100 Å,

\[
r_{\text{BLR}} \propto L^\alpha
\]

with \(\alpha \approx 0.5–0.7\) and recent studies favoring a value between 0.5 (Bentz et al. 2009) and 0.6 (Marziani et al. 2009). Apart from the uncertainty in the power-law exponent (and any possible dependence of \(\alpha\) on the luminosity range considered) the rms intrinsic scatter associated with \(r_{\text{BLR}}\) in the Bentz et al. (2009) data is \(\approx 0.28\) dex. This method has the advantage of being straightforwardly applicable to large samples of quasars for which single-epoch spectra are available requiring only moderate resolution spectrophotometry involving a broad emission line assumed to be a valid virial estimator. Equation (2) has paved the way toward definition of “scaling laws” between central black hole mass \(M_{\text{BH}}\), line width, and luminosity (Shen & Liu 2012, and references therein). Estimating the black hole mass is plagued by large uncertainties because several other variables are at play: emitting region structure, orientation effects, emitting gas dynamics, etc. They will be briefly discussed in Section 5. However, estimated uncertainties in \(\log M_{\text{BH}}\) associated with scaling laws are \(\approx 0.3–0.4\) dex at the 1\(\sigma\) confidence level, implying that a large fraction of the scatter is due to the assumption of Equation (2).

The aim of this paper is to reduce the uncertainty in individual estimates of \(r_{\text{BLR}}\) and hence \(M_{\text{BH}}\). Rather than relying on the \(r_{\text{BLR}}\sim L\) correlation we propose an alternative approach for \(r_{\text{BLR}}\) estimation based on the simple assumption that gas giving rise to the UV resonance lines is photoionized by the central continuum source. \(r_{\text{BLR}}\) is then estimated not from a correlation but on an
object-by-object basis. The photoionization method is explained in Section 2, while the sample is described in Section 3. We compare photoionization and reverberation values in Section 4. Discussion of the potential advantages are given Section 4.1. Computations were made considering $H_0 = 70 \text{ km s}^{-1}\text{Mpc}^{-1}$ and a relative energy density $\Omega_\Lambda = 0.7$ and $\Omega_M = 0.3$.

2. METHOD

The BLR radius $r_{\text{BLR}}$ is linked to physical parameters such as hydrogen density ($n_H$) and ionization parameter ($U$) by the definition of the ionization parameter itself:

$$r_{\text{BLR}} = \left(\frac{\int_{v_{\text{rest}}}^{\infty} L_{\nu} dv}{4\pi n_H U c}\right)^{1/2},$$

where $L_{\nu}$ is the specific luminosity per unit frequency $\nu$, $h$ is the Planck constant, and $c$ the speed of light. The integral is carried out from the Lyman limit to the largest frequency on the rest-frame specific flux $f_\nu = L_{\nu}/(4\pi d^2)$. For the integral, we will use an average of two spectral energy distributions (SEDs) described by Mathews & Ferland (1987) and Laor et al. (1997). This assumption will be further discussed in Section 4.1. We can estimate $r_{\text{BLR}}$ if we have a reasonable estimate of the product $n_H U$ (Padovani & Raffanelli 1988; Padovani et al. 1990; Negrete 2011; Negrete et al. 2012). Recently, Negrete et al. (2012), hereafter Paper I, derived $n_H$ and $U$ for two high Eddington ratio sources that at low and moderate $L$ show the typical spectra of narrow-line Seyfert 1s (NLSy1). These findings cannot be easily generalized; however, we show in the following that the product $n_H U$ can still be estimated from a set of diagnostic ratios.

2.1. Emission Line Ratios

Emission line ratios such as $\text{C}\text{\textsc{iv}}\lambda 1549/\text{Si}\text{\textsc{iii}}\lambda 1892$ and $\text{Al}\text{\textsc{iii}}\lambda 1860/\text{Si}\text{\textsc{iii}}\lambda 1892$ are important diagnostics for ranges of density that depend on their transition probabilities (e.g., Feldman et al. 1992). Emission lines originating from forbidden or semi-forbidden transitions become collisionally quenched above the critical density and hence are weaker than lines for which collisional effects are negligible. $\text{C}\text{\textsc{iii}}\lambda 1909/\text{Si}\text{\textsc{iii}}\lambda 1892$ is suitable as a diagnostic when $n_H \lesssim 10^{11} \text{ cm}^{-3}$. The $\text{Al}\text{\textsc{iii}}\lambda 1860/\text{Si}\text{\textsc{iii}}\lambda 1892$ ratio is well suited over the density range $10^{11} - 10^{13} \text{ cm}^{-3}$ (Paper I; Marziani et al. 2011). The ratios $\text{Si}\text{\textsc{iii}}\lambda 1814/\text{Si}\text{\textsc{iii}}\lambda 1892$ and $\text{Si}\text{\textsc{iv}}\lambda 1397/\text{Si}\text{\textsc{iii}}\lambda 1892$ are independent of metallicity and sensitive to ionization. The ratio $\text{Si}\text{\textsc{iv}}\lambda 1397/\text{C}\text{\textsc{iv}}\lambda 1549$ is mainly sensitive to metallicity. Measuring $\text{Si}\text{\textsc{ii}}\lambda 1814$ is a challenge in most spectra because of its weakness. Emission line ratios involving $\text{Si}\text{\textsc{ii}}\lambda 1814$ are therefore subject to large uncertainty and poorly constrain physical conditions. We do not use ratios involving this line. $\text{Si}\text{\textsc{iv}}\lambda 1397$ is a stronger line but severe blending with $\text{O}\text{\textsc{iv}}\lambda 1402$ hampers its use. In the extreme sources considered in Paper I the high inferred broad component (BC) density led us to expect an insignificant $\text{O}\text{\textsc{iv}}\lambda 1402$ contribution. However, this might not be true for a more general population of quasars (Wills & Netzer 1979).

We exclude the $\text{Si}\text{\textsc{iv}}\lambda 1397 + \text{O}\text{\textsc{iv}}\lambda 1402$ blend and restrict our analysis to three diagnostic ratios involving the four remaining strongest metal lines in the spectra: (1) $\text{C}\text{\textsc{iii}}\lambda 1909/\text{Si}\text{\textsc{iii}}\lambda 1892$, which is important because several sources show large $\text{C}\text{\textsc{iii}}\lambda 1909$ equivalent widths (unlike sources included in Paper I), (2) $\text{Al}\text{\textsc{iii}}\lambda 1860/\text{Si}\text{\textsc{iii}}\lambda 1892$, which is sensitive to $n_H$ and believed to reflect the densest regions which are most optically thick to the ionizing continuum, and (3) $\text{C}\text{\textsc{iv}}\lambda 1549/\text{Si}\text{\textsc{iii}}\lambda 1892$ as a marker of ionization level. A quantitative interpretation of these diagnostic ratios requires supporting photoionization simulations. CLOUDY simulations (Ferland et al. 2013) at fixed $n_H$ and $U$ values allow us to study how these parameters influence the diagnostic ratios we have adopted. Our simulations span the density range $7.00 \leq \log n_H \leq 14.00$ and $-4.50 \leq \log U \leq 0.00$ in intervals of 0.25 dex assuming plane-parallel geometry, solar metallicity, column density $10^{23} \text{ cm}^{-2}$ as well as a “standard” quasar continuum as parameterized by Mathews & Ferland (1987). Further details are given in Paper I. Sources in Paper I show weak $\text{C}\text{\textsc{iii}}\lambda 1909$ emission (relative to $\text{Si}\text{\textsc{iii}}\lambda 1892$) which simplifies interpretation of the emission-line spectrum. In those cases computation of constant value contours for the diagnostic ratios in the $U$ versus $n_H$ plane show convergence toward a low-ionization plus high-density range. In the case of the sources considered here, we show that $\text{Al}\text{\textsc{iii}}\lambda 1860/\text{Si}\text{\textsc{iii}}\lambda 1892$ and $\text{C}\text{\textsc{iv}}\lambda 1549/\text{Si}\text{\textsc{iii}}\lambda 1892$ along with any other ratio not involving $\text{C}\text{\textsc{iii}}\lambda 1909$ converge toward a low-ionization, high-$n_H$ region while ratios involving $\text{C}\text{\textsc{iii}}\lambda 1909$ converge to a higher ionization, low-$n_H$ zone (Section 4).

In the photoionization computations with CLOUDY, we have made several simplifying assumptions. The main one consists in deriving a single value of $r_{\text{BLR}}$ from fixed physical conditions. It is known that the BLR is not a shell nor a sequence of nested shells; however, a gradient of ionization is indicated by the shorter reverberation time responses of lines coming from ions of higher ionization potential (e.g., Peterson & Wandel 1999; Netzer 2008). The $r_{\text{BLR}}$ values derived here are probably biased toward the inner radius of the BLR. This is likely to be true for both our method and the RM because gas close to the continuum source responds more strongly to the incoming ionizing radiation. The $\text{Al}\text{\textsc{iii}}\lambda 1860, \text{Si}\text{\textsc{iii}}\lambda 1892, \text{C}\text{\textsc{iv}}\lambda 1549$ lines are all emitted in the fully ionized zone of emitting gas clouds or slabs (Paper I), so that they are sensitive to the ionizing photon flux which is exactly the product $n_H U$. A more realistic approach would be to consider a model that allows gas density $n_H$, column density $N_e$, and ionization parameter $U$, to be functions of $r$ (Devereux 2013; Devereux & Heaton 2013). As pointed out by Devereux (2013) the $r_{\text{BLR}}$ derived from RM is an abstraction that may not have a clear structural counterpart, and the RM $r_{\text{BLR}}$ can indeed be lower than an emissivity weighted average if the geometry of the BLR is thick (Netzer 1990). Nonetheless, RM $r_{\text{BLR}}$ has been considered as the best approximation available for the “virial radius” of the BLR and widely employed as such (e.g., Dultzin-Hacyan et al. 2006; Marziani & Sulentic 2012; Shen 2013, and references therein). Our approach is probably good enough to provide an estimate of the “virial radius” equivalent to the one based on RM. In addition, in Paper I we show that our method allows us to solve for $n_H, U$ and metal content in extreme NLSy1 sources that are $\approx 10\%$ of all quasars.

2.2. Extraction of the Broad Component

Step 1 of our method involves isolation of the BC in the selected emission lines. The BC is believed to be associated, at least in part, with the region predominantly emitting low-ionization lines (LILs) such as Mg II λ2800, Fe II, some of the Balmer lines, Si II λ1814, O I λ1304, Ca II λ8579, as well as intermediate ionization lines such as C III λ1909, Al III λ1860, and Si III λ1892 (Baldwin et al. 2004; Matsuoka et al. 2008;
Figure 1. Multicomponent fits for the 13 objects of our sample. The upper abscissa is rest-frame wavelength in Å, the lower abscissa is in radial velocity units, and the ordinate is specific flux per unit wavelength in arbitrary units. Panels under the fits are the residuals. The vertical long dashed line is the rest frame for (left) C\textsc{iv} λ1549, (middle) C\textsc{iii} λ1909, and (right) Hβ. The short purple dashed line is the fit to the whole spectrum. Black lines are the broad central components. Green lines represent the Fe\textsc{ii} template emission. The red lines are the VBC. The dashed gray lines are narrow components. The blue line in C\textsc{iv} λ1549 corresponds to the blue component. The solid gray lines in Hβ and C\textsc{iv} λ1549 represent the contribution of various underlying weaker emission lines. The orange line in the λ1900 Å blend is the Fe\textsc{ii} template. In the panels of the residuals, the thin red lines are absorption lines considered in the fits.

(A color version of this figure is available in the online journal.)

Marziani et al. 2010; Negrete et al. 2012). A BC is present in the overwhelming majority of Seyfert 1 and Type 1 quasar spectra. In order to isolate this component in UV lines, we use the Hβ BC to define a BC profile shift and width. We take advantage of the fact that the BC is the dominant component in all LILs if FWHM(Hβ) \( \lesssim \) 4000 km s\(^{-1}\) (Population A; Zamfir et al. 2010). We will use the definition of Population A (with an FWHM(BC) \( \lesssim \) 4000 km s\(^{-1}\) and Lorentzian BC profile) and Population B (with a FWHM(BC) > 4000 km s\(^{-1}\) and Gaussian BC profile) objects as well as the Eigenvector 1 (E1) parameter space described in Paper I and Sulentic et al. (2000a). In Population A sources C\textsc{iv} λ1549 is often dominated by blueshifted emission probably associated with a high-ionization outflow (Richards et al. 2002; Sulentic et al. 2007). In order to extract BC C\textsc{iv} λ1549, we assume that the broad profile of C\textsc{iv} λ1549 can be described as the sum of the BC (assumed FWHM equal or larger than FWHM Hβ) + a blueshifted component (Marziani et al. 1996, 2010; Leighly 2000). This approach is further supported by recent work indicating that virial and outflow motions can coexist in quasars (Richards et al. 2011; Wang et al. 2011). For broader (Population B) sources Hβ can be modeled as the sum of BC and redshifted very broad components (VBC; FWHM \( \sim \) 10,000 km s\(^{-1}\); as in the spectrum of PG0052+251 shown in Figure 1). For both populations, we
fit $\text{C} III \lambda 1909$ with the same components of H$\beta$. In the case of Si$\text{II} \lambda 1892$, Al$\text{III} \lambda 1860$, and Si$\text{II} \lambda 1814$, we fit a single BC. The sum of the three components (broad, blueshifted, very broad) reproduce the line profiles of the strongest lines in low-$z$ quasars (Sulentic et al. 2000b; Marziani et al. 2010). The relative intensity is different in the various line components but shifts and widths are roughly consistent for all lines. More details are given by Marziani et al. (2010) where line component trends along the E1 sequence are shown.

In practice, we apply a multicomponent profile decomposition using IRAF task specfit in order to extract the broad-line component (Marziani et al. 2010): (1) a relatively unshifted, symmetric BC representative gas whose broadening is assumed to arise in a virial velocity field. Our aim is to isolate the BC from (2) a blueshifted component associated with outflow or wind emission and (3) a VBC whose strength relative to the BC is set by an inflection observed in the H$\beta$ profile.

3. THE SAMPLE OF SOURCES WITH $r_{\text{BLR}}$

OBTAINED BY REVERBERATION

Reverberated sources allow the product $n_{\text{H}} U$ to be independently estimated from $r_{\text{BLR}}$ and the source luminosity by inverting Equation (3) or, almost equivalently, $r_{\text{BLR}}$ derived from photoionization consideration can be directly compared to $c\tau$. We selected 13 of 35 active galactic nuclei (AGNs) with reverberation data (Peterson et al. 2004, hereafter P04) showing high enough signal-to-noise ratio in the rest-frame range 1400–2000 Å to allow accurate decomposition of $\text{C} III \lambda 1909$, Si$\text{II} \lambda 1892$, Al$\text{III} \lambda 1860$, and $\text{C} IV \lambda 1549$. We extracted UV spectra from the Hubble Space Telescope archive and carried out data reduction using standard IRAF tasks. Optical spectra were taken from Marziani et al. (2003). Data were corrected for Galactic extinction. Table 1 presents the sample with IDs given in Column 1 and other columns described below. The redshift of this sample is $z < 0.24$, but the luminosity range is relatively
large (\(\lambda L_\lambda(5100) \sim 10^{43} - 10^{45} \) erg s\(^{-1}\)) and almost uniformly covered.

4. RESULTS

Figure 1 shows the spectra of Population A and Population B objects; see Column 2 of Table 1. Fits to Population A sources yield line intensities of (1) \(\text{C}^4 \lambda 1549\) BC + narrow component (NC) + blueshifted component; (2) the 1900 Å blend that includes \(\text{C}^3 \lambda 1909\) BC, \(\text{Si}^3 \lambda 1892\) BC, \(\text{Al}^3 \lambda 1860\) BC, and \(\text{Si}^2 \lambda 1814\) BC; and (3) \(\text{H}\beta\) BC. Narrow components are fitted whenever clearly visible. For Population B sources, the fits yield line intensities of (1) \(\text{C}^4 \lambda 1549\) BC + NC + blueshifted + VBC; (2) 1900 Å blend that includes \(\text{C}^3 \lambda 1909\) BC + VBC, \(\text{Si}^3 \lambda 1892\) BC, \(\text{Al}^3 \lambda 1860\) BC, and \(\text{Si}^2 \lambda 1814\) BC; and (3) \(\text{H}\beta\) BC + NC + VBC. In Table 1, Column 3 lists the rest-frame specific continuum flux at 1700 Å, Columns 4–7 are the rest-frame line flux of the BCs of \(\text{C}^4 \lambda 1549\), \(\text{Al}^3 \lambda 1860\), \(\text{Si}^3 \lambda 1892\), and \(\text{C}^3 \lambda 1909\), Column 8 is the FWHM of the \(\text{H}\beta\) BC, Column 9 is the FWHM of \(\text{Si}^3 \lambda 1892\), \(\text{Al}^3 \lambda 1860\), and of the \(\text{C}^4 \lambda 1549\) BC, Column 10 is the dispersion in the FWHM of the BCs. Figure 1 indicates that a BC whose width is consistent with \(\text{H}\beta\) can be straightforwardly extracted from the \(\text{Al}^3 \lambda 1860\) and \(\text{Si}^3 \lambda 1892\) lines. The same approach yields also the BC of \(\text{C}^4 \lambda 1549\).

Armed with line intensities of the BCs, we can compute line ratios \(\text{Al}^3 \lambda 1860/\text{Si}^3 \lambda 1892\), \(\text{C}^4 \lambda 1549/\text{Al}^3 \lambda 1860\) (or \(\text{Si}^3 \lambda 1892\)), and \(\text{C}^3 \lambda 1909/\text{Si}^3 \lambda 1892\). These values allow us to draw isopleths, i.e., curves representing measured values of these ratios in the \(n_H\) and \(U\) plane. The left panels of Figure 2 show the isocontour maps based on line ratios for \(\text{Si}^3 \lambda 1892\), \(\text{Al}^3 \lambda 1860\), and \(\text{C}^4 \lambda 1549\) emission lines. The right panels show isocontours maps based on line ratios for \(\text{C}^3 \lambda 1909\), \(\text{Si}^3 \lambda 1892\), and \(\text{C}^4 \lambda 1549\). The crossing points...
Figure 1. (Continued)
Table 1
Measured Quantities

| Object      | Population Type | $f_x$ (1700 Å) Å$^{-1}$ | C iv λ1549 (4) | Al iii λ1860 (5) | Si iii λ1892 (6) | C iii λ1909 (7) | Hβ (8) | UV (9) | σ (10) |
|-------------|-----------------|--------------------------|----------------|-----------------|-----------------|----------------|--------|-------|--------|
| AKN120      | B               | 8.1 ± 0.5                | 828.8±4.1     | 4.7±2.6         | 13.0±1.2        | 13.2±0.6       | 5480   | 4990  | 420    |
| Fairall 9   | B               | 3.6 ± 0.4                | 25.3±2.5      | 1.4±0.4         | 4.5±0.5         | 5.3±0.5        | 4540   | 4550  | 50     |
| MRK 335     | A               | 7.1 ± 0.7                | 54.8±5.5      | 1.4±0.4         | 4.2±0.5         | 10.6±1.1       | 1960   | 1870  | 200    |
| MRK 509     | A               | 8.9 ± 0.6                | 116.5±5.3     | 5.1±1.6         | 12.5±0.9        | 20.6±1.4       | 3390   | 3290  | 300    |
| NGC 3516    | A               | 4.7 ± 0.2                | 49.1±2.4      | 2.3±0.6         | 7.5±0.5         | 7.4±0.4        | 6530   | 5270  | 700    |
| NGC 3783    | A               | 10.9 ± 0.1               | 106.9±4.1     | 2.5±0.9         | 5.9±1.3         | 17.3±0.5       | 2870   | 2860  | 100    |
| NGC 5548    | A               | 3.1 ± 0.1                | 51.1±2.4      | 1.6±0.3         | 4.3±0.2         | 7.0±0.2        | 5820   | 5390  | 330    |
| NGC 7469    | A               | 4.7 ± 0.4                | 57.0±1.9      | 4.2±0.8         | 7.8±0.7         | 12.7±0.5       | 2850   | 3090  | 210    |
| PG 0052+251 | B               | 2.4 ± 0.1                | 15.0±0.5      | 0.6±0.3         | 2.0±0.3         | 2.7±0.2        | 5340   | 5240  | 530    |
| PG 0953+414 | A               | 1.9 ± 0.1                | 16.8±0.4      | 1.0±0.1         | 1.0±0.3         | 2.8±0.2        | 3390   | 3520  | 210    |
| PG 1211+143 | B               | 2.9 ± 0.1                | 25.6±0.8      | 0.6±0.3         | 1.6±0.2         | 3.9±0.2        | 2440   | 2350  | 280    |
| PG 1307+685 | B               | 1.6 ± 0.1                | 111.8±2.4     | 3.4±1.2         | 10.8±2.3        | 17.7±0.9       | 5290   | 4970  | 330    |
| PG 1411+442 | A               | 1.5 ± 0.1                | 11.9±0.5      | 0.4±0.1         | 1.2±0.1         | 3.4±0.1        | 2540   | 2270  | 220    |

Notes.

a Rest-frame line flux of C iv λ1909, Si iii λ1892, Al iii λ1860, and of the C iv λ1549 BC in units of 10$^{-13}$ erg s$^{-1}$ cm$^{-2}$.

b Rest-frame FWHM of the Hβ BC. UV is for Si iii λ1892, Al iii λ1860, and of the C iv λ1549 BC in units of km s$^{-1}$.

c As defined in Paper I and Sulentic et al. (2000a).

d Rest-frame specific continuum flux at 1700 Å in units of 10$^{-14}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$.

Table 2
Derived Products

| Object Name | $n_HU$ | $n_{BLR}$ |
|-------------|--------|-----------|
| (1)         | c · τ  | AI/Si m  | C m/Si m  |
|             |        | m         | m         | Corr.     |
|             |        | m         | m         | m         | Corr.     | c · τ  | AI/Si m  | C m/Si m  |
|             |        | m         | m         | m         | m         | (6)    | (7)    | (8)    | (9)    |
| AKN 120     | 9.86   | 0.11      | 9.70      | 0.22      | 8.17      | 0.07      | 10.44   | 0.36   |
| Fairall 9   | 10.55  | 0.19      | 9.70      | 0.10      | 7.99      | 0.02      | 9.92    | 0.12   |
| MRK 335     | 10.39  | 0.20      | 9.44      | 0.14      | 7.91      | 0.08      | 9.68    | 0.15   |
| MRK 509     | 10.34  | 0.07      | 9.90      | 0.11      | 8.09      | 0.07      | 10.21   | 0.16   |
| NGC 5516    | 10.08  | 0.01      | 9.60      | 0.07      | 8.20      | 0.02      | 10.20   | 0.19   |
| NGC 3783    | 10.11  | 0.24      | 10.15     | 0.07      | 8.07      | 0.26      | 9.77    | 0.19   |
| NGC 5548    | 9.58   | 0.03      | 9.93      | 0.12      | 8.30      | 0.03      | 10.15   | 0.19   |
| NGC 7469    | 10.91  | 0.14      | 9.83      | 0.08      | 7.90      | 0.05      | 10.41   | 0.17   |
| PG 0052+251 | 9.94   | 0.21      | 9.64      | 0.16      | 8.07      | 0.05      | 9.81    | 0.31   |
| PG 0953+414 | 9.77   | 0.12      | 10.49     | 0.24      | 8.24      | 0.28      | 17.59   | 0.17   |
| PG 1211+143 | 9.45   | 0.32      | 10.00     | 0.17      | 8.17      | 0.23      | 9.95    | 0.35   |
| PG 1307+685 | 9.63   | 0.25      | 9.77      | 0.22      | 8.17      | 0.07      | 9.76    | 0.35   |
| PG 1411+442 | 9.01   | 0.35      | 9.87      | 0.22      | 7.53      | 0.21      | 9.41    | 0.30   |

Notes. a c · τ is derived from RM data. The AI/Si m ratio represents the high-density solution, while the C m/Si m ratio is the low-density solution (see Section 4). Corr. is the correction due systematic effects (see Section 4.1).
Figure 2. Identification of the "solutions" in the plane \((n_H, U)\). Abscissa is \(n_H\) in \(\text{cm}^{-3}\), ordinate is the ionization parameter, both in logarithm scale. Left panels are the high-density solution. Right panels are the low-density solution. The point where the isocontours cross determines the values of \(\log n_H + \log U\). The width of the isocontours are 1\(\sigma\) confidence.

(A color version of this figure is available in the online journal.)
gas that can also emit Si \( \text{iii} \) \( \lambda \) 1892, C \( \text{iv} \) \( \lambda \) 1549, and other lines. All contribute to the BC line profile since the emitting region is unresolved. Even if C \( \text{iii} \) \( \lambda \) 1909 \( \approx \) Si \( \text{iii} \) \( \lambda \) 1892, it is possible to predict a correction to the line fluxes and compute ratios that are meant to be free of the low-density gas emission (Negrete 2011; Marziani et al. 2011). If C \( \text{iii} \) \( \lambda \) 1909 \( \gtrsim \) Si \( \text{iii} \) \( \lambda \) 1892, this approach is not possible. Figure 1 shows that C \( \text{iii} \) \( \lambda \) 1909 is prominent in all of our sources. From the crossing points
between Al $\text{III} \lambda 1860$/Si $\text{III} \lambda 1892$ and C $\text{IV} \lambda 1549$/Si $\text{III} \lambda 1892$ on the one hand, and between C $\text{IV} \lambda 1549$/Si $\text{III} \lambda 1892$ and C $\text{III} \lambda 1909$/Si $\text{III} \lambda 1892$ on the other, we derive two mutually exclusive solutions.

In Figure 2, we show isopleth diagrams in the log $U$ versus log $n_H$ plane. In the right panels of Figure 2 we show the solution for a low-density emitting region, involving the C $\text{III} \lambda 1909$/Si $\text{III} \lambda 1892$ ratio. In the left panels, we present the high-density
emitting region solution that includes the $\text{Al}^\text{iii} \lambda 1860/\text{Si}^\text{iii} \lambda 1892$ ratio. Table 2 compares values obtained from the $\text{Al}^\text{iii} \lambda 1860/\text{Si}^\text{iii} \lambda 1892$ and $\text{C}^\text{iii} \lambda 1909/\text{Si}^\text{iii} \lambda 1892$ solution. The $\text{Al}^\text{iii} \lambda 1860/\text{Si}^\text{iii} \lambda 1892$ solution closely corresponds to the one derived from RM extracting the product $n_H U$ from Equation (3). The average $\log n_H U$ is different by only 0.1 dex in the two cases. The $\text{Al}^\text{iii} \lambda 1860/\text{Si}^\text{iii} \lambda 1892$ values tightly cluster around the average (9.86) with a dispersion.
of just 0.23 dex, not much larger than the typical uncertainty in individual log n_HU measures. The distribution of log n_HU from the C III] λ1909/Si III] λ1892 is significantly offset, with average ≈ 8.0.

We can therefore draw two conclusions: (1) the C III] λ1909/Si III] λ1892 ratio is not representative of gas responding to the continuum changes. As mentioned, the C III] λ1909 emitting gas must be in a lower density region whose extent and location is, at present, a matter of guesswork (conceivable scenario may involve low-density tails trailing dense clouds, Maiolino et al. 2010, although a larger distance of the C III] λ1909 emitting gas seems more likely, as inferred below); (2) the high-density solution derived from Al III λ1860/Si III] λ1892 is more representative of the reverberating gas. The uncorrected Al III λ1860/Si III] λ1892 solution offers a reasonable estimate of the n_HU value derived from RM. The n_HU(RM) and Al III λ1860/Si III] λ1892 n_HU solutions are uncorrelated. The dispersion for n_HU(RM) values is significantly larger indicating however that there could be a dependence between n_HU estimates and additional parameters.

4.1. Comparison between r_BLR Determinations

As mentioned, the RM sample has the advantage that r_BLR is independently known from reverberation. The n_HU and r_BLR values are related rewriting Equation (3) as Equation (4) of Paper I:

\[
    r_{BLR} \approx 93 \left[ \frac{f_{\lambda_0} \cdot \bar{Q}_H}{n_H U_{10}} \right]^{\frac{1}{2}} \zeta(0.3, 0.7) \Delta \text{lt - day},
\]

where \( \lambda_0 = 1700 \ \AA \), \( f_{\lambda_0} \) is the specific rest-frame flux (measured on the spectra) in units of \( 10^{-15} \ \text{erg} \ \text{s}^{-1} \ \text{cm}^{-2} \ \text{\AA}^{-1} \), the product \( n_H U_{10} \) is normalized to \( 10^{10} \ \text{cm}^{-3} \), and \( r_{BLR} \) is now expressed in units of lt-day. Note that \( \int_{\lambda_{0}}^{\lambda_{c}} f_{\lambda} d\lambda = f_{\lambda_0} \cdot \bar{Q}_H \) with \( \bar{Q}_H = \int_{0}^{\lambda_c} S_3 \lambda d\lambda \), where \( \bar{Q}_H \) depends only on the shape of the ionizing continuum for a given specific flux, and the integral is carried out from the Lyman limit to the shortest wavelengths. \( \zeta \) is an interpolation function for radial comoving distance as a function of redshift (given by Sulem et al. 2006) with \( \Omega_M = 0.3 \) and \( \Omega_{\Lambda} = 0.7 \). We use the SEDs \( S_3 \) by Mathews & Ferland (1987) and by Laor et al. (1997) that have been conveniently parameterized as a set of broken power laws. \( Q_H \) is \( \approx 0.00963 \ \text{cm} \ \text{\AA} \) and \( \approx 0.02181 \) in the case of the Laor et al. (1997) and Mathews & Ferland (1987) continuum, respectively. We use an average \( S_3 \) value, since the derived \( n_H U \) through the photoionization maps is not sensitive to the two different shapes to a first approximation.5

Using Equation (4) to compute \( r_{BLR} \) for the low- and high-ionization solutions, the differences in \( r_{BLR} \) between the two cases confirm that the BLR is stratified, with C III] λ1909 likely emitted at a much larger distance (as indicated in Columns 7 and 8 of Table 2 and by reverberation studies; see also the recent analysis of NGC 5548 by Kollatschny & Zetzl 2013). The low-density BLR zone is therefore not responding to continuum changes on the same timescale of \( H\beta \). Hence, the \( r_{BLR} \) derived for the high-density region is the one that we shall use for any further comparison with the \( r_{BLR} \) derived from reverberation of the \( H\beta \) emission line. The \( r_{BLR} \) derived from the high-density photoionization solution based on the Al III λ1860/C III] λ1909 ratio will be denoted as \( r_{BLR, II} \) in what follows.

In Figure 3, we display the residuals \( \Delta \log \lambda L_{\lambda} = \log \lambda L_{\lambda} - \log c \tau \) between the distance computed with four different methods and the reverberation based distance. In Figure 3 (upper left), we show the distribution of the \( \Delta \log \lambda L_{\lambda} \) difference between the photoionization and the reverberation distance, as reported in Columns 6 and 7 of Table 2. From this figure, we see that the agreement between log \( r_{BLR, II} \) and log \( c \tau \) is good with an average of \( \Delta \log \lambda L_{\lambda} = 0.07 \pm 0.29 \) dex with a significant scatter. In only two cases (Fairall 9 and NGC 7469), a t-test indicates a significant difference between the two methods.

We use the values of \( \lambda L_{\lambda} \) (5100 Å) and the \( H\beta \) time lags given by Bentz et al. (2009) for the 13 objects of this paper which are included in their sample. We obtain

\[
    \log r_{BLR}(L) \approx -(9.91 \pm 0.34) + (0.61 \pm 0.02) \log \lambda L_{\lambda}(5100 \ \text{Å})
\]

with residuals \(-0.01 \pm 0.20 \) dex (Figure 3, upper right).

For the sample with RM data of \( \approx 50 \) objects, Bentz et al. (2009) derive the equation

\[
    \log r_{BLR}(L) \approx -21.3 + 0.519 \log \lambda L_{\lambda}(5100 \ \text{Å}).
\]

5 Since the Laor et al. (1997) continuum produces fewer ionizing photons, the same value of \( U \) is obtained at a smaller distance. However, the \( n_H U \) values are, to a first approximation, independent on the frequency distribution of the ionizing photons in the two SEDs considered.
Figure 3. Residuals \( \Delta \) between the reverberation based distance and \( r_{BLR} \) with four different methods. Upper left: \( r_{BLR} \) with the photoionization method; upper right: \( r_{BLR} \) with the luminosity correlation defined on the present sample; lower left: \( r_{BLR} \) with the luminosity correlation of Bentz et al. (2009); lower right: \( r_{BLR} \) with the photoionization method after correcting for a systematic effect dependent on the ratio \( W(\text{Al} \, \text{iii} \, \lambda 1860)/W(\text{C} \, \text{iii} \, \lambda 1909) \). The two values in the lower right panel refer to the average and rms excluding/including PG 0953+414.

If we apply this correlation to our sample (Figure 3, lower left), we obtain a residual rms \( \pm 0.20 \) dex but with a significant bias \((-0.09 \) dex) that makes the uncertainty again \( \approx 0.3 \) dex, as also indicated by the full sample of Bentz et al. (2009). Therefore, \( r_{BLR, \Phi} \) estimates show precision and accuracy that are similar to the ones based on the luminosity correlation of Bentz et al. (2009). In our case, the luminosity correlation of Bentz et al. (2009) systematically overpredicts \( r_{BLR} \) by \( \Delta \log r_{BLR} \approx 0.1 \) dex, as shown also in Figure 3 (lower left).

The formal median uncertainty at 1\( \sigma \) confidence level is \( \pm 0.1 \) dex in \( r_{BLR} \) for RM (Figure 3, lower left), and comparable to the photoionization method (Figure 3, upper right). If the RM values are assumed to be the “true” \( r_{BLR} \) values, the photoionization method (in its simplest formulation) yields information that is not accurate in 2 of 13 cases, as mentioned above. Its precision is comparable to the luminosity correlation.

4.2. Analysis of Systematic Differences

Emission line ratios used for the computation of the high-density solution are most likely affected by lower density \( \text{C} \, \text{iii} \, \lambda 1909 \) emission. Therefore, we expect that any
The disagreement between \( n_\text{H} U \) might be influenced by the equivalent widths and the relative strength of the emission lines considered, and especially by the prominence of \( \text{C III} \lambda 1909 \).

Three correlations emerge from the consideration of the residuals \( \Delta \log n_\text{H} U = \log n_\text{H} U(\Phi) - \log n_\text{H} U(\text{RM}) \), where we have again conventionally indicated with \( n_\text{H} U(\Phi) \) the solution based on the \( \text{Al III} \lambda 1860 / \text{Si III} \lambda 1892 \) ratio. The \( n_\text{H} U(\text{RM}) \) is derived from Equation (4) using \( \zeta \) from reverberation. Figure 4 presents comparisons of \( \Delta \log n_\text{H} U \) as a function of luminosity, and the equivalent widths of \( \text{C III} \lambda 1909, \text{Si III} \lambda 1892, \) and \( \text{Al III} \lambda 1860 \). Errors on line intensity (computed considering continuum level uncertainty) are quadratically propagated to compute errors for the diagnostic ratios and hence for the product \( n_\text{H} U \). Best-fit least-squares quadratic solutions are as follows:

\[
\Delta \log n_\text{H} U \approx (1.49 \pm 0.05) \log \lambda L_\lambda (5100 \text{ Å}) - (65.76 \pm 2.39) 
\]

\[
\Delta \log n_\text{H} U \approx (-4.29 \pm 0.45) \log W(\text{C III} \lambda 1909) + (5.73 \pm 0.43) 
\]

\[
\Delta \log n_\text{H} U \approx (-2.98 \pm 0.27) \log W(\text{Si III} \lambda 1892) + (3.28 \pm 0.43) 
\]

\[
\Delta \log n_\text{H} U \approx (-3.00 \pm 0.66) \log W(\text{Al III} \lambda 1860) + (1.98 \pm 0.87). 
\]

The equations of this section yielding a correction for \( n_\text{H} U \) as a function of equivalent widths can be used to recompute \( r_{\text{BLR}} \). This operation would eliminate any bias between \( n_\text{H} U(\Phi) \) and \( n_\text{H} U(\text{RM}) \) estimates but the scatter in the \( r_{\text{BLR}} \) residuals computed after applying a correction would remain large, \( \approx 0.3 \text{ dex} \). A similar scatter is obtained if a correction is defined directly correlating \( \Delta \log r_{\text{BLR}} \) against the equivalent widths of \( \text{C III} \lambda 1909, \text{Si III} \lambda 1892, \) and \( \text{Al III} \lambda 1860 \). It is perhaps not surprising that the scatter is not reduced since equivalent widths are expected to be influenced by several factors affecting the gas physical conditions (i.e., continuum luminosity, covering factor, etc.). We can improve the correction if we use the ratios of line equivalent widths or fluxes, as shown below.

### 4.2.1. Improving the Agreement

The relation between \( \log \zeta \) versus \( r_{\text{BLR}}, \Phi \) (Figure 5, upper panel) is given by

\[
\log \zeta \approx (1.16 \pm 0.07) \log r_{\text{BLR}}, \Phi - (2.74 \pm 0.40). 
\]

The Pearson correlation coefficient is \( R \approx 0.82 \), implying probability \( P \approx 0.003 \) for the correlation to occur by chance. This equation yields an rms \( \approx 0.30 \text{ dex} \), a value similar to the scatter in \( r_{\text{BLR}} \) values obtained through the correlation with luminosity.

In order to obtain an even better correlation, we apply a correction using the equivalent width ratio \( W(\text{Al III} \lambda 1860)/...
an estimate of the $W(\text{Al} \text{III} \lambda 1860)/W(\text{C} \text{III} \lambda 1909)$ ratio rather difficult.

The correlation of $r_{\text{BLR}}$, corrected and $c \tau$ is (Figure 5, lower panel):

$$
\log r_{\text{BLR}, \phi} \approx (0.77 \pm 0.14) \log c \tau + (3.94 \pm 0.75)
$$

with a scatter of $\approx 0.23$ dex and a correlation coefficient of 0.89. The absence of a significant bias in the corrected $r_{\text{BLR}}$, comes from the definition of the correlation on the present sample. However, since $r_{\text{BLR}}$ is computed on an object-by-object basis it is reasonable to assume that no bias will be introduced in different samples. The photoionization method is therefore expected to be also somewhat more accurate than the luminosity correlation.

5. DISCUSSION

The preceding sections showed that the photoionization method used in this paper is yielding physically meaningful values that are consistent with $r_{\text{BLR}}$ derived from RM. Values of $r_{\text{BLR}}$ derived from photoionization arguments are known to be consistent with $c \tau$. A similar method assuming a constant $n_{\text{H}}U$ also provides consistent agreement (Padovani et al. 1990; Padovani & Rafanelli 1988; Wandel et al. 1999; see also Chapter 4 of D’Onofrio et al. 2012). A reassessment of the method of Dibai (1977) based on the luminosity of Balmer line shows agreement with reverberation-derived masses within $\pm 0.3$ dex (Bochkarev & Gaskell 2009).

The agreement between photoionization results and the correlation with luminosity is expected since the diagnostic ratios measure the product $n_{\text{H}}U$ that is the ionizing photo flux. If the correction provided by Equation (12) is valid in general, then the photoionization method can provide a significant improvement in precision for single epoch $r_{\text{BLR}}$, lowering the dispersion around RM-derived $r_{\text{BLR}}$ from more than a factor two (if the luminosity correlation is used) to $\approx 70\%$.

5.1. Influence of Continuum

We adopted a very simplified approach that neglects (1) the diversity in the ionizing continua among sources and (2) the dependence of $n_{\text{H}}U$ on ionizing continuum shape. It is unlikely that, with the chosen simplified approach, a better agreement between photoionization and RM $r_{\text{BLR}}$ estimates can be achieved. First, $r_{\text{BLR}}$ from RM is subject to a significant uncertainty, and shapes of the cross-correlation function are not always regular. Second, a significant part of the scatter is associated with the assumption of an average SED. Using the SEDs of each individual source, and repeating the photoionization simulation array that defines $n_{\text{H}}U$, should lead to a significant improvement. The simplified approach is meant to make the method easily applicable to high-$z$ quasars for which SED data are most often unavailable at present.

5.2. Interpretation of the Empirical Correction

Equation (12) needs to be confirmed by more extended data. It is based on an heterogeneous sample of 12 objects only. Physical properties within the BC are not found to be identical across the E1 sequence. In principle, Equation (12) should be built separating the most populated spectral types along E1. This feat is however beyond the possibilities offered by available data. Given the unclear role of continuum diversity, it is not easy to derive a unique physical interpretation beyond the following
qualitative considerations. Equation (12) indicate that $r_{\text{BLR}}(\Phi)$ for smaller $\text{Al} \, \text{III} \, \lambda 1860/\text{C} \, \text{III} \, \lambda 1909$ ratio sources significantly underpredicts $c_t$, while the agreement is better for relatively large $\text{Al} \, \text{III} \, \lambda 1860/\text{C} \, \text{III} \, \lambda 1909$ ratios. This is consistent with the results of Paper I. Stronger $\text{C} \, \text{III} \, \lambda 1909$ emitters (for example PG 1211+143 and PG 1411+442 of spectral type A1 of the E1) may appreciably respond to continuum changes at a systematically larger distance with respect to the denser, low-ionization gas. This may account for a small fraction of the emitting gas if $\text{C} \, \text{III} \, \lambda 1909/\text{Al} \, \text{III} \, \lambda 1860 \gg 1$.

5.3. Influence of Continuum Variability

The previous results rely on the assumption that we can take an average AGN ionizing continuum. In fact, however, we know that the continuum is variable and in some cases very variable. When the ionizing continuum varies Equation (4) predicts a variation in $r_{\text{BLR}}$. The physical reasons for the variation in $r_{\text{BLR}}$ may be twofold: (1) the ionizing continuum may penetrate further among the BLR clouds and/or (2) the effect of radiation pressure can push the clouds further away. Regardless of the ultimate physical interpretation, we can confront $r_{\text{BLR}}$ derived from RM and from photoionization in different continuum states. We considered the case of NGC 5548 which is a very well monitored object. The lowest and highest value for the flux at 1700 Å were retrieved from the AGN watch Web site.\(^6\) We then calculated $n_H$ and $U$ for the two states. For the lowest value ($0.94 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$), we obtain $\log n_H U = 9.85$, and for the highest value ($4.78 \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$), we obtain $\log n_H U = 10.04$. These products yield a variation from $\log(r_{\text{BLR}}) = 16.26$ to $\log(r_{\text{BLR}}) = 16.52$. The isopleths indicate that the change in $n_H U$ is driven by a change in $U$ that is affecting strongly $\text{C IV} \, \lambda 1549$, remaining the $n_H$ value almost constant. The $r_{\text{BLR}}$ change goes in the same sense of the ones derived from the AGN watch and reported by Bentz et al. (2009) although $c_t$ seems to be affected more strongly by continuum changes, with a three-fold increase in $r_{\text{BLR}}$ for a three-fold increase in continuum.

5.4. $M_{\text{BH}}$ Computation

Knowing $r_{\text{BLR}}$ enables us to estimate the black hole mass ($M_{\text{BH}}$) assuming virial motions of the gas using

$$M_{\text{BH}} = f \frac{\Delta v^2 r_{\text{BLR}}}{G} = \frac{3}{4G} f_{0.75} \text{FWHM} r_{\text{BLR}},$$

(14)

\(^6\) http://www.astronomy.ohio-state.edu/~agnwatch/n5548/spectra
where \( G \) is the gravitational constant. If \( \Delta v = \text{FWHM of a line} \), the geometry factor \( f = \sqrt{3}/2 \) if the orbits of the BLR clouds are randomly oriented. We use \( f_{BLR} = 1.4 \) (Graham et al. 2011).

As mentioned earlier, the BC of \( \text{C\text{ IV}} \lambda 1549 \), \( \text{Si\text{ III}} \lambda 1892 \), and \( \text{Al\text{ III}} \lambda 1860 \) isolates emission that is believed to come from the same low-ionization region emitting the core of \( \text{H}\beta \), and LILs like \( \text{Mg\text{ II}} \lambda 2800 \), \( \text{Fe\text{ II}} \), \( \text{Si\text{ II}} \lambda 1814 \). It is believed that the BC broadening is due to Keplerian motions since the BC does not present strong asymmetries or centroid shifts with respect to the rest frame. Therefore, use of \( \text{Al\text{ III}} \lambda 1860 \) or \( \text{Si\text{ III}} \lambda 1892 \) BC FWHM derived from the multicomponent fits should be regarded as “safe” as the use FWHM(\( H\beta \)) for obtaining a BLR velocity dispersion indicator. This is not true for the blueshifted component and for the VBC. The \( \text{C\text{ IV}} \lambda 1549 \) blueshifted asymmetry found in many quasars is read as the signature of an outflowing wind (Marziani & Sulentic 2012, and references therein). The large shift of the VBC similarly suggests that non-virial motions play a significant role. The low-ionization part of the BLR that should emit the BC we isolated is still prominent in high-luminosity quasars (Marziani et al. 2009), and this makes the photoionization method discussed in this paper straightforwardly applicable to high-redshift quasars (C. A. Negrete et al. 2013, in preparation). The RM sample offered the possibility to check that the BC FWHM of \( \text{Al\text{ III}} \lambda 1860 \) and \( \text{Si\text{ III}} \lambda 1892 \) is indeed consistent with the BC FWHM of \( H\beta \) (last columns of Table 1). \( \text{Al\text{ III}} \lambda 1860 \), \( \text{Si\text{ III}} \lambda 1892 \) may offer the most consistent FWHM estimators. \( \text{C\text{ IV}} \lambda 1549 \) should be avoided unless a detailed analysis as in Figure 1 can be carried out since it is often blueward asymmetric. \( \text{C\text{ IV}} \lambda 1909 \) may be significantly narrower than \( \text{Si\text{ III}} \lambda 1892 \) and \( \text{Al\text{ III}} \lambda 1860 \), and, as stressed, is not associated with the high-density solution. Therefore also \( \text{C\text{ IV}} \lambda 1909 \) FWHM should be avoided as a virial broadening estimator.

Figure 6 compares the mass computed from Equation (14) using \( r_{BLR} \) estimated from RM, our photoionization method, and two luminosity correlations. As seen for \( r_{BLR} \) the agreement is improved if systematic effects are corrected with the \( W(\text{Al\text{ III}} \lambda 1860)/W(\text{C\text{ IV}} \lambda 1909) \) relation. The scatter and the bias in the \( \text{C\text{ IV}} \lambda 1549 \) luminosity-derived masses of Shen et al. (2011) is probably related to significant broadening of the \( \text{C\text{ IV}} \) line by non-virial motion (e.g., Netzer et al. 2007; Sulentic et al. 2007). In contrast, the Vestergaard & Peterson (2006) relationship provides more accurate values since it has been calibrated on a data set that includes the sources considered in this paper.

5.5. Further Considerations

The assumption of RM values as the true values is a working hypothesis. RM based masses may be accurate to within a factor \( \approx 3 \) (Vestergaard & Peterson 2006), if they are compared to the masses derived from the \( M_{BH} \)–bulge velocity dispersion. However, the origin of this dispersion may include statistical (i.e., orientation) and systematic effects (as the geometry factor \( f \)) that do not enter in the \( r_{BLR} \) measures. The determination of \( r_{BLR} \) on an individual source basis allows an immediate comparison with RM values and to independently consider other systematic and statistical effects involved in the \( M_{BH} \) estimate. An average \( f \) value for all AGNs is unlikely to be appropriate (as derived from the scaling with the \( M_{BH} \)–bulge velocity dispersion) since the line profiles of the strongest emission lines suggest structural and dynamical changes along the so-called Eigenvector 1 sequence. Therefore, the photoionization method has the potential advantage (unlike methods based on \( M_{BH} \)–FWHM–luminosity correlation) to “reproduce” RM \( r_{BLR} \) values at high redshift, leaving the possibility to consider \( f \) and orientation effects on an individual basis.

6. CONCLUSION

In summary, we are able to estimate BLR distances using an independent photoionization method that yields results consistent with reverberation values for 13 sources in common (Bentz et al. 2009). Although we cannot constrain BLR physical conditions as well as we were able to do for extreme Population A sources (Paper I), we are nonetheless able to derive empirical relations that further improve the agreement between photoionization and RM \( r_{BLR} \) determinations. We suggest that the derived \( r_{BLR} \) values can significantly improve black hole mass estimation especially at \( z \geq 2 \) when the intermediate ionization lines are shifted into the wavelength range accessible to optical spectrometers. The width of the broad intermediate ionization lines likely provides a reliable virial estimator leaving the geometry factor \( f \) and poorly understood orientation effects as the main sources of uncertainty.

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