BROAD-LINE REGION PHYSICAL CONDITIONS IN EXTREME POPULATION A QUASARS: A METHOD TO ESTIMATE CENTRAL BLACK HOLE MASS AT HIGH REDSHIFT

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ABSTRACT

We describe a method for estimating physical conditions in the broad-line region (BLR) for a significant subsample of Seyfert 1 nuclei and quasars. Several diagnostic ratios based on intermediate (Al\textsc{iii} $\lambda$1860, Si\textsc{iii} $\lambda$1892) and high (C\textsc{iv} $\lambda$1549, Si\textsc{iv} $\lambda$1397) ionization lines in the UV spectra of quasars are used to constrain density, ionization, and metallicity of the emitting gas. We apply the method to two extreme Population A quasars—the prototypical NLSy1 I Zw 1 and higher z source SDSS J120144.36+011611.6. Under assumptions of spherical symmetry and pure photoionization we infer BLR physical conditions: low ionization (ionization parameter $<10^{-2}$), high density ($10^{12}–10^{13}$ cm$^{-3}$), and significant metal enrichment. Ionization parameter and density can be derived independently for each source with an uncertainty that is less than $\pm0.3$ dex. We use the product of density and ionization parameter to estimate the BLR radius and derive an estimation of the virial black hole mass ($M_{\text{BH}}$). Estimates of $M_{\text{BH}}$ based on the “photoionization” analysis described in this paper are probably more accurate than those derived from the mass–luminosity correlations widely employed to compute black hole masses for high-redshift quasars.

Key words: quasars: general – quasars: individual (I Zw 1, SDSS J120144.36+011611.6)

Online-only material: color figures

1. INTRODUCTION

We lack a simple diagnostic method to estimate physical conditions (density, ionization parameter, metallicity) in the broad-line region (BLR) of quasars. Techniques for estimating electron density and ionization in nebular astrophysics (Osterbrock & Ferland 2006) are not straightforwardly applicable to broad lines in quasars. Reasons include large line widths, line doublets too closely spaced to resolve individual components, and density at least an order of magnitude higher than the critical density assumed for forbidden transitions modeled in spectra of planetary nebulae and H\textsc{ii} regions. The ionization parameter $U$, which represents the dimensionless ratio of the number of ionizing photons and the electron density $n_{e}$ or, equivalently, the total number density of hydrogen $n_{\text{H}}$ ionized and neutral, can be estimated from the intensity ratio of two strong resonance lines arising from different ionic stages of the same element (Davidson & Netzer 1979). It is again not easy to interpret the results in the case of quasars. For example, the ratio C\textsc{iii} $\lambda$1909/C\textsc{iv} $\lambda$1549 may not yield a meaningful value if the relatively low C\textsc{iii} $\lambda$1909 critical density implies that the line is formed at larger radii than C\textsc{iv} $\lambda$1549. Using lines of different ions widens the choice of diagnostic line ratios although additional sources of uncertainty are introduced.

The presence of the strong C\textsc{iii} $\lambda$1909 emission line implies that electron density $n_{e}$ cannot be very high. However, high density ($n_{e} \sim 10^{11}$–$10^{13}$ cm$^{-3}$) is invoked to explain the rich low-ionization spectrum (especially Fe\textsc{ii}) observed in quasars (e.g., Baldwin et al. 2004). Several lines in the UV spectrum of I Zw 1 (prominent Fe\textsc{ii}, relatively strong Al\textsc{iii} $\lambda$1860, and C\textsc{iii} $\lambda$1176) point toward high density at least for the low-ionization line (LIL) emitting zone (Baldwin et al. 1996; Laor et al. 1997b). This low-ionization BLR (LIL BLR) has very similar properties to the O\textsc{i}- and Ca\textsc{ii}-emitting region identified by Matsuoka et al. (2008). The region where these LILs are produced cannot emit much C\textsc{iii} $\lambda$1909 if electron density exceeds $10^{11}$ cm$^{-3}$. But is the C\textsc{iii} $\lambda$1909 line really so strong in most quasars? BLR conditions are certainly complex, and the assumption of a single emitting region cannot explain both LILs and high-ionization lines (HILs; Marziani et al. 2010; Wang et al. 2011, and references therein).

In this paper we report an analysis based on several diagnostic ratios used to constrain density, ionization parameter, and metallicity in the BLR of two sources that are representative of the narrow-line Seyfert 1 (NLSy1) subsample of quasars (Section 2). We use methodological considerations that enable us to deblend and identify the principal lines of the spectra (Section 3.1). Our sources show weak C\textsc{iii} $\lambda$1909 emission (relative to Si\textsc{iii} $\lambda$1892), simplifying interpretation of the emission-line spectrum (Section 3.2). Diagnostic ratios are heuristically defined (Section 4.1) and interpreted through an array of photoionization simulations (Section 4.2). We show that they converge toward well-defined values of ionization and density (Section 5). We also consider the influence of heating sources other than photoionization (Section 6.1). Under the assumption of a pure photoionized gas, the present analysis can be used to determine the product of density and ionization parameter enabling us to estimate the distance of the BLR from the central continuum source ($\rho_{\text{BLR}}$) and the virial black hole mass ($M_{\text{BH}}$, Section 6.2). Finally, in Section 7 we give our conclusions.

1.1. The Eigenvector 1 Parameter Space

Boroson & Green (1992, BG92) identified a series of correlations from principal component analysis (PCA) of the correlation matrix of emission-line measures for a bright low-redshift quasar sample. The sample contained 87 PG quasars with $z \sim 0.5$ (17 of them radio-loud, RL). The first PCA
eigenvector (hereafter E1) identified correlations involving broad Hβ, broad Fe ii, and narrow [O iii] \( \lambda 4959, 5007 \) emission lines. In an effort to clarify the meaning of the E1, Sulentic et al. (2000) searched for a correlation diagram that showed maximal discrimination between the various active galaxy nucleus (AGN) subclases. The best E1 correlation space that we could identify involved measures of (1) equivalent width (EW) of the Fe ii \( \lambda 4570 \) blend (defined as the ratio \( R_{\text{Fe II}} = W(\text{Fe II } \lambda 4570)/W(\text{H}\beta) \)) and (2) FWHM(\( \text{H}\beta \)). These were supplemented with (3) the soft X-ray photon index, \( \Gamma_{\text{soft}} \), and the centroid line shift of high-ionization C iv \( \lambda 1549 \). Figure 7 of Sulentic et al. (2000) shows two-dimensional projections of this four-dimensional E1 (4DE1) space: FWHM(\( \text{H}\beta \)) versus \( R_{\text{Fe II}} \), \( \Gamma_{\text{soft}} \) versus \( R_{\text{Fe II}} \), and FWHM(\( \text{H}\beta \)) versus \( \Gamma_{\text{soft}} \). They supplemented the BG92 RL sample with an additional 18 sources (with comparable signal-to-noise (S/N) spectra) taken from Marziani et al. (1996), who reported \( W(\text{Fe II}) \) measures over the range 4240–5850 Å. The range 4240–5850 Å, Fe ii flux was divided by a factor \( \approx 3.3 \) in order to obtain the flux in the range 4434–4684 Å that was used by BG92 (both works relied on the same Fe ii template based on I Zw 1). Sulentic et al. (2000) separated various subclases of AGNs into two populations: Populations A and B (Pops. A and B) separated at FWHM(\( \text{H}\beta \)) = 4000 km s\(^{-1} \). Physica l drivers for the correlation were discussed in, e.g., Marziani et al. (2003) with black hole mass and Eddington ratio \( L/L_{\text{Edd}} \) (where \( L_{\text{Edd}} = 1.5 \times 10^{38}(M/M_\odot) \)) is the Eddington luminosity) identified as the principal drivers of change along the 4DE1 sequence. Black hole mass increases from Pop. A to Pop. B, while Eddington ratio decreases from Pop. A to Pop. B.

The division into two populations is, at least, useful for highlighting major differences among Type 1 AGNs, although spectral differences among objects within the same population are still noticeable, especially for Pop. A sources (Figure 2 of Sulentic et al. 2002). This is the reason why they also divided the 4DE1 optical plane into bins of \( \Delta \text{FWHM}(\text{H}\beta) = 4000 \) km s\(^{-1} \) and \( \Delta R_{\text{Fe II}} = 0.5 \). Bins A1, A2, A3, and A4 are defined in terms of increasing \( R_{\text{Fe II}} \), while bins B1, B1*, and B1** are defined in terms of increasing FWHM(\( \text{H}\beta \)) (see Figure 1 of Sulentic et al. 2002). Sources belonging to the same spectral type show similar spectroscopic measures and physical parameters (e.g., line profiles and UV line ratios). Systematic changes are minimized within each spectral type so that an individual quasar can be taken as representative of all sources within a given spectral bin. The binning adopted in Sulentic et al. (2002) is valid for low-\( z \) (<0.7) quasars. At higher \( z \) an adjustment must be made since no sources with FWHM(\( \text{H}\beta \)) < 3500 km s\(^{-1} \) are found above redshift \( z \approx 3 \) (Marziani et al. 2009).

2. THE TARGETS

In this study we choose two representative examples of extreme Pop. A objects that show prominent Al iii \( \lambda 1860 \) and weak/absent C iii \( \lambda 1909 \) emission lines. The objects are the low-redshift (\( z = 0.06 \)) NLSy1 prototype I Zw 1 and the much more distant (\( z = 3.23 \)) SDSS J12014+0116 (see the young and highest accreting sources (Sulentic et al. 2000), we might well expect to find more of them at high \( z \). SDSS J12014+0116 is a good example of a high-redshift, high-luminosity analog of I Zw 1 with broader lines (as can be seen in the right panels of Figure 2, where we show the line fits and can identify the broad component (BC) width of each object). In this paper, we shall use the acronym BC for this core or central component only. The spectrum of SDSS J12014+0116 shows lines that have FWHM(BC) \( \approx 4000 \) km s\(^{-1} \), which is much broader than the nominal NLSy1 cutoff of 2000 km s\(^{-1} \) at low redshift. Emission-line ratios (such as Al iii \( \lambda 1860/\text{Si iii} \) \( \lambda 1892 \) that can be derived from Table 2) and hence inferred physical conditions are very close to those inferred for I Zw 1. This extends to other properties such as strong iron emission and a large blue asymmetric/blueshifted component of C iv \( \lambda 1549 \) (extreme Pop. A objects in Sulentic et al. 2007). Thus, the “NLSy1 definition” seems to be luminosity dependent (see also Netzer & Trakhtenbrot 2007; Marziani et al. 2009) in the sense that we can extend this definition to high-luminosity and high-redshift objects by extending the line width limit to 4000 km s\(^{-1} \) and leaving all other properties unchanged (Dultzin et al. 2011).

A search in the Sloan Digital Sky Survey (SDSS) DR7 for quasars in the redshift range where both C iv \( \lambda 1549 \) and the \( \lambda 1900 \) blend are observed at optical wavelengths (2 \( \lesssim z \lesssim 3 \)) yields more than 200 sources (out of 3000 candidates) with spectra resembling I Zw 1 on the basis of Al iii \( \lambda 1860/\text{Si iii} \) \( \lambda 1892 \) intensity ratio. As approximate as these measurements are, they are nonetheless suitable for identifying strong Al iii \( \lambda 1860 \) emitters. SDSS J12014+0116 is a prototype of these strong Al iii \( \lambda 1860 \) emitters selected on the basis of moderate/high S/N.

In summary, at both low and high \( z \), as well as at low and high luminosities, around 10% of quasars are I Zw 1-like (i.e., NLSy1 type) on the basis of their emission-line strengths. Particularly strong Al iii \( \lambda 1860 \) emission is observed in SDSS J12014+0116 with almost the same intensity as Si iii \( \lambda 1892 \). It also shows weak C iii \( \lambda 1909 \) (discussed in Section 3.2.2). In this paper we limit and justify the application of our method to NLSy1s, which compose around 10% of quasars. In a forthcoming paper, we shall address the applicability of our method to broader line quasars of both Pops. A and B.
3. OBSERVATIONS AND DATA ANALYSIS

We retrieve the UV spectrum of I Zw 1 (upper panel of Figure 1), obtained with the Faint Object Spectrograph, from the Hubble Space Telescope archives. This instrument had a spectral resolution of about 1300 over the 1150–8500 Å range. The spectrum covers the range from 1150 to 3000 Å with S/N of ~45 around 1900 Å. The SDSS J12014+0116 spectrum (lower panel of Figure 1) covers the rest-frame range from 1000 to 2100 Å with S/N of ~30 around 1900 Å. This spectrum was taken from the SDSS DR7 site within the Legacy project. The spectroscopy in this project covers a wavelength range from 3800 to 9200 Å with spectral resolution of 1800–2200.

3.1. Methodological Considerations

In order to deblend and identify the principal lines, as well as to extract the core of the broad emission lines, we use the following previous results:

1. As mentioned above, Sulentic et al. (2002) divided Pop. A and B sources into bins according to FWHM(Hβ) and $R_{\text{FeII}}$ measures. In 2010, Zamfir et al. computed median composite Hβ spectra for each of the bins and showed that the broad Hβ profiles in composite spectra of Pop. A sources are best fit by Lorentzian functions. In Pop. B objects, on the other hand, they are best described by Gaussian profiles (see also Marziani et al. 2010). This is an empirical result clearly shown in these works. Our sources are extreme Pop. A objects (bin A3), and thus we shall use Lorentzian profiles to model the BCs.

2. Marziani et al. (2010) analyze six sources (including I Zw 1) representative of the six most populated bins of Pops. A and B. They show that FWHM and profile shape of BCs of Si iii λ1892, Al iii λ1860, and C iv λ1549 are similar to those of Hβ. We do not have an Hβ spectrum for SDSS J12014+0116 since there are no near-IR data for this object. However, for other high-z quasars, there are high-S/N IR spectra (Sulentic et al. 2004) that show NLSy1-like sources (defined in Section 2), with $M_{\text{z}} = -28$ and FWHM(Hβ) as much as 2000 km s$^{-1}$ broader than those with $M_{\text{z}} = -22$. SDSS J12014+0116 shows $M_{\text{z}} = -29.8$ with FWHM ~ 4000 km s$^{-1}$, while for I Zw 1 $M_{\text{z}} = -23.5$ and FWHM ~ 2000 km s$^{-1}$. With larger samples at high redshift (e.g., Marziani et al. 2009) the result that the FWHM(Hβ) can be as high as 4000 km s$^{-1}$ for NLSy1-like objects is confirmed. Following these results, we use a Lorentzian profile with the same width (FWHM ~ 4000 km s$^{-1}$ in SDSS J12014+0116).
and FWHM ~ 2000 km s^{-1} in I Zw 1) for all the BCs of the broad emission lines.

3. HII. CIV λ1549 profiles show significant differences between Pop. A and B sources. In Pop. A the peak of the line is often blueshifted and the profile blue asymmetric. We model this as a strongly blueshifted (≪1000 km s^{-1}) CIV λ1549 BC (hereafter labeled BLUE; Sulentic et al. 2007) plus an unshifted BC analogous to the one seen in Hβ. We assume that the profile of this blueshifted component is Gaussian as discussed in Marziani et al. (2010).

4. In Pop. A objects, low (Si ii λ1814) and intermediate (Al iii λ1860, Si iii λ1982) ionization lines offer the simplification of showing only the BC associated with low-ionization emission (Marziani et al. 2010).

All the above results are taken into account for modeling the lines in this paper.

### 3.2. Measurements

After identifying the emission lines needed for our study, we isolate the broad central component in each of them using spectral decompositions as explained below. We need the line fluxes to obtain n_H and U, the rest-frame specific flux at λ = 1700 Å to compute r_{BLR}, and the FWHM of the BCs to estimate M_{BLR}. We use the specfit IRAF task (Kris 1994), which enables us to fit the continuum, emission, and absorption line components, as well as Fe ii and Fe iii contributions. We work with emission lines in the spectral range 1400–2000 Å that have been studied in great detail in both high- and low-z quasars and where identification of prominent resonance and intercombination lines is well established.

The steps we followed to accomplish identification, deblending, and measurement of lines in each object were the following:

1. **The continuum.** We adopted a single power-law fit to describe it (Figure 1) using the continuum windows around 1700 and 1280 Å (see, e.g., Francis et al. 1991). Fe ii emission in these ranges is weak, leading us to assume that continuum measurement in those windows is reliable enough for our method (within the uncertainties, see Section 3.2.1).

2. **BC line widths and shifts.** We assume that a single value of FWHM (last column of Table 2) is adequate to fit the BCs of all lines. BC shifts of all lines are the same and consistent with the redshift reported in the table. Due to the fact that the C iii λ1909 emission line is mostly emitted in a different region than the rest of the broad lines (see discussion in Section 3.2.2), we do not impose the same restriction on the FWHM of C iii λ1909.

3. **λ1900 blend.** In Table 1 we summarize the properties of the strongest features expected that contribute to the λ1900 blend. Column 1 lists the ion, Column 2 lists rest-frame wavelength, Columns 3 and 4 list the ionization potential and energy levels of the transition, respectively. Column 5 gives the configuration of the levels for the transition. Columns 6 and 7 give the transition probabilities and critical densities, respectively. And in Column 8 we give some notes for each ion. Forbidden lines of Si and C are not expected to be significantly emitted in the BLR and will not be further considered.

Fe ii lines are frequent and strong in the vicinity of C iii λ1909 as seen in the SDSS template quasar spectrum (Vanden Berk et al. 2001). They appear to be strong when Al iii λ1860 is also strong (Hartig & Baldwin 1986). They are included in the photoionization simulations described below (Sigut et al. 2004). Lyα pumping enhances Fe iii λ1914.0 (UV 34; Johansson et al. 2000), and this line can be a major contributor to the blend on the red side of C iii λ1909. The spectrum of I Zw 1 convincingly demonstrates this effect: both C iii λ1909 and Fe iii λ1914 are needed to account for the double-peaked feature at 1910 Å that is too broad to be explained by a single line (Figure 2).7 We adopt the template (option B) of

### Table 1

| Ion  | λ (Å) | X (eV) | EJ - ES (eV) | Transition | A_H (s^{-1}) | n_e (cm^{-3}) | Note |
|------|-------|--------|-------------|------------|--------------|--------------|------|
| Si ii | 1808.00 | 8.15 | 0.000–6.857 | ^2D_{3/2} → ^2P_{1/2} | 2.54 × 10^6 | ... | 1 |
| Si ii | 1816.92 | 8.15 | 0.036–6.859 | ^2D_{5/2} → ^2P_{1/2} | 2.65 × 10^6 | ... | 1 |
| Al iii | 1854.716 | 18.83 | 0.000–6.858 | ^2P_{0} → ^2S_{1/2} | 5.40 × 10^8 | ... | 1 |
| Al iii | 1862.790 | 18.83 | 0.000–6.656 | ^2P_{1/2} → ^2S_{1/2} | 5.33 × 10^8 | ... | 1 |
| [Si iii] | 1882.7 | 16.34 | 0.000–6.585 | ^3P_{2} → ^1S_{0} | 0.012 | 6.4 × 10^4 | 1 | 2 | 3 |
| Si iii | 1892.03 | 16.34 | 0.000–6.553 | ^3P_{1} → ^1S_{0} | 16700 | 2.1 × 10^{11} | 1 | 4 | 5 |
| [C iii] | 1906.7 | 24.38 | 0.000–6.502 | ^3P_{2} → ^1S_{0} | 0.0052 | 7.7 × 10^6 | 1 | 2 | 6 |
| C iii | 1908.734 | 24.38 | 0.000–6.495 | ^3P_{1} → ^1S_{0} | 114 | 1.4 × 10^{10} | 1 | 2 | 4 | 5 |
| Fe iii | 1914.066 | 16.18 | 3.727–10.200 | ^2P_{0} → ^2S_{1/2} | 6.6 × 10^8 | ... | 7 |

Notes. All wavelengths are in vacuum.
(1) Ralchenko, Yu., Kramida, A. E., Reader, J., and NIST ASD Team (2008). NIST Atomic Spectra Database (version 3.1.5). Available at: http://physics.nist.gov/asd3.
(2) Feibelman & Aller (1987).
(3) n_e computed following Shaw & Dufour (1995).
(4) Morton (1991).
(5) Feldman (1992).
(6) Zheng (1988).
(7) Wavelength and A_H from Ekberg (1993), energy levels from Edlén & Swings (1942).
Vestergaard & Wilkes (2001) plus additional Fe\textsc{iii} λ1914, with the same profile as the other BC lines, for modeling Fe\textsc{iii} emission in our sources.

Fe\textsc{ii} emission is not strong in the spectral range we studied, and the UV Fe\textsc{ii} template we adopt is based on a suitable cloudy simulation. Results on the λ1900 blend are not significantly affected by the assumed Fe\textsc{ii} contribution since it appears as a weak pseudo-continuum underlying the blend. We explore maximum and minimum contributions of Fe\textsc{ii} by placing the highest and lowest possible continua, as shown in Figure 1, and as explained below in Section 3.2.1. In Figure 2 we show the contribution of Fe\textsc{ii}. If we increase or decrease this contribution, we will see an intensity variation of the strength of the lines, with Si\textsc{ii} λ1814 being the most affected due its weakness (see error bands in Figure 6). We take into account these strength variations for the error estimations.

Then, for both objects, we sequentially model Fe\textsc{ii} and Fe\textsc{iii} as preliminary steps. We anchor the Fe\textsc{ii} template to the 1785 Å feature in order to normalize it. We continue with the fit of the Si\textsc{ii} λ1814 and Al\textsc{iii} λ1860 emission lines, which are fairly unblended. The main challenge is therefore to deconvolve Si\textsc{iii} λ1892, C\textsc{iii} λ1909, and Fe\textsc{iii} λ1914, noting that we will use only the less blended line, Si\textsc{iii} λ1892, for the eventual computation of diagnostic ratios.

The next step is different for each object. The deblending of Si\textsc{iii} λ1892, C\textsc{iii} λ1909, and Fe\textsc{iii} λ1914 can be easily accomplished in the case of I Zw 1 because the lines are narrow. In the case of SDSS J12014+0116 the peak at λ1910 is consistent with Fe\textsc{ii} λ1914, indicating that Fe\textsc{iii} emission is dominating over C\textsc{iii} λ1909. Thus, we first fit Si\textsc{iii} λ1892 and Fe\textsc{iii} λ1914 to the observed peaks and the remaining part of the blend, as C\textsc{iii} λ1909. We emphasize that in the λ1900 blend, the only two lines that are severely blended are C\textsc{iii} λ1909 and Fe\textsc{iii} λ1914. This is more evident in the case of I Zw 1 because C\textsc{iii} λ1909 and Fe\textsc{iii} have similar intensities. In the case of SDSS J12014+0116, C\textsc{iii} λ1909 is much weaker than Fe\textsc{iii} λ1914 but still blended. We are not interested in the intensity of these two lines, but only in a confirmation that C\textsc{iii} λ1909 is weak with respect to Si\textsc{iii} λ1892. In Figure 3 we show that this is valid even for the highest possible contribution of C\textsc{iii} λ1909. The residuals in Figures 2 and 3 reflect the noise. If we consider 1σ above and below zero, then we say that a line is weak when it is below 1σ. For example, in the lower right panel of Figure 2, C\textsc{iii} λ1909 is below 1σ, while Si\textsc{ii} λ1814 is around 1.5σ.

4. \textit{λ1550 feature}. As in the case of the previous blend, we need to keep in mind the complexity of this feature. In order to fit the HIL C\textsc{iv} λ1549, we have to take into account that it is decomposed into a Lorentzian BC with the same width and shifts of the intermediate-ionization lines plus a blueshifted residual (assumed to be Gaussian in the specfit procedure, discussed in Section 3.1). So, in both objects, we fit first the Fe\textsc{ii} template with the same intensity as in the λ1900 blend. Then we fit the BC, and looking at the residuals, we fit the BLUE component. Finally, we fit the underlying weaker emission lines N\textsc{iv} λ1486, Si\textsc{ii} λ1533, and He\textsc{ii} λ1640, when visible. We assume that the latter line has two components (BC and BLUE) with the same shift and width as C\textsc{iv} λ1549. An equivalent approach has been successfully followed by several authors (Baldwin et al. 1996; Leighly & Moore 2004; Marziani et al. 2010; Wang et al. 2011).

We need to point out that in the case of I Zw 1, we observed a narrow component (NC) with a width of ∼800 km s\(^{-1}\), close to the width of the BCs of the broad lines. The NC of C\textsc{iv} λ1549 is observed in several low-z quasars (also RL) and Seyfert 1 nuclei, as well as in type 2 quasars (Sulentic et al. 2007). Even if the line is collisionally excited (hence with an intensity proportional to the square of electron density), the larger volume of the narrow-line region (NLR, proportional to \(R_{\text{NLR}}/R_{\text{BLR}}\)) and the absence of collisional quenching at a relatively low density (as in the case of the [O\textsc{iii}] λλ4959, 5007 lines) make it possible to expect a significant C\textsc{iv} λ1549 NC emission. We also observed that for I Zw 1, the NC of C\textsc{iv} λ1549 is blueshifted. This is also observed in other narrow lines (Marziani et al. 2010), in agreement with expectations for the NLR of the extreme NLSy1s. For example, [O\textsc{iii}] λλ4959, 5007 is blueshifted with respect to Hβ and to the systemic radial velocity of the host galaxy. In this way the analysis of the C\textsc{iv} λ1549 NC is fully consistent with the [O\textsc{iii}] λλ4959, 5007 and Hβ analysis.

5. \textit{λ1400 blend}. This blend has been one of the most enigmatic features in quasar spectra (e.g., Wills & Netzer 1979). It is known that the Si\textsc{iv} λ1397 doublet is blended with O\textsc{iv} intercombination lines (Nussbaumer & Storey 1982). In our sources the λ1400 blend is very prominent, approximately 3–4× stronger relative to C\textsc{iv} λ1549 than in the SDSS composite quasar spectrum (Vanden Berk et al. 2001). This is consistent with the extreme metal enrichment we found in these sources (Section 6.1.1).

We are able to obtain a reliable measurement of the Si\textsc{iv} λ1397 doublet, even when we cannot measure all the components of the λ1400 blend. Any O\textsc{iv} λ1402 contribution to the
BCs is expected to be negligible. We follow the same procedure to fit this blend as in the λ1550 blend. Note that the Si iv λ1397 low-ionization emission line shows a double-horned profile in I Zw 1 because of the large doublet separation and of the relatively narrow lines of this source. Since the peak at \( \approx 1401 \) Å is somewhat broader than the peak of the individual component of Si iv λ1397, some O iv λ1402 emission might be associated with the O iii λ1663-emitting region. This is an additional, minority component that is needed to obtain a very good fit of the λ1400 blend.

In summary, the three following features were independently fitted (using specfit, see Figure 2):

The \( \lambda 1400 \) blend (whose profile is very similar to the one of C iv λ1549), with BC of Si iv λ1397 (we fit the doublet with individual lines at 1402 and 1394 Å), and one blueshifted component accounting for the contribution of both Si iv λ1397 and O iv λ1402 (+ semi-BC most probably associated with O iv λ1402 in I Zw 1).

The \( \lambda 1550 \) feature, with C iv λ1549 BC + BLUE + Fe ii + Si ii λ1531. We expect a contribution of He ii λ4686 with a profile similar to C iv λ1549. In SDSS J1201+0116 we can see He ii λ4686 BLUE.

The \( \lambda 1900 \) blend considering Fe ii, Fe iii, Si ii λ1814, Al iii λ1860 (we fit the doublet with independent lines, at 1855 and 1862 Å; in Figure 2 we show only the sum), Si iii λ1909, C iii λ1909, and Fe iii λ1914. The latter line is assumed to be an independent additional line of unknown intensity and with the same profile as the other BCs.

All BCs of the broad emission lines are assumed to have the same width and shift, leaving only their intensity as free parameters. The HIL blends involve mainly only two components. As a result, the free parameters are reduced to the intensity of the BC lines (C iii λ1909, Si iii λ1909, Al iii λ1860, Si iii λ1814, C iv λ1549, and Si iv λ1397), the intensity of the Fe ii and Fe iii templates, and the width and flux of the Gaussian minor components under C iv λ1549 (N iv λ1486, Si iii λ1533, He ii λ1640) and Si iv λ1397 (O iv λ1402). Table 2 reports the fluxes of the BCs for intermediate- and high-ionization lines. Column 1 is the object name. Column 2 is the redshift; for I Zw 1 we adopted the one reported in Marziani et al. (2010), for the SDSS J1201+0116 object we use one reported in the SDSS database. Column 3 is the rest-frame specific flux at \( \lambda = 1700 \) Å. Columns 4–9 are the rest-frame line flux for the BCs only, and Column 10 is the FWHM of all the BCs.

### Notes.

- a Rest-frame-specific continuum flux at 1700 Å in units of \( 10^{-14} \) erg s^{-1} cm^{-2} Å^{-1}.
- b Rest-frame line flux of the intermediate-ionization line BC and of the C iv λ1549 BC in units of \( 10^{-14} \) erg s^{-1} cm^{-2}.
- c Rest-frame FWHM of the intermediate-ionization line BC and of the C iv λ1549 BC in units of km s^{-1}.

#### 3.2.1. Uncertainties

The main sources of uncertainties in the measurements are the following:

- **Fe ii intensity (continuum placement).** Broad Fe ii emission can produce a pseudo-continuum affecting our estimates of emission-line intensities. Si iv λ1814 is especially affected in our spectra because it is weak (Figure 1). The effect is less noticeable for C iv λ1549 and Si iv λ1397, since the expected Fe ii emission underlying those lines is weak. The placement of this pseudo-continuum also affects the determination of \( F_{\text{BLR}} \), for which we use the continuum flux measured at \( \lambda = 1700 \) Å (see Column 3 of Table 2 and Equation (8)).

- **Fe ii intensity.** These multiplets affect mainly the intensity of the C iii λ1909 emission line. We measured the maximum and minimum possible contributions of C iii λ1909 depending on the intensity of Fe iii λ1914. The contribution of C iii λ1909 has no considerable effect to the intensity of Si iii λ1892 even in the case where Fe iii λ1914 is maximum. This is important for the case of the SDSS object. In order to reproduce the observed λ1900 blend, if we increase the intensity of the C iii λ1909 emission line, the intensity of Fe iii λ1914 necessarily has to decrease and vice versa. As a result, Si iii λ1892 is not really affected by these variations, and the line intensity of Si iii λ1892 is affected only by about ~10%, which is within the uncertainties, as shown in Table 2. In the lower right panel of Figure 2 and in Figure 3 we show the maximum and minimum contributions of C iii λ1909 and Fe iii λ1914.

- **BLUE component.** In the case of the C iv λ1549 and Si iv λ1397 emission lines, the main source of error is the contribution of the BLUE component on the blue side of the central component. To a less extent, we may have a BLUE component contribution of He ii λ4686 on the red side of C iv λ1549. In the previous section we describe how we deal with these contributions.

- **FWHM.** When we run the specfit routine, we set the same FWHM for all the BCs of the broad emission lines. However, the routine introduces slight fluctuations around this initial value in order to obtain the best fit. When we vary the placement of the continuum, the FWHM determination is also affected. This source of error is reflected in the computation of the \( M_{\text{BH}} \).

#### 3.2.2. C iii λ1909 Emission

One must work carefully with the λ1900 blend because of the close proximity of the C iii λ1909, Fe iii λ1914, and Si iii λ1892 emission lines. Both of our targets are extreme Pop. A sources, and one characteristic of this extreme population is that C iii λ1909 is weak or even absent (Figure 2). Extreme Pop. A sources show the lowest C iii λ1909/Si iii λ1892 ratio among all quasars in the E1 sequence (Bachev et al. 2004). We can see this effect in the upper right panel of Figure 2, where
we show the \( \lambda 1909 \) blend for I Zw 1. The resolution is good enough to separate the peaks of Fe\( \text{iii} \) \( \lambda 1914 \) and C\( \text{iii} \) \( \lambda 1909 \). After fitting the Fe\( \text{iii} \) template (including the Fe\( \text{iii} \) \( \lambda 1914 \) line), we see that in order to fit the observed spectrum the intensity of the C\( \text{iii} \) \( \lambda 1909 \) line turns out to be comparable to Fe\( \text{iii} \) \( \lambda 1914 \). In the right lower panel, for the SDSS J12014+0116 object, the spectrum is noisier and the peaks of the lines of C\( \text{iii} \) \( \lambda 1909 \) and Fe\( \text{iii} \) \( \lambda 1914 \) are not clearly seen. However, the observed peak is at the position of Fe\( \text{iii} \) \( \lambda 1914 \), and if we follow the same procedure to fit the Fe\( \text{iii} \) template in order to deconvolve the blend, it turns out that the contribution of the C\( \text{iii} \) \( \lambda 1909 \) emission line is practically insignificant. To estimate an upper limit to the C\( \text{iii} \) \( \lambda 1909 \) line, we remove Fe\( \text{iii} \) \( \lambda 1914 \) (Figure 3).

This estimate is C\( \text{iii} \) \( \lambda 1909 \approx 0.5 \) Si\( \text{iii} \) \( \lambda 1892 \) for the SDSS J12014+0116 object, but the fit is poor on the red side of the blend, leaving a large residual. In order to minimize the residual, we added the maximum possible contribution of C\( \text{iii} \) \( \lambda 1909 \) emission line (Figure 3). We can safely conclude that C\( \text{iii} \) \( \lambda 1909 \)/Si\( \text{iii} \) \( \lambda 1892 < 0.5 \) in this object. C\( \text{iii} \) \( \lambda 1909 \) emission line in I Zw 1 is about \( \approx 0.6 \) Si\( \text{iii} \) \( \lambda 1892 \). The very dense region emitting the LILs should produce no C\( \text{iii} \) \( \lambda 1909 \) line because it is collisionally quenched; thus, any emission from this line should arise in a different region.

Available reverberation mapping results suggest that C\( \text{iii} \) \( \lambda 1909 \) line is mainly emitted farther out from the central continuum source than some LILs and HILs. The results of reverberation mapping analysis are limited to a handful of low-luminosity objects and cannot be generalized in a straightforward way. However, in these low-luminosity objects C\( \text{iii} \) \( \lambda 1909 \) line responds to continuum changes on timescales much longer than C\( \text{iv} \) \( \lambda 1549 \) and other HILs. This result comes from the analysis of total C\( \text{iii} \) \( \lambda 1909 + \) Si\( \text{iii} \) \( \lambda 1892 \) in NGC 3783 (Onken 

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Figure 4 reproduces also the structure and emissivity of a typical log

4. DEFINITION OF DIAGNOSTIC RATIOS AND THEIR INTERPRETATION

4.1. Definition

Our method for estimating \( n_H \) and \( U \) involves several ratio pictures. We discuss the product \( n_H \cdot U \) in the following sections, and in Section 6.2 we use it to compute \( r_{BLR} \). We define three groups of diagnostic ratios, which should define density, ionization parameter, and metallicity for a given continuum shape and geometry.

Line ratios such as Al\( \text{iii} \) \( \lambda 1860/\)Si\( \text{iii} \) \( \lambda 1892 \) are useful diagnostics over a range of density that depends on their transition probabilities. Emission lines originating from forbidden or semi-forbidden transitions become collisionally quenched above the critical density and therefore relatively weaker than lines for which collisional effects are still negligible. The Al\( \text{iii} \) \( \lambda 1860/\)Si\( \text{iii} \) \( \lambda 1892 \) ratio is well suited to sample the density range \( 10^{11}-10^{13} \) cm\(^{-3} \). This corresponds to the densest emitting regions likely associated with production of LILs like the Ca\( \text{ii} \) IR triplet (Matsuoka et al. 2008) and Fe\( \text{ii} \) (Baldwin et al. 2004).

The ratios Si\( \text{ii} \) \( \lambda 1814/\)Si\( \text{iii} \) \( \lambda 1892 \) and Si\( \text{iv} \) \( \lambda 1397/\)Si\( \text{iii} \) \( \lambda 1892 \) are sensitive to ionization but roughly independent of metallicity since the lines come from different ionic species of the same element. Metallicity influences thermal and ionization conditions that in turn affect these ratios. The effect is, however, second order: cloudy simulation sets for different Z indicate that, for a fivefold increase in metal content, the ratio Si\( \text{iv} \) \( \lambda 1397/\)Si\( \text{iii} \) \( \lambda 1892 \) changes from \( \approx 0.5 \) to 0.6.

The ratio Si\( \text{iv} \) \( \lambda 1397/\)C\( \text{iv} \) \( \lambda 1549 \) is mainly sensitive to the relative abundances of Si and C. The reason is that the ground and excited energy levels of these ions are very similar (the ionization potentials are close: 33.5 and 48 eV for creation of Si\( ^{+3} \) and C\( ^{+3} \), respectively). This implies that the dependence on continuum shape and electron temperature of the ratio of these two resonance lines is small (see also Simon & Hamann 2010).

4.2. Interpretation

In order to illustrate how we employ cloudy simulations to estimate where the bulk of the line emission arises, we refer to Figure 4. The left panel shows the ionization fraction as a function of geometrical depth in a slab (within a single BLR cloud) for which we choose a fixed column density\(^9\) \( (N_c = 10^{25} \) cm\(^{-2} \)) and density \( (n_H = 10^{12.5} \) cm\(^{-3} \)) exposed to a “standard” quasar continuum (the parameterization of Mathews & Ferland 1987). It is customary to consider this parameterization as standard for the ionizing continuum. However, that parameterization has been sometimes criticized and is not unique, so that we also consider as an alternative the ionizing continuum parameterization of Laor et al. (1997b). In this work, we use the term “typical continuum” to designate the average of the two, with the two continua providing two extrema in number of ionizing photons expected at a specific flux measured on the

\(^9\) The value of \( N_{c} = 10^{25} \) cm\(^{-2} \) was needed to show that the Strömgren depth is less than the size of the clouds for the ionic states we are considering, e.g., that clouds are radiation bounded. In Figure 4 we show that if we assume \( N_{c} = 10^{25} \) cm\(^{-2} \), the clouds become optically thick to electron scattering and we use them just to show the ionization structure and the line emissivity. Figure 4 reproduces also the structure and emissivity of a typical log \( N_{c} = 10^{25} \) slab (in this case the limit of geometrical depth is \( \log h \approx 10.5 \)).
Figure 4. We show the result of cloudy simulations for the behavior of the emission lines in a gas slab. Left: ion fractions as a function of the logarithm of geometric depth \(h\) in a gas slab. Plotted ionic stages (H\(^+\), thick solid black; Si\(^{+2}\), solid red; Al\(^{+2}\), solid blue; Fe\(^{+2}\), solid black; Si\(^{+3}\), dashed black; Fe\(^{+3}\), dashed black; C\(^{+3}\), thick gray; Si\(^{+3}\), dotted red) are the ones relevant to the emission lines considered in this paper. Right: local line emissivity per unit volume in units of erg s\(^{-1}\) cm\(^{-3}\) multiplied by depth \(h\) in cm as a function of the logarithm of geometric depth \(h\) for Si \(\lambda 1397\) (red dotted), C \(\lambda 1549\) (thick gray), Si \(\lambda 1814\) (dashed red), Al \(\lambda 1860\) (solid blue), Si \(\lambda 1892\) (solid red), C \(\lambda 1909\) (thick dashed gray), H\(^\beta\) (thick black). The continuum photons enter from left. The partially ionized zone (PIZ) is on the right side of the dot-dashed line. Ion fraction and emissivity are calculated through a dedicated cloudy simulation extending up to \(N_c = 10^{23}\) cm\(^{-2}\).

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

non-ionizing part of the continuum. The “typical continuum” is the one used for our computation of \(\tau_{BLR}\) (see Section 6.2).

Computing simulations at fixed \(n_H\) and \(U\) values allows us to study how these parameters influence the diagnostic ratios we have defined. We make no assumptions about the geometry or kinematics of the BLR. The slab of gas (i.e., a single cloud) might as well involve magnetically confined clouds (Rees et al. 1989) or individual elements in an accretion disk atmosphere—provided that photoionization is the only heating mechanism.

Al\(^{+2}\), Fe\(^{+2}\), and Si\(^{+3}\) are intermediate-ionization lines sharing a region of dominance deep within a cloud—where the HILs also arise. It is therefore appropriate to consider intermediate-ionization line ratios between geometric depths \(h \sim 10^6-10^8\) cm (right panel of Figure 4). We prefer to show the product of the local line emissivity times the depth within the slab since the total line intensity is proportional to \(\int \epsilon(h) dh\) (in the absence of radiation transfer effects, i.e., in a cloud where lines are optically thin), and hence the product \(\epsilon(h) \cdot h\) gives a better idea of the total line emission at a distance \(h\) than simply showing \(\epsilon(h)\) versus \(h\). Figure 4 shows that C \(\lambda 1909\) emission is expected to be orders of magnitude lower than the other lines and therefore likely undetectable.

Once we have ascertained that the computed line ratios are physically consistent (i.e., all refer to a single emitting region except the ones involving Si \(\lambda 1814\), whose intensity is significantly affected by a partially ionized zone (PIZ) emission), a multidimensional grid of cloudy simulations is needed to derive estimates for \(U\), \(n_H\), and metallicity from the spectral measurements (Ferland et al. 1998; Korista et al. 1997). cloudy computes population levels of the relevant ionic stages of Si, C, Al, and especially for lines emitted in the fully ionized part of a gas slab (Figure 4). Also, cloudy is expected to be especially good for predicting intermediate- and high-ionization line fluxes that are produced in the fully ionized region within the gas slab. LILs are produced in the cloudy by photoionization of hydrogen—primarily by soft X-ray photons. Since these X-ray photons create suprathermal electrons and have a relatively low cross section for photoionization, the heating processes in the PIZ are inherently non-local, making the mean escape probability formalism used by cloudy to treat radiation transfer a very rough approximation.

New simulations were needed since cloudy has undergone steady and significant improvements since the time of Korista et al. (1997). The most relevant improvement is the addition of more ion species in the simulations, with a 371-level of the Fe\(^+\) ion. This will make computation of equilibrium conditions more realistic even if, in the end, we expect that predictions of line intensity ratios will not be dramatically affected: ion is singly ionized only in the PIZ (Figure 4, left panel). Other relevant improvement for our study is the post-Korista et al. (1997) update of the transition probability for Si \(\lambda 1814\) following Callegari & Trigueiros (1998) that changes the intensity of the line by a factor of \(\sim 2\) in the high-density regime of the BLR. We present the results of our simulations in Figure 5. Our results are not inconsistent with those obtained by Korista et al. (1997), for the same ranges of density and ionizing parameter: the overall behavior in the plane \((U, n_H)\) of their Figure 3 is qualitatively consistent with the one derived from our simulations.

Simulations assume (1) pure photoionization (see also Section 6.1) and (2) spherical symmetry in continuum emission, i.e., that the ionizing continuum incident on a slab of gas of fixed density is similar to the observed continuum (see Section 6.2.1 for caveats concerning this assumption).

The ionization state of the gas will be mainly defined by the ionization parameter:

\[
U = \frac{\int v L_v \frac{dv}{4 \pi n_H c r^2}}{1 - \frac{v_0}{v}},
\]

where \(L_v\) is the specific luminosity per unit frequency, \(h\) is the Planck constant, \(v_0\) is the Rydberg frequency, \(n_H\) is the hydrogen density, \(c\) is the speed of light, and \(r\) is the distance between the central source of ionizing radiation and the line-emitting region.

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 assuming plane-parallel geometry. We assume the standard value of \(N_c = 10^{23}\) cm\(^{-2}\) (Netzer & Marziani 2010, and references therein). In Figure 5 we show the isocontours for
the ratios $\text{Al}^\text{III}\lambda 1860/\text{Si}^\text{III}\lambda 1892$, $\text{Si}^\text{II}\lambda 1814/\text{Si}^\text{III}\lambda 1892$, $\text{Si}^\text{IV}\lambda 1397/\text{Si}^\text{III}\lambda 1892$, $\text{C}^\text{IV}\lambda 1549/\text{Al}^\text{III}\lambda 1860$, $\text{C}^\text{IV}\lambda 1549/\text{Si}^\text{III}\lambda 1892$, and $\text{Si}^\text{IV}\lambda 1397/\text{C}^\text{IV}\lambda 1549$ derived from \textsc{cloudy} simulations, for solar metallicity and “standard” quasar continuum, as parameterized by Mathews & Ferland (1987, see above). We considered three chemical compositions: (1) solar metallicity; (2) constant abundance ratio Al:Si:C with $Z = 5 Z_\odot$; (3) an overabundance of Si and Al with respect to carbon by a factor of three, again with $Z = 5 Z_\odot$ ($5 Z_\odot$SiAl). This last condition comes from the yields listed for Type II supernovae (Woosley & Weaver 1995). The Si overabundance is also supported by the chemical composition of the gas returned to the interstellar medium by an evolved population with a top-loaded initial mass function (IMF) simulated using \textsc{starburst99} (Leitherer et al. 1999). The abundance of Al is assumed to scale with the one of Si (see also Section 6.1 on this assumption).

5. RESULTS

5.1. Density and Ionization Parameter

In this section, we compute the ratios analyzed above from the flux values and estimate the physical parameters $n_H$ and $U$ of the BLR, for I Zw 1 and SDSS J12014+0116. We derived these values from the emission-line measurements, reported in
overabundance of Si and Al with respect to carbon by a factor of three, described in Section 4.2. The left panels refer to the case of solar metallicity, the right ones to the case of five times solar plus an overabundance of Si and Al with respect to carbon by a factor of three, described in Section 4.2 (5 \( Z_\odot \) SiAl). Each arrow points toward the point of convergence that defines the most likely value of \( U \) and \( n_H \). The bands are the uncertainty bands of the ratios (except for Si\ IV \( \lambda 1397 / C \ IV \lambda 1549 \)). Note that the Si\ IV \( \lambda 1397 / C \ IV \lambda 1549 \) ratio is not a useful constraint in the 5 \( Z_\odot \) SiAl case, since it varies little in a wide area around the intersection point in the \((n_H, U)\) plane.

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

Table 2, and the `cloudy` simulations of Figure 5. Asymmetric errors due to the uncertainties described in Section 3.2.1 have been quadratically propagated following Barlow (2003, 2004).

In the left panels of Figure 6 we show the same \( n_H \) versus \( U \) plane as in Figure 5 (in right panels, we use the 5 \( Z_\odot \) SiAl simulation defined above). We choose only one isocontour for each ratio, and it is the one that corresponds to the measured value. There is a convergence of the contour lines defined by several crossing points of the contour of the Al\ III \( \lambda 1860 / \) Si\ III] \( \lambda 1892 \) ratio versus the contour of the other five ratios. This convergence defines the \( n_H \) and \( U \) values that point toward a low ionization plus high-density range. We use the average value of all of the crossing points to define a single \( n_{HI} \) \( U \) value, which is used to compute the \( n_{BLR} \) and the \( M_{BH} \) (Section 6.2).

The uncertainties associated with a line ratio, \( R \), broaden the lines defined by constant \( R \) to a band limited by the ratios \( R \pm \delta R \). In Figure 6, we show them with bands. The largest of all uncertainties is related to Si\ II \( \lambda 1814 \). This is the weakest line that we use, and thus it is the line most strongly affected by the continuum placement. The value of Si\ II \( \lambda 1814 \) intensity is probably underestimated, and if it were higher, the crossing point of Al\ III \( \lambda 1860 / \) Si\ III] \( \lambda 1892 \) versus Si\ II \( \lambda 1814 / \) Si\ III] \( \lambda 1892 \) would be closer to the other crossing points, marked by an arrow in Figure 6. We also stress that Si\ II \( \lambda 1814 \) is the only LIL considered in this study, and its formation is sensitive to the assumed X-ray continuum and other LIL formation issues (Dumont & Mathez 1981; Baldwin et al. 1996).

The discrepancy in the intersection point of diagnostic ratios in the plane \((n_H, U)\) is significant for the Si\ IV \( \lambda 1397 / C \ IV \lambda 1549 \) ratio that depends mainly on the Si abundance relative to C. The \( \lambda 1400 / C \ IV \lambda 1549 \) intensity ratio has been used as a metallicity indicator also by other authors (Juarez et al. 2009; Simon & Hamann 2010). The discrepancy is less but still significant for the case when we consider the 5 \( Z_\odot \) SiAl case. For this reason, we do not consider this ratio in the computation of the product of density and ionization parameter.

In similar plots made for \( Z = 5 \) \( Z_\odot \) SiAl (right panels of Figure 6), the agreement of all the crossing points improves: the isocontour lines converge toward a better defined crossing point.

The high-metallicity case 5 \( Z_\odot \) SiAl indicates higher \( U \) and smaller \( n_H \) with respect to the case of solar abundances, if emission-line ratios involving C\ IV \( \lambda 1549 \) are considered. This reflects the increase in abundance of Si and Al relative to C with respect to solar: Si and Al lines appear stronger with respect to the C\ IV \( \lambda 1549 \) line because the elements Si and Al are more abundant, and not because a lower ionization level enhances Si\ II \( \lambda 1814, \) Si\ III] \( \lambda 1892, \) and Al\ III] \( \lambda 1860 \) emission with respect to C\ IV \( \lambda 1549 \).

In the case of SDSS J1201+0116 we can see from Table 3 that the density is even higher than for I Zw 1, suggesting that Si\ III] \( \lambda 1892 \) is collisionally quenched to make possible a rather high Al\ III \( \lambda 1860 / \) Si\ III] \( \lambda 1892 \) ratio, \( \approx 1 \). The line intensity of Si\ III] \( \lambda 1892 \) is thus the result of the physical conditions of the emitting region, and in fact we measure a relatively low line intensity. The ratio Al\ III \( \lambda 1860 / \) Si\ III] \( \lambda 1892 \) has a value of 0.6 for I Zw 1.  

5.2. The Product \((n_H \cdot U)\)

The products \((n_H \cdot U)\) derived from Figure 6 and reported in Table 3 are marginally different for the two sources. It is intriguing, however, that while the values of \( n_H \) and \( U \) taken separately depend significantly on metallicity, their product shows a weaker dependence: for \( Z = 1 \) \( Z_\odot \), we obtain \( \log(n_H \cdot U) \approx 9.4 \) for I Zw 1 and 9.8 for SDSS J1201+0116.
Similar results also seem to hold for a larger sample, including the objects monitored for reverberation mapping (Negrete 2011).

We also note that the log(n_H \cdot U) values are very close to the results of several independent, previous studies summarized in Table 4.

Baldwin et al. (1996) presented a similar analysis. Their Figure 2 organizes spectra in a sequence that is roughly corresponding to E1, going from Al III λ1860-strong sources to objects whose spectra show prominent C III| λ1909 along with weak Al III λ1860 (Bachev et al. 2004). The line components they isolated correspond to the ones we consider in this paper: a blueshifted feature, and a more symmetric, unshifted, and relatively NC that we call LIL-BC. They derive log n_H ≈ 12.7 and log U ≈ −2.5. A somewhat lower density and higher ionization are indicated to optimize Fe II emission, while the Ca II IR triplet requires conditions that are very similar to the ones derived from the intermediate-ionization lines.

We are not claiming that there is a single region that is able to account for all broad lines in all AGNs. However, a low-ionization, high-density region can account for Fe II, Ca II, and the intermediate-ionization line emission. This region is dominating the BC of emission lines (save weak C III| λ1909) in the objects considered in this paper but apparently becomes less relevant along the E1 sequence (Marziani et al. 2010). The properties of the emitting BLR seem to be remarkably stable, keeping an almost constant log(n_H \cdot U) (also seen in previous work, e.g., Wandel et al. 1999; Baldwin et al. 1995). The issue is therefore whether we can apply the physical conditions (n_H and U) we deduce to derive information of r_{BLR} and M_{BH}.

6. DISCUSSION

6.1. Alternative Interpretations

In this section we discuss other possible scenarios considering the influence of other sources of heating, besides photoionization. We again remark that, on the basis of the analysis of Section 3, the use of intermediate- and high-ionization lines takes advantage of the most robust results of photoionization computations for AGNs. The complex issue of LIL formation is mostly avoided since we do not rely on the PIZ, whose physical properties may not be adequately modeled. Nonetheless, results on density stem mainly from the Al III λ1860 line being over-strong with respect to Si III| λ1892. The observed Al III λ1860/ Si III| λ1892 line ratio is inconsistent with density ~10^{11} cm^{−3} that would make some C III| λ1909 emission possible. Low ionization is inferred from the intrinsic weakness of C IV λ1549 in these Pop. A sources with respect to C IV λ1549 that is observed in Pop. B objects (Sulentic et al. 2007).

While there is little doubt about the identification of the Al III λ1860 line doublet (a resonance line with large transition probability; in several NLSy1s the doublet is resolved with ratio ~1–1.2, suggesting large optical depth), this line could be enhanced with respect to Si III| λ1892 by some special mechanism. We can conceive two ways of increasing Al III λ1860 with respect to Si III| λ1892: (1) a selective enhancement of the Al abundance with respect to Si or (2) collisional ionization due to a heating mechanism different from photoionization.

6.1.1. Anomalous Chemical Composition

Evidence based on the strength of the N v λ1240 line relative to the C IV λ1549 and He II λ1640 lines indicates that chemical abundances may be 5–10 times solar (Dhanda et al. 2007) in high-redshift quasars, with Z ≈ 5 Z⊙ reputed typical of high-z quasars (Ferland et al. 1996). The [Si/C] enhancement (over solar) is supported by both starburst 99 simulations (Leitherer et al. 1999) and supernova yields (Woosley & Weaver 1995).

The production factors for progenitors reported by Woosley & Weaver (1995) indicate that there should be little [Al/C] enhancement for 11–20 M⊙ supernova progenitors of solar metallicity of Z⊙. Massive progenitors are needed to raise the [Al/C] enrichment as they are the most efficient producers of aluminum. We integrate the production factors over a top-loaded mass function Φ(M) ∝ M^{−3}. If x = 1.3 (for M ≤ 8 M⊙, a value held canonical for the IMF of young star-forming systems), we obtain production factor ratios of ≈3.0 and ≈2.5 for aluminum over carbon and silicon over carbon, respectively. We also try changing the high-mass end of the IMF. With x = 2.1, we obtain a factor of two enhancement for both aluminum and silicon. With x = 1.1, we obtain a significantly larger enhancement.

### Table 3: Derived Quantities

| Object   | log(n_{HI}) | log U | log(n_{HI}U) | log(U_{BLR}) | log(M_{BH}) | log(M_{BH}(VP06)) |
|----------|-------------|-------|--------------|--------------|-------------|------------------|
| I Zw 1   | 12.00±0.32  | −2.65±0.21 | 9.35±0.33 | 17.30±0.17 | 7.30±0.23 | 6.70             |
| SDSS J1201+0116 | 12.63±0.24 | −2.79±0.12 | 9.84±0.23 | 18.31±0.14 | 9.39±0.17 | 9.29             |

**Notes.**

* n_{HI} in units of cm^{−3}.
* M_{BLR} in units of cm.
* M_{BH} in units of M⊙ computed with the FWHM values of Table 2.
* M_{BH} ±0.66 dex at a 2σ confidence level, in units of M⊙ computed following Vestergaard & Peterson (2006), and input parameters reported in note (b). See the text for details.

### Table 4: Results from Previous Studies

| Reference          | log(n_{HI}) | log U | log(n_{HI}U) | Line               |
|--------------------|-------------|-------|--------------|--------------------|
| Matsuoka et al. (2008) | 12.         | −2.5 to −2.0 | 9.5–10 | Ca IR triplet      |
| Sigut & Pradhan (2005)  | 11.6        | −2.0  | 9.6          | Their model B for Fe II |
| Padovani & Rafanelli (1988) | ...       | ...   | 9.8±0.3      | Hβ                |
| Baldwin et al. (1996)      | 12.7        | −2.5  | ~10.2        | λ1900 blend       |
in aluminum than in silicon over carbon, with production factor ratios \(\approx 3.5\) and \(\approx 2.7\). This condition is, however, rather extreme and the change in enrichment is rather small and will not affect significantly our diagnostic ratios.

The observed values are more consistent with the assumption of a starburst. A factor of \(\approx 3\) enhancement of Si and Al over C indicates that BLR is made of gas whose chemical composition might reflect the enrichment due to a “young” starburst (\(\lesssim \text{few } 10^7\) yr): a starburst 99 simulation indicates that ejecta from a stellar system formed in an instantaneous burst should be enriched in Si in between \(2 \times 10^7\) and \(4 \times 10^7\) yr.

6.1.2. Mechanical Heating and \(\text{Fe}^\text{II}\) Emission

NLSy1s of spectral types A3 and A4 are the sources for which pure photoionization models are deficient as far as the prominence of \(\text{Fe}^\text{II}\) emission is concerned (Joly et al. 2008). Since Al \(\lambda 1860\) prominence correlates with \(\text{Fe}^\text{II}\) prominence along the E1 sequence, there might be a mechanical heating contribution to the thermal and ionization balance that is often invoked to explain \(\text{Fe}^\text{II}\) emission (Collin & Joly 2000; Baldwin et al. 2004). This second possibility reopens the issue of LIL formation, which is too complex to be discussed in the present paper.

We can consider whether gas in collisional equilibrium at a fixed electron temperature could give rise to a spectrum accounting for the strong \(\text{Fe}^\text{II}\) \(\lambda 4570\) and Al \(\lambda 1860\) emission lines, as well as the line ratio Si \(\text{III}\) \(\lambda 1892/C/\text{III}\) \(\lambda 1909 \approx 2\) as observed in I Zw 1. We cannot ignore, however, that Balmer-line-emitting gas appears to be pre-emminently photoionized, also in NLSy1 objects, as convincingly demonstrated by several reverberation mapping campaigns, and that the width of \(\text{Fe}^\text{II}\) is consistent with the width of the H\(\beta\) rms spectrum (Sulentic et al. 2006a). Continuity arguments along the E1 sequence and monitoring studies indicate that photoionization cannot be fully dismissed. Also, I Zw 1 is among the strongest emitter along the E1 “main sequence” of Sulentic et al. (2000), but not an ultrastrong \(\text{Fe}^\text{II}\) emitter as defined by Lipari et al. (1993). Ultrastrong \(\text{Fe}^\text{II}\) emitters are outliers in the E1 optical plane (Sulentic et al. 2006b), and often ultra-luminous IR galaxies and extreme broad absorption line sources. It is legitimate to suspect very different physical conditions in that case.

There is convincing evidence that \(\text{Fe}^\text{II}\) is responding to continuum changes, although measurements are very difficult and the response of \(\text{Fe}^\text{II}\) might be more erratic than H\(\beta\) (Vestergaard & Peterson 2005; Peterson 2011). PG 1700 + 518 is a strong \(\text{Fe}^\text{II}\) emitter, and monitoring of Fe \(\text{II}\) \(\ell\ell\ell\) indicates a response on a timescale consistent with the one obtained for H\(\beta\) (Bian et al. 2010; Peterson et al. 2004; note that Bian et al. 2010 are not able to derive a reverberation radius for H\(\beta\), unlike previous monitoring campaigns). On the contrary Akn 120, a source with significant \(\text{Fe}^\text{II}\) (Marziani et al. 1992; Korista 1992) shows a response that may be consistent with a region more distant than the one of H\(\beta\), or with a region that is not photoionized (Kuehn et al. 2008). A recent work suggests that the large range of observed \(R_{\text{Fe}^\text{II}}\) values can be explained by photoionization, if the variation of iron abundance in dusty gas is taken into account (Shields et al. 2010).

The \((n_H, U)\) solution we find falls below the ionization level that maximizes Fe \(\lambda 4570\) emission. Adopting the suggestion of S. Collin and Collaborators (e.g., Joly 1987), a simulation computed in the case of a very weak photoionizing continuum and dominance of collisional ionization at \(T = 7000\) K would enhance the \(R_{\text{Fe}^\text{II}}\) ratio to levels even in excess of the one observed, leaving, however, unaffected the intermediate- and high-ionization lines (since there are few electrons with energies sufficient to ionize their parent ionic species).

A system dominated by collisions at a fixed, single temperature higher than \(\approx 10,000\) K would yield contradictory results. For example, a collisional equilibrium solution at \(T = 20,000\) K and log \(n_H = 10\) would imply \(R_{\text{Fe}^\text{II}}\) exceeding by a factor of the observed value. Ratios involving the Al \(\lambda 1860\), Si \(\text{III}\) \(\lambda 1892\), and Si \(\text{IV}\) \(\lambda 1397\) emission lines would be consistent with the observed ones, but the solution overpredicts the intensity of intermediate-ionization emission lines by a factor of \(\approx 100\), with little C \(\text{III}\) \(\lambda 1909\) and no C \(\text{IV}\) \(\lambda 1549\). If any such region exists, it must contribute little to Ca \(\text{II}\) and \(\text{Fe}^\text{II}\) emission. Another paradox of this case would be that Si \(\text{IV}\) \(\lambda 1397\) and C \(\text{IV}\) \(\lambda 1549\) require different \(T\) to account for their intensity ratio. Reverberation mapping of Seyfert nuclei indicates, however, that the two lines are most close in response times (Korista et al. 1995; Wanders et al. 1997), which is thus inconsistent with a different temperature of the emission-line gas.

If the only and dominant source of ionization were mechanical deposition of energy due to shocks and/or friction (shear), our analysis based on photoionization would not be valid. Clearly, an ad hoc solution can be found invoking a range of temperatures. However, considering the low EW of all lines in the sources of this paper, and the continuity with the other sources in the E1 sequence, we conclude that there is no convincing evidence that shocks are dominating the emission of HIL and intermediate-ionization lines. An additional heating source might significantly affect only the low-\(T\) PIZ, where most \(\text{Fe}^\text{II}\) is emitted (Collin & Joly 2000).

6.2. Implications

In Section 5 we estimate the product \(n_H \cdot U\), and now we can compute the distance of the BLR (\(r_{\text{BLR}}\)) from the central continuum source and the black hole mass (\(M_{\text{BH}}\)). They are key parameters that allow us to better understand gas dynamics in the emitting region, as well as quasar phenomenology and evolution. The dependence of \(U\) on \(r_{\text{BLR}}\) was used to derive black hole masses assuming a plausible average value of the product \(n_H \cdot U\). We also use FWHM(H\(\beta\)) to derive the BC from a virialized medium (Padovani et al. 1990; Wandel et al. 1999). Equation (1) can be rewritten as

\[
r_{\text{BLR}} = \left[ \frac{\int_{\nu_0}^{\nu} L_{2\nu} d\nu}{4\pi n_H U C} \right]^{1/2}
\]

and as

\[
r_{\text{BLR}} = \frac{1}{h U c} (n_H U)^{-1/2} \left( \int_0^{\lambda_{\text{Ly}}} f_{\lambda} \lambda d\lambda \right)^{1/2} d_c,
\]

where \(d_c\) is the total line-of-sight comoving distance (Hogg & Fruchter 1999):

\[
d_c = \frac{c}{H_0} \zeta(z, \Omega_M, \Omega_{\Lambda}) = \frac{c}{H_0} \int_0^z \frac{dz'}{\sqrt{\Omega_M (1 + z)^3 + \Omega_{\Lambda}}}
\]
\[ \xi(z, \Omega_m, \Omega_\Lambda) \approx \left[ 1.500 \left( 1 - e^{-\frac{r}{300}} \right) + 0.996 \left( 1 - e^{-\frac{r}{500}} \right) \right], \]

with \( \Omega_m = 0.3 \) and \( \Omega_\Lambda = 0.7 \), given by Sulentic et al. (2006b).

In Equation (3), we transformed the integral from units of frequency to wavelength and rewrote the expression for \( r_{BLR} \) in terms of the rest-frame specific flux \( f_s \) that can be easily derived from the observed flux, namely,

\[ L_e \nu^{-1} d\nu = 4\pi c^{-1} d_L^2 f_s \lambda d\lambda, \]

with \( d_L \) the luminosity distance that is related to \( d_c \) by the formula \( d_L = d_c(1+z) \).

Note that

\[ \int_0^{\lambda_{H,0}} f_s \lambda d\lambda = f_s,0 \cdot \tilde{Q}_H, \quad \text{with} \quad \tilde{Q}_H = \int_0^{\lambda_{H,0}} \tilde{s}_\lambda d\lambda, \]

where \( \lambda_0 = 1700 \) Å. \( \tilde{Q}_H \) depends on the shape of the ionizing continuum for a given specific flux with the integral carried out from the Lyman limit to the shortest wavelengths. We use \( \tilde{s}_\lambda \) to define the spectral energy distribution (SED) following Mathews & Ferland (1987) and Laor et al. (1997a) conveniently parameterized as a set of broken power laws.

Expressing \( r_{BLR} \) in units of lt-day, and scaling the variables to convenient units, Equation (3) becomes

\[ r_{BLR} \approx 93 \left[ \frac{f_{\lambda_{H,0} - 15} \tilde{Q}_{H,0.01}}{(n_H U)_0} \right]^{1/2} \xi(z, 0.3, 0.7) \text{ lt-day}. \]

In this equation, \( f_{\lambda_{H,0} - 15} \) is the specific rest-frame flux (measured on the spectra) in units of \( 10^{-15} \) erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\), and \( \tilde{Q}_{H,0.01} \) is normalized to \( 10^{-2} \) cm Å. The product \( n_H U \) is normalized to \( 10^{10} \) cm\(^{-3}\), \( \xi(z, 0.3, 0.7) \) is derived from Equation (5), and \( r_{BLR} \) is now expressed in units of lt-day.

Knowing \( r_{BLR} \), we can calculate the \( M_{BH} \) assuming virial motions of the gas

\[ M_{BH} = \frac{f \Delta v^2 r_{BLR}}{G}, \]

or

\[ M_{BH} = \frac{3}{4G} f_{0.75}(\text{FWHM})^2 r_{BLR}, \]

with the geometry term \( f \approx 0.75 \), corresponding to \( f_{0.75} \approx 1.0 \) (Graham et al. 2011). The factor \( f \) depends on the details of the geometry, kinematics, and orientation of the BLR and is expected to be of order unity. This factor converts the measured velocity widths into an intrinsic Keplerian velocity (Peterson & Wandell 2000; Onken et al. 2004; Graham et al. 2011).

Resultant \( r_{BLR} \) and \( M_{BH} \) estimates are reported in Table 3. Errors in this table are at 2\( \sigma \) confidence level. They are not symmetrical around this value. They were propagated quadratically, following Barlow (2003, 2004). We consider three sources of uncertainty in the \( r_{BLR} \) computations.

1. The error in the determination of \( n_H \) and \( U \), which is described in detail in Section 5.1. We use the average value for all of the crossing points in Figure 6 to define a single \( n_H \cdot U \) value that is used in Equation (3) to compute the \( r_{BLR} \).

2. The error derived from the shape of the ionizing continuum, which is used in the computation of the \( r_{BLR} \). The two SEDs that we assumed as extreme yield a difference in ionizing photons of a factor 0.17 dex. At a 2\( \sigma \) confidence level this corresponds to an uncertainty in the number of ionizing photons of \( \pm 0.057 \) dex.

3. Errors in the specific fluxes (at \( \lambda = 1700 \) Å, Column 3 of Table 2), intrinsic to the spectrophotometry. We also consider the error in the continuum placement (discussed in Section 3.2.1).

In the determination of \( M_{BH} \) we consider two sources of error:

1. The combined error of the three sources of uncertainties on the \( r_{BLR} \) computation described above.

2. The error on the determination of the FWHM, which is discussed at the end of Section 3.2.1.

Using our derivations for \( n_H \) and \( U \), we obtain the \( r_{BLR} \) and \( M_{BH} \) values listed in Table 3. The last two columns give virial black hole masses following our method and using the \( M_{BH} \)–luminosity correlation from Vestergaard & Peterson (2006), respectively. Note that Vestergaard & Peterson (2006) used a different value for the geometry term, which is \( f = 1.4 \) (Onken et al. 2004; Woo et al. 2010), and the implication in the mass computation is that our masses are lower by a factor of two. This was taken into account, making the correction \( \log(f_{0.75}) = \log(0.75/1.4) = -0.27 \). We subtract this quantity from the Vestergaard & Peterson (2006) \( M_{BH} \) formula used to compute the masses in Column 7 of Table 3.

The intrinsic dispersion in the Vestergaard & Peterson (2006) relation is \( \pm 0.66 \) dex in black hole mass at a 2\( \sigma \) confidence level. We are not considering here the scatter in the relation \( r_{BLR} \)–\( L \) derived by Bentz et al. (2009) that involves sources, where \( r_{BLR} \) was derived from reverberation mapping. The scatter in the \( r_{BLR} \)–\( L \) correlation is \( \approx 0.2 \) dex in \( r_{BLR} \). These \( r_{BLR} \) determinations are, in spite of many caveats recently summarized in Marziani & Sulentic (2012), probably the best ones available. Kaspi et al. (2007) were able to derive one point in the \( r_{BLR} \)–\( L \) correlation directly from reverberation mapping of a high-\( z \) (2.17) object. Additional observations will allow us to check whether the Kaspi empirical relationship holds at high redshift. At the moment we cannot rely on the mass derivation of one source only. The UV extrapolation for single-epoch virial-broadening estimates in Vestergaard & Peterson (2006) shows a much larger scatter but is the only relation that provides an \( M_{BH} \) suitably comparable with our result. Errors obtained with our method are a factor of \( \sim 3 \) smaller than the dispersion in the Vestergaard & Peterson (2006) relation. However, the latter errors are statistical, making the comparison not very straightforward. In a forthcoming paper (C. A. Negrete et al. 2012, in preparation) we will give the results of a statistical analysis applying our method to a larger number of quasars than reported here (8 at high \( z \) and 14 at low \( z \), belonging to both Pops A and B). Preliminary results are given in Negrete (2011). These are all Type 1 (broader line) quasars.

6.2.1. Caveats

Our estimation of \( r_{BLR} \) assumes that the continuum incident on the line-emitting gas is “as observed” by us. Leighly (2004) suggests (for two I Zw 1-like sources: IRAS 13224-3809 and 1H0707-495) that a high-ionization wind producing the BLUE component (we fit to the HILs; Marziani et al. 2010) intercepts most of the ionizing flux—leaving only a small fraction available for photoionizing the LIL-emitting
region. The empirical analysis of their UV spectra is similar to ours with separation of unshifted BC and BLUE components (Leighly & Moore 2004). While continuum absorption should not strongly influence the determination of \( n_H \) and \( U \) (they are set by line ratios dependent on physical conditions in the gas), the \( r_{BLR} \) value will be affected (Equation (8)). Absorption as extreme as hypothesized by Leighly (2004, a factor of 10) would lead to a decrease of \( r_{BLR} \) by \( \approx 0.5 \) dex. However, any consideration is highly dependent on the assumed geometry. The configuration envisaged by Leighly (2004) suffers from an immediate observational difficulty. If the LIL-emitting regions were being hit by a wind, then the LILs should be emitted by gas ablated from a thick structure and with some of the wind momentum transferred to the ablated gas. There is no observational (kinematical) evidence for this: the LILs and intermediate-ionization lines show stable, unshifted (to within a few hundred km\ s\(^{-1}\)), and symmetric profiles. It is worth noting that the LILs are even unaffected by the presence of a powerful radio jet in RL quasars (Marziani et al. 2003). In summary, current evidence suggests that the LIL-emitting region is not strongly affected by quasar outflows.

7. CONCLUSION

Diagnostic line ratios for estimation of density, ionization, and metallicity can be found and exploited for NLSy1-like sources at high redshift. Accurate diagnostics require high-S/N and moderate-dispersion spectra but in principle can be applied to very high \( z (>6.5) \) using data from IR spectrometers. The product \( (n_H \cdot U) \) yields the possibility of deriving \( r_{BLR} \) and \( M_{BH} \) for a significant number of sources for comparison with estimates derived from extrapolation of the Kaspi relation. C. A. Negrete et al. (2012, in preparation) will present an analysis of the applicability of the photoionization method described here to the general population of quasars starting from the sources with reverberation mapping determinations of \( r_{BLR} \).

It is important to stress, however, that the line deblending that allows us to obtain the line fluxes used to compute \( n_H \) and \( U \) is not a trivial task. There is a wide diversity in the quasar spectra, and one must consider previous results that allow us to predict and/or expect the presence and shape of various components in the broad lines (as discussed in Section 3.1). One also has to take into account expectations on certain line ratios (e.g., the extreme Pop. A sources show the lowest \( \lambda 1909/\lambda 3727 \) ratio among all quasars in the E1 sequence; see Section 3.2.2).

The results of this study are preliminary in many ways. Several issues remain open: (1) Is there a “universal” \( n_H \cdot U \) product that can be used for all AGNs? The consistency among our results, the ones reviewed in Section 5.2 and the \( r_{BLR}-L \) relation, suggest that this might be the case, at least to a first approximation and especially for Pop. A sources. (2) A grid of simulations could be refined considering more intermediate-metallicity cases. (3) Application of this method has been carried out without considerations about the geometry and kinematics of the BLR. A more refined treatment should consider likely scenarios and investigate their influence on derived physical parameters. (4) Considerations of geometry and kinematics could lead to a physical model accounting for non-thermal heating and production of Fe \( \Pi \) emission in a context more appropriate than that of pure photoionization.

As a final remark, we stress that values of \( M_{BH} \) derived from photoionization considerations, even assuming an average \((n_H \cdot U)\), are probably more accurate than the ones derived from the mass–\( L \) relation. The main reason is that we are using each individual quasar luminosity (and not a correlation with scatter) and the properties of a region that remains similar to itself over a wide range of luminosity.

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