LOW-IONIZATION OUTFLOWS IN HIGH EDDINGTON RATIO QUASARS

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1 by definition, the Mg II λ 2800 line width—affected by blueshifted emission—is unsuitable for virial mass estimation in ≈10% of quasars.

Key words: quasars: emission lines – quasars: general – quasars: individual (SDSS J150813.02+484710.6)

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1. INTRODUCTION

Estimation of black hole mass (M_{BH}) and Eddington ratio (L/L_{Edd}) for quasars is of great interest both to researchers working on models of the broad-line region (BLR) structure and to cosmologists. Therefore, we need a large number of accurate-as-possible estimates over the widest possible range of redshift, source luminosity, and line/continuum properties. FWHM(Hβ) is the principal virial estimator at low redshifts. While Hβ can be followed into the infrared (out to z ≈ 3.7), at least one additional line is needed to provide complementary M_{BH} estimates over the full redshift range where quasars are observed. Mg II λ 2800 is the best candidate since it is a low-ionization line (LIL) and avoids some of the difficulties associated with CIV λ 1549 (e.g., Netzer et al. 2007; Sulentic et al. 2007; Steinhardt & Silverman 2011; Marziani & Sulentic 2012; Trakhtenbrot & Netzer 2012; Denney 2012).

The advent of the Sloan Digital Sky Survey (SDSS) database has made it possible to perform a direct calibration of Mg II λ 2800 using sources where both Mg II λ 2800 and Hβ appear in the same SDSS spectra. Only high signal-to-noise composite spectra can provide an ideal vehicle for such comparisons. In addition, one must consider that a source diversity found within the context of a formalism like four-dimensional eigenvector 1 (4DE1; Sulentic et al. 2000, 2007; Marziani et al. 2010) is large and likely driven by the Eddington ratio L/L_{Edd} (e.g., Boroson & Green 1992; Marziani et al. 2001; Boroson 2002; Grupe 2004; Krucezk et al. 2011; Tang et al. 2012). The 4DE1 allows us to identify whole emission line profiles of sources whose spectrophotometric properties are strikingly different. A notable empirically motivated boundary at low and moderate luminosity is set by FWHM(Hβ) ≈ 4000 km s^{-1}. Sources narrower than this limit show Hβ profiles that are well fit by a Lorentzian function, while broader sources show prominent redward asymmetries in their Hβ profiles (e.g., Véron-Cetty et al. 2001; Marziani et al. 2003b). Sources with FWHM(Hβ) ≤ 4000 km s^{-1} by definition include narrow-line Seyfert 1s (NL Sy1s) and are characterized by a significant high-ionization outflow, revealed by a CIV λ 1549 blueshift with respect to the rest frame or to broad LILs (e.g., Gaskell 1982; Tytler & Fan 1992; Marziani et al. 1996; Sulentic et al. 2007; Richards et al. 2011). The outflow has been ascribed to a radiative or magnetically driven wind (e.g., Murray & Chiang 1997; Bottorff et al. 1997; Proga et al. 2000). Therefore, it is important to at least distinguish between sources that appear to be wind- or disk-dominated (Richards et al. 2011), applying the limit at FWHM(Hβ) = 4000 km s^{-1} that separates Population A and B sources (Sulentic et al. 2000; see Collin et al. 2006).

A finer subdivision is still needed even with the restriction to Populations A and B sources. A B source spans a relatively large range in Eddington ratio, Δ log L/L_{Edd} ≈ 0.5, that likely does not only involve the highest Eddington radiators. We apply the spectral classification of Sulentic et al. (2002) which divides the plane FWHM(Hβ) – R_{FeII} into bins of Δ R_{FeII} = 0.5 and Δ FWHM(Hβ) = 4000 km s^{-1}, where R_{FeII} is computed as the equivalent width (EW or intensity) ratio of the Fe ii λ 2570 blend and broad Hβ (see their Figure 1). Extreme Pop. A (A3 and A4) sources with R_{FeII} ≳ 1 are characterized by the strongest high-ionization outflow, with the largest CIV λ 1549 blueshifts (Marziani et al. 2006; Sulentic et al. 2007), and are believed to be the highest Eddington ratio sources. A large low-z sample covering the Hβ and Mg II λ 2800 emission lines is defined (Section 2). We point out intriguing changes of the Hβ and Mg II λ 2800 line profile occurring in bins A3 and A4 (Section 3) and discuss first-order considerations about the physics involved (Section 4).

2. SAMPLE SELECTION AND CONSTRUCTION OF COMPOSITE SPECTRA

We searched SDSS Data Release 7 for sources catalogued as type 1 active galactic nuclei (quasars) in the redshift range 0.4–0.75 and with magnitudes brighter than g ≈ 18.5 in the g, r, or i bands, as well as in the Zhou et al. (2006) catalog.
The resultant sample consisted of 716 quasars reduced to 680 (all of Pop. B:369 sources; A1:97, A2:156, A3:43, A4:15) by discarding very noisy spectra and some sources with unusually red colors. Broad absorption line (BAL) quasi-stellar objects were excluded from the sample.

The rest frame was set by measuring the wavelengths of three of the most prominent narrow lines ([O II] λ3727, Hβ, and [O III] λ5007) when they were detected. Residual systematic wavelength shifts (Hewett & Wild 2010), in addition to the SDSS-provided redshift values, were computed by taking an average of the three lines in each source spectrum, clipping individual measurements in cases of disagreement because of poor data or intrinsic blueshift of [O II] λ5007 (Hu et al. 2008). We used IRAF SPLOT to estimate FWHM(Hβ) in order to better separate sources into spectral bins, following the prescription in Sulentic et al. (2002). Assignments for all bins were made by visual inspection of each spectrum and estimation of $R_{Fei}$ through NGaussfft. Median composites were constructed, respectively, for Hβ and Mg II λ2800 after redshift correction and continuum normalization at 5050 Å and 3050 Å. The rest-frame radial velocity of the composites (defined by the average of peak radial velocity of narrow [O II] λ3727, Hα, Hγ, Hβ, and [O III] λλ4959, 5007) was found to be $<10$ km s$^{-1}$ in bins A1 and A2, and $<20$ km s$^{-1}$ in bins A3 and A4, with an rms value that was always less than 50 km s$^{-1}$. A line can be considered unshifted with respect to the rest frame if it is $|\Delta\nu| \leq 100$ km s$^{-1}$. The relative uncertainty of $\nu_o$ measurements for the Hβ and Mg II λ2800 peak velocities on the composite spectra is somewhat less and has been estimated by determining three sources of error: (1) zero point, where [O II] λ3727 and Hβ narrow component peak wavelengths measured in the four composites agree within rms $\pm 10$ km s$^{-1}$; (2) wavelength calibration, by measuring the dispersion in wavelength measurements of strong sky lines, typically $\pm 15$ km s$^{-1}$: systematic shifts are consistent with 0 ($\leq 25$ km s$^{-1}$) for Hg I λ4359 and OH λ8401 lines whose wavelengths correspond roughly to the wavelengths of the redshifted Mg II λ2800 doublet and Hβ line, respectively; and (3) peak line position determined by the multicomponent fit, as provided by the fitting program SPECTFIT (Section 3).

Interpretation of the Hβ spectral range closely follows previous work (Boroson & Green 1992; Marziani et al. 2003a, 2009). Along with continuum and Fe II emission fitted over the spectral range 4430–5510 Å, we will include possible contribution from He I lines at 4471 and 5016 Å (which appear to be significant only for bin A1), He II λ4686, and a contribution due to [Fe II] and [N II] lines at $\approx 5150–5200$ Å. The region around Mg II λ2800 has been studied by several authors since the mid-1980s (Wampler 1985; Brotherton et al. 1994; Graham et al. 1996; Laor et al. 1997; Vestergaard & Wilkes 2001). Emission blends near Mg II λ2800 are mainly due to Fe II. We define a range for our SPECTFIT analysis (2600–3050 Å) that is a compromise between proximity to the line and the necessity of having sufficient continuum coverage to properly map the broad Fe II blends. We also include other known lines, e.g., semi-forbidden Al II] 2669.95 and O III 2672.04 in the fits. Brühweiler & Verner (2008) provide Fe II emission templates computed from CLOUDY simulations and using an 830 level model of the Fe$^+$ ion. Use of the Brühweiler & Verner (2008) Fe II emission template results in a systematic residual near 2950 Å (Figures 1 and 2). The excess flux is probably due to the blend of He I λ2945 and Fe I emission from a cluster of lines produced by transitions from the terms $z^2F$ and $a^2D$ to the ground state ($a^2D$). Fe I emission has been predicted by photoionization models (Sigut et al. 2004) and was suggested by previous observations (e.g., Kwan et al. 1995; Graham et al. 1996). The flux deficit is larger than the Fe I predicted by photoionization models, at least by a factor of several with respect to a low-ionization, three-times solar metallicity case (model u20h11 of Sigut et al. 2004). However, several lines associated with Fe I multiplets 1 and 9 and opt 30 have been convincingly identified in a strong Fe II emitter (Graham et al. 1996), and the emission of Fe I with respect to Fe II might increase with metallicity (Sigut et al. 2004). The issue of Fe I emission deserves further investigation not least because Fe I intensity is strongly dependent on the assumed Fe II model at 2900–3000 Å. For the sake of the present paper, we checked that the peak shift of Mg II λ2800 is basically unaffected even by strong changes in the assumed Fe I strength.

3. RESULTS

3.1. Broad-line Profile Analysis

Composite spectra were analyzed using SPECTFIT with $\chi^2$ minimization techniques appropriate for nonlinear multicomponent fits (Kriss 1994). The procedure allows for simultaneous continuum, Fe II, and narrow-line fitting. Two Fe II emission templates were applied: the theoretical one by Brühweiler & Verner (2008) and an empirical template produced by Tsuzuki et al. (2006). The use of two independent templates was justified by possible effects that Fe II subtraction might have on the measurements of line shifts. Continuum-subtracted composite spectra are shown in Figure 1 for bins A1 and A2, and in Figures 2 and 3 for bins A3 and A4. The Mg II λ2800 doublet was first modeled as two Lorentzian-like functions of the same width and relative intensity ratio, 1.25:1. This assumption is justified by the value of the prototypical A3 source I Zw1, and by the physical conditions within the BLR (Laor et al. 1997). The lines may become fully thermalized at the extreme optical depth of the LIL BLR, justifying the assumption of a 1:1 ratio. We have also carried out several fits for the 1:1 case, but the results for the line shifts and widths are very close to the 1.25:1 case and do not affect any of the conclusions discussed below.

Table 1 reports the results of the our multicomponent analysis: intensity, shift $\pm$ uncertainty at 2$\sigma$ confidence level (estimated as described at the end of Section 2), and FWHM of the two line components used to model line profiles, i.e., the broad component (BC) and, when appropriate, a blueshifted component (blue). The radial velocity was measured with reference to the vacuum wavelength of the $^2P_{3/2} \rightarrow ^2S_{1/2}$ component, 2796.35 Å. Uncertainties in BC centroid shifts are significantly larger toward the line profile base than at peak, and are estimated to be $\pm 400$ km s$^{-1}$ for the centroid at 1/4 peak intensity. Columns BC and blue Int. report the Hβ and Mg II λ2800 line intensity normalized by continuum flux at 5050 Å. The normalization at 5050 Å ensures that the Hβ value roughly corresponds to the line EW, and that meaningful intensity ratios for Mg II λ2800/Hβ can be computed from the values reported in the table. Note that Mg II λ2800 intensity values are for the doublet, while reported FWHMs are for an individual component. The formal uncertainty in FWHM measurements of Hβ and Mg II λ2800 BC is, in the absence of systematic effects, around 2% for spectral types A1 and A2, and 5% in all other cases. The shifts and width of the blue components are subject to considerably larger uncertainties since they are close to the much stronger BC. In addition, their values depend on the line profile assumed for the fit. The formal

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Figure 1. Spectra of Hβ (left panels) and Mg II λ2800 (right panels) for spectral types A1 (top) and A2 (bottom). The horizontal scale is the rest-frame wavelength (Å) or radial velocity with the origin indicating rest-frame (laboratory) wavelength. In the Mg II λ2800 panels, the vertical dot-dashed line is drawn at the reference wavelength 2799.4, which corresponds to a component ratio 1.25:1.00. The black lines show the original continuum-subtracted spectrum, while the dashed magenta line shows the model including all emission-line components. The thick black lines show the broad component and the thin black lines show the individual components of the Mg II λ2800 doublet. The green lines trace Fe II opt and Fe II UV emission and the gold-brown lines trace various contributions associated with the narrow-line region (HβNC, [O iii] λλ4959,5007). In the Hβ panels, significant He II λ4686 is revealed (thick blue line). In the A1 Hβ panel, He I λ4924 and He I λ5016 (black lines) almost overlap with the m42 Fe II opt lines. The Fe I + He I λ2945 emission (modeled as the sum of two Gaussians) is also traced by a brown line and is visible toward the right end of the Mg II λ2800 panel at ≈2950 Å.

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

uncertainty (i.e., without considering the possibility of different profile shapes) derived for the FWHM of the blue components is ≲10% in all cases.

Fits to Hβ and Mg II λ2800 in the A1 and A2 bins needed only symmetric, unshifted Lorentzian line components. The BC accounts for the entire Hβ and Mg II λ2800 profiles in the A1 and A2 sources where the ratio FWHM(Mg II λ2800)/FWHM(Hβ) ≈ 0.75–0.80 (Table 1). This FWHM ratio also holds for Pop. B sources and, therefore, for 90% of quasars (Wang et al. 2009; Trakhtenbrot & Netzer 2012; J. W. Sulentic et al. 2013, in preparation). The simplest interpretation is that the emissivity-weighted distance of the Mg II λ2800 emitting gas is somewhat larger than that for Hβ (≈1.5 following the virial assumption, see also Section 4).

The Hβ profiles in the A3 and A4 bins also involve an (almost) unshifted, symmetric component (the BC) with
FWHM(Hβ$_{BC}$) $\sim 2000$ km s$^{-1}$ which we assume to be the virial broadening estimator. However, fits to the Hβ profile for sources in the A3 and A4 bins require an additional blueshifted (column “blue” in Table 1) component in order to minimize residuals (e.g., Leighly 2000; Leighly & Moore 2004; Marziani et al. 2010; Wang et al. 2011). The “blue” component was modeled first as a symmetric Gaussian, in agreement with past work. The right panels of Figure 2 show that a good fit to the Mg II $\lambda 2800$ profiles in A3 and A4 is possible using a shifted symmetric Lorentz function with a profile shift of a few hundred km s$^{-1}$.

At second glance, a skewed Gaussian (Azzalini 1985) was considered for both Hβ and Mg II $\lambda 2800$ (Figure 3). In this case, a two-component model is also possible for the spiky Mg II $\lambda 2800$ profile. We assumed unshifted BC Mg II $\lambda 2800$ emission with FWHM(Mg II $\lambda 2800$) = 0.8 FWHM(Hβ), plus an additional blueshifted component described by a skewed Gaussian as for Hβ. The resulting Mg II $\lambda 2800$ line decomposition is shown in the right panels of Figure 3. Line parameters are reported in Table 1 (A3b and A4b).

### 3.2. A Systematic Mg II $\lambda 2800$ Blueshift

Bins A3 and A4 (10% of all quasars) behave differently than the wide majority of quasars since their FWHM(Mg II $\lambda 2800$) $\geq$ Hβ. The ratio of FWHM(Mg II $\lambda 2800$)/FWHM(Hβ) is larger...
than unity in bin A4, with Hβ and Mg II λ2800 showing the same width in bin A3 (lower panel of Figure 5) where a peak blueshift is already highly significant. As was mentioned previously, the Mg II λ2800 doublet appears to be blueshifted with respect to rest frame and Hβ in spectral types A3 to A4, where Hβ shows evidence for a blueshifted component (Figure 2; see also Marziani et al. 2010). The Mg II λ2800 blueshift reaches ≈20% of the half line width in bin A4. In bins A3 and A4, the core of the Mg II λ2800 profile is narrow enough to appear visually displaced relative to the rest frame (Figure 2). Even when measuring the position of the broad-line core (without any correction because of contaminant lines) with SPLOT, we obtain consistent values. The effect is too large to be ascribed to sources of uncertainty on the rest frame, and it is even more significant if relative line shifts are considered. As was mentioned previously, we repeated the fits for all bins assuming that the doublet ratio is 1.0:1.0. This results in a slightly larger Mg II λ2800 blueshift. To further test the reality of the shift, we considered the maximum doublet ratio for expected physical conditions in the BLR to be 1.5:1.0. We constructed noiseless mock profiles to derive a peak
Figure 4. Spectra of Hβ (left panels) and Mg II λ2800 (right panels) for quasar SDSS J150813.02+484710.6. The vertical scale is the specific flux in units of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. The meaning of all of the other symbols is the same as in Figures 1 and 3.

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

Table 1

| Sp. T. | Hβ | Mg II λ2800 |
|-------|-----|-------------|
|       | BC  | Blue        | BC  | Blue        |
|       | Int.a | Shift.b | FWHM.b | Int.c | Shift.b | FWHM.b |
| A1    | 96.0 | 20 ± 40   | 3180.0 | 0.0 | n.a. | n.a. |
| A2    | 85.0 | -20 ± 40  | 2900.0 | 0.0 | n.a. | n.a. |
| A3    | 45.0 | 45 ± 40   | 2190.0 | 12  | -1240 ± 230 | 4250.0 |
| A3b   | 54.0 | 45 ± 40   | 2190.0 | 6.5 | -1420 ± 510 | 4100.0 |
| A4    | 28.0 | 70 ± 50   | 1980.0 | 16  | -1240 ± 220 | 4870.0 |
| A4b   | 29.0 | 70 ± 50   | 1940.0 | 13  | -1530 ± 200 | 4460.0 |
| J1508+48 | 32  | -5d       | 2300.0 | 5.0 | -1540 ± 100 | 4000.0 |
|       | 111 | 35 ± 50   | 2710.0 | 0.0 | n.a. | n.a. |
|       | 73  | -70 ± 50  | 2320.0 | 0.0 | n.a. | n.a. |
|       | 65  | -150 ± 50 | 2240.0 | 0.0 | n.a. | n.a. |
|       | 54  | 0d        | 1750.0 | 5.6 | -880 ± 170 | 3100.0 |
|       | 68  | -265 ± 90 | 2650.0 | 0.0 | n.a. | n.a. |
|       | 46  | 0d        | 1585.0 | 10  | -1010 ± 130 | 3300.0 |
|       | 37  | 0d        | 2190.0 | 20  | -1490 ± 160 | 3500.0 |

Notes.

Line intensity normalized to the continuum at 5050 Å. The value roughly corresponds to the rest-frame equivalent width in Å. For J1508+48, values are in units of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. In units of km s$^{-1}$. Line intensity normalized to the continuum at 5050 Å. The value can be used an estimate of the Mg II λ2800/Hβ intensity ratio. For J1508+48, values are in units of $10^{-15}$ erg s$^{-1}$ cm$^{-2}$ Å$^{-1}$. Imposed to be consistent with rest frame. FWHM(Mg II λ2800) = 0.8 FWHM(Hβ), for broad component.

wavelength in the case of Mg II λ2800 treated as single line, for doublet ratios 1.5, 1.25, 1 to 1. The effective wavelength of the doublet is 2799.1, 2799.4, and 2800.1 for the three ratios, respectively. Also, in the case of 1.5:1.0, the peak shift will remain significant.

The Mg II λ2800 A3 and A4 fits with a shifted symmetric function probably only yield a lower limit to the shift amplitude since, if a two-component interpretation is correct, they also include unshifted emission line gas. Yet these Mg II λ2800 fits are meaningful since they provide a robust measurement of a significant blueshift affecting the Mg II λ2800 line profile. Renouncing the symmetric Gaussian approximation for the blueshifted emission (in Hβ) provides support for profile decomposition into two components (Figure 3). With the exception of A4 Hβ, both Hβ and Mg II λ2800 median spectra show blue components with strong blueward asymmetry: the blue component profiles vaguely resemble the “trapezoidal” shape of the I Zw 1 C IV λ1549 profile (see Leighly 2000). The lower $v_\lambda$ derived for the Mg II λ2800 blueshifted component with respect to that of Hβ in bins A3 and A4 is consistent with the profile shape difference since Hβ is more affected toward the line base, while Mg II λ2800 is affected closer to the line core. Indeed, in all cases, the shift of Hβ is larger than the shift of Mg II λ2800. This result provides an important constraint on the emitting region structure (Section 4). Considering the strongly skewed blue component line profiles in A3 and A4, the estimated shifts...
reported in Table 1 could be more properly considered as upper limits, since symmetric blueshifted Gaussians would yield some emission under the BC with lower shift values.

The most extreme source in our sample involves SDSS J150813.02+484710.6, whose Mg II λ2800 and Hβ profiles are shown in Figure 4. Hβ shows a prominent blue asymmetry, while Mg II λ2800 is fully blueshifted with width and shift amplitude similar to those measured for C IV λ1549 in extreme Pop. A sources such as I Zw 1. For this source, we apply to the Mg II λ2800 profile only the profile model appropriate for C IV λ1549 of extreme Pop. A quasars, i.e., an unshifted double Lorentzian plus a blueshifted component approximated with a skewed Gaussian. While uncommon, other sources like J1508+48 have been found (see, e.g., Q1258+1404; Barthel et al. 1990).

3.3. Major Trends

3.3.1. Spectral Types

The upper panel of Figure 5 shows radial velocity \( v_r \) trends of BC peaks as a function of spectral type, while the lower panel shows trends of the ratio FWHM(Mg II λ2800)/FWHM(H/β). Mg II λ2800 line shift measurements shown in Figure 5 were carried out in three different ways: (1) using SPECFIT with the theoretical Fe II template, (2) using SPECFIT with the Fe II template from Tsuzuki et al. (2006), and (3) measuring the position of the broad-line core without any correction. The three sets of measures yield consistent trends. The interesting change in the lower panel of the figure involves a tendency for the FWHM ratio to increase first to parity in bin A3, and finally to FWHM(Mg II λ2800) > FWHM(H/β) in bin A4 (see Trakhtenbrot & Netzer 2012). This trend likely accounts for the large scatter (and convergence toward parity) of single-source measures in Figure 2 of Wang et al. (2009). The consistent behavior of both shift and FWHM strengthens our confidence that the trends are real. The increase in FWHM(Mg II λ2800) lends support to the hypothesis that an additional blueshifted component is emerging on the blue side of an shifted BC with FWHM(Mg II λ2800) ≈ 0.8 FWHM(H/β). A symmetric blueshifted Lorentzian model is helpful for ascertaining the reality of the blueshifts but seems physically unrealistic. The blueshifts are more likely associated with a Mg II λ2800 component due to gas moving at larger velocity than the ones inferred from the global shift of the line core (Table 1).

3.3.2. Eddington Ratio

We estimated the median \( M_{bol} \) values by computing median 5100 Å luminosities from fluxes of all of the sources in each bin and with FWHM measures of the median composites following the prescription of Assef et al. (2011). A bolometric correction to the 5100 Å luminosities was applied following Nemmen & Brotherton (2010) in order to derive \( L/L_{Edd} \) values. The semi inter-quartile range (SIQR) of \( L/L_{Edd} \) has been estimated using the individual FWHM H/β measurements carried out for spectral bin assignment (Section 2). All of the bins show very similar median bolometric luminosities, log \( L \approx 46.2 \) (erg s\(^{-1}\)). Figure 6 shows the peak shift of the Mg II λ2800 broad and blue components as a function of \( L/L_{Edd} \). Shift values have been normalized by the H/β half-width-at-half-maximum (HWHM) in order to provide an indicator of dynamical significance to the shifts. The peak Mg II λ2800 shift is consistent with zero for spectral types A1 and A2 but begins to appear at
log $L/L_{\text{Edd}} \sim -0.5$ at type A2, increasing to 0.2/0.3 of half-width for A3 and A4. The shift amplitude is much larger when the blueshifted component is considered. If 0.8: HWHM can be considered to be rough estimator of the virial velocity of the Mg $\Pi$ $\lambda$2800 emitting gas, then A4 and SDSS J1508+4847 show outflows close to escape velocity. The main difference between median A4 and the source SDSS J1508+4847 is related to the amount of outflowing gas: in A4, the blue component is contributing 1/7 of the total line emission while it exceeds 1/3 in SDSS J1508+4847.

4. DISCUSSION

The Mg $\Pi$ $\lambda$2800 profile in the median spectra is different from both C IV $\lambda$1549 and H$\beta$. A comparison between the latter two lines provided clues about the BLR structure (Marziani et al. 1996). The C IV $\lambda$1549 blueshift in low-z sources is thought to be associated with a wind component whose prominence increases with $L/L_{\text{Edd}}$ along the 4DE1 sequence. The C IV $\lambda$1549 profile in bins A2–A4 can be modeled as a combination of the H$\beta$ BC profile plus a fully blueshifted component that accounts for most of the flux. This basic scenario has been confirmed by recent work (see, e.g., Richards et al. 2011; Wang et al. 2011).

In the case of Mg $\Pi$ $\lambda$2800, we see a $v_\lambda$ displacement that is also significant with 200–300 km s$^{-1}$ if the shift is measured on the full profile. As has been pointed out, this is likely a lower limit. If the blue component is considered, then the shift amplitude is much larger ($\sim$1000 km s$^{-1}$) but significantly lower in Mg $\Pi$ $\lambda$2800 than in H$\beta$. We are considering median spectra so the profiles represent the median behavior of line profiles—in some sense, equivalent to a single-source rms profile. So we can ask: What is the typical relation between the blueshifted C IV $\lambda$1549 and H$\beta$ on the one hand and the blueshifted Mg $\Pi$ $\lambda$2800 emission on the other?

4.1. Mg $\Pi$ $\lambda$2800 Blueshift: Emission from a Radiation-driven Wind

The Mg $\Pi$ $\lambda$2800 blueshift is most straightforwardly interpreted as being due to outflow motions of the line-emitting gas with preferential obscuration of the receding part of the flow. The fact that large blueshifts are observed when $L/L_{\text{Edd}}$ is highest indicates a role of the radiation force in the acceleration of the gas. If we consider gravitation and ionizing radiation to be the only forces (neglecting drag forces and pressure gradients), then the radial acceleration can be written as $a(r) \propto \sigma M_{\text{BH}}/r^2 [a(r)/(\sigma N_{\text{e}})L/L_{\text{Edd}} - k]$, where $\sigma$ is the fraction of bolometric luminosity absorbed, $N_{\text{e}}$ is the column density, and $k$ is the Thompson scattering cross-section, and $k$ is a constant term. If the first term in the square brackets exceeds $k$, then the outflowing velocity field of the gas will follow the form $v(r) = v_\lambda \sqrt{r/r_{\text{min}}}$, where $r_{\text{min}}$ is the launching radius of the wind and $v_\lambda$ is the terminal velocity ($\propto \sqrt{L/r_{\text{min}}}$). Outflows driven by line and/or ionizing photon pressure can accelerate the line-emitting gas to $v_\lambda \approx k (ML/L)^{1/2} \approx (ML/L_{\text{Edd}})^{1/2} v_{\text{Kepler}}$, where $v_{\text{Kepler}}$ is the Keplerian velocity at the launching radius of the wind (e.g., Laor & Brandt 2002). In the case of outflows driven by ionizing radiation, the force multiplier $M$ is expected to be $M = (\alpha/\sigma N_{\text{e}}) \approx 7.50.5 N_{\text{e}}^{-1.23}$, where $\alpha \approx 0.5$ for Compton-thick gas that is optically thick to the ionizing continuum (Netzer & Marziani 2010). $M$ can be $\gg 1$ in the case of line-driven winds (Proga et al. 2000).

The largest C IV $\lambda$1549 blueshifts are observed in spectral types A3 and A4 (in A3, $-1000 \lesssim \Delta v_\lambda \lesssim -2000$ km s$^{-1}$), where the Mg $\Pi$ $\lambda$2800 shifts also occur. It therefore seems unlikely that there is no connection between C IV $\lambda$1549 and Mg $\Pi$ $\lambda$2800: both lines may be emitted as part of the same flow. However, bulk emissions are expected to occur at different distances and/or in different physical condition. In the framework of photoionization, Mg $\Pi$ $\lambda$2800 emission is associated with low-ionization and relatively large column density gas (Netzer 1980; Korista et al. 1997). Within a gas slab or cloud, Mg $\Pi$ $\lambda$2800 is emitted mainly beyond the fully ionized zone of geometrical depth $h \sim 10^2 U n_{\text{H}}^{-1}$ (with $U$ being the ionization parameter) where all of the C IV $\lambda$1549 is emitted. The total column density needed for substantial Mg $\Pi$ $\lambda$2800 production is not well constrained at very low ionization, since the fully ionized zone is already a tiny fraction of the emitting gas slab if $N_{\text{c}} \sim 10^{23}$ cm$^{-2}$ and log $U \lesssim -1$.

Since $v_\lambda$ is proportional to both $N_{\text{c}}^{-1/2}$ and $r_{\text{min}}^{-1/2}$, Mg $\Pi$ $\lambda$2800 emission may occur at a higher column density and/or larger distance than blueshifted C IV $\lambda$1549. A large $r_{\text{min}}$ is consistent with the overall symmetry of the Mg $\Pi$ $\lambda$2800 profile base (Section 3.2; Figures 1–3). Reverberation mapping indicates that high-ionization lines are emitted closer to the central continuum than LILs (e.g., Peterson & Wandel 1999). It is possible to ascribe the blueshifted Mg $\Pi$ $\lambda$2800 emission entirely to a larger radial distance if Mg $\Pi$ $\lambda$2800 arises ~2 times more distant than C IV $\lambda$1549. On the other hand, if $L/L_{\text{Edd}} \rightarrow 1$, $v_\lambda \approx \sqrt{M v_{\text{vir}}}$. Restricting our considerations to coarse estimates due to uncertain shift values, a reasonable increase in column density over the standard value $N_{\text{c}} \sim 10^{23}$ cm$^{-2}$ would also suffice to reduce the Mg $\Pi$ $\lambda$2800 shifts to close to the observed values.

An assumption from the behavior of the FWHM ratio is that the Mg $\Pi$ $\lambda$2800 flows start close to where the bulk of the LILs (H$\beta$ in the present case) are emitted. The following considerations also apply if FWHM(Mg $\Pi$ $\lambda$2800)/FWHM(H$\beta$) $\approx 0.8$ implies a $\approx 1.5 \times$ larger emissivity-weighted distance for Mg $\Pi$ $\lambda$2800 than for H$\beta$. The distance from the continuum source of the emitting gas $r_{\text{em}}$ can be derived from the continuum luminosity at 5100 Å following Bentz et al. (2009): $\log r_{\text{em}} \approx 17.6$ (cm) for spectral type A4. If $\log n_{\text{H}} = 12$ (cm$^{-3}$), then the ionization parameter is log $U \approx -2.8$. The Mg $\Pi$ $\lambda$2800 luminosity is then $L(\text{Mg }\Pi \lambda 2800) = 4 \pi r_{\text{em}}^2 f_c \sigma_{\text{em}} = 4 \pi r_{\text{em}}^2 f_c \bar{\epsilon}(N_{\text{c}}/n_{\text{H}})$, where $f_c$ is the covering factor, $\sigma_{\text{em}}$ is the emerging line flux for unit surface, and $\bar{\epsilon}$ is the depth-averaged volume emissivity. CLOUDY (Ferland et al. 1998) simulations indicate that $\sigma_{\text{em}}$ has a minimum value $\approx 10^{-8}$ erg s$^{-1}$ cm$^{-2}$ at log $n_{\text{H}} = 12$ if $-2.8 \lesssim \log U \lesssim -2$, $10^{23}$ cm$^{-2} \lesssim N_{\text{c}} \lesssim 10^{25}$ cm$^{-2}$, and $12 \lesssim \log n_{\text{H}} \lesssim 13$. In these ranges, $\sigma_{\text{em}}$ depends slightly on $N_{\text{c}}$ and $U$. The computed $L(\text{Mg }\Pi \lambda 2800)$ extrapolated to full continuum coverage is always larger than the observed $L(\text{Mg }\Pi \lambda 2800) \approx (10^{43} \text{ erg s}^{-1})$ for A4. This is the case if the geometry is assumed to be static and open or if a velocity field appropriate for a wind (i.e., with a photon local escape probability following Sobolev’s approximation) is considered. The derived $f_c \lesssim 0.2$ indicates a partial covering of the continuum as in a wind or in an ensemble of outflowing clouds.

Resonant line acceleration is expected to contribute to the dynamics of the flow in the physical scenario outlined above. Circumstantial evidence in favor of line acceleration is provided by the difference between a resonance UV line (Mg $\Pi$ $\lambda$2800) and a non-resonance line (H$\beta$). From a purely observational point of view, a line-driven outflow would be convincingly demonstrated if the ionizing photon flux were found to be unable
to drive the line-emitting gas to the observed outflow velocity or, in the context of absorption lines, from “line locking” (e.g., Cottis et al. 2010). However, the ionizing photon flux appears to be sufficient to accelerate the gas to the observed Mg II λ2800 velocities and to escape velocity in A4 sources: for log L/LEdd ≈ −0.2, M ≈ 7.5, and vL ≈ 1.8vKep. If vKep ≈ 0.8 FWHM(Hβ), then vL ≈ 1500 km s⁻¹. This value exceeds the peak velocity of the blue component in bin A3, and is in agreement with the ones measured in A4 and in SDSS J1508+4847. Resonant line acceleration might be needed if the gas has a large Nv (≥ 10^{23} cm⁻²) or if the Mg II λ2800 emitting gas is shielded by part of the continuum.

4.2. Alternate Interpretations

Both Mg II λ2800 and Hβ line profile widths are probably modified by the viewing angle of the outflow/jet axis. Evidence exists that the line width of Hβ is affected by line-of-sight orientation of the jet axis in radio-loud sources (Wills & Browne 1986; Wills & Brotherton 1995; Rokaki et al. 2003; Suletic et al. 2003; Zamfir et al. 2008). An effect on the FWHM of a factor ≈2 is likely between core and lobe-dominated sources. Orientation effects are also expected for radio-quiet quasars (e.g., Jarvis & McLure 2006; Punsly & Zhang 2010). Extreme and variable soft X-ray emission from some NLSy1s (Pop. A) sources has been interpreted as a signature of pole-on orientation (Sulentic et al. 2000 and references therein). Recent work confirms a dependence on orientation for Hβ in radio-loud sources and further suggests a less-strong dependence for Mg II λ2800 (Runnoe et al. 2013). Following this line of reasoning, the occurrence of blueshifts in bin A3/A4 might involve sources viewed at a favorable line-of-sight orientation. It is not clear whether the results of Runnoe et al. (2013) for different orientation sensitivity can be extended to Pop. A, where radio-loud sources are almost absent in bins A2, A3, and A4. Even if the FWHM(Hβ) change could be explained on the basis of an orientation effect, several line intensity ratios change very strongly going from A1 to A4 (e.g., Wills et al. 1999; Aoki & Yoshida 1999; Suletic et al. 2000; Bachev et al. 2004; Baldwin et al. 2004; Negrete et al. 2012; Shin et al. 2013). RFeII by definition, but also CIIλ1909/SiIIIλ1892, AlIIλ1860/SiIIIλ1892, and SiIVλ1397+O+SiIVλ1402/CIVλ1549. Emission line equivalent widths change as well. For instance, the EW of Hβ BC shows a decrease from A1 to A4 by a factor ≈2 (Table 1), as found previously (e.g., Suletic et al. 2000). The large difference in EW also persists if the flux of the blueshifted component is included. Line intensity ratios and line EWs are most likely sensitive to density, ionization state, and chemical composition of the gas, along with ionizing continuum shape (ultimately thought to be governed by Eddington ratio). In this respect, we note that the decrease of W(Mg II λ2800) from ≈110 to ≈70 Å is also consistent with a study showing an anticorrelation between W(Mg II λ2800) and L/LEdd (Dong et al. 2009). It is unclear how orientation might drive such changes. We are probably dealing with a restricted range of L/LEdd in each spectral bin “convolved” with the effect of orientation (Marziani et al. 2001). If a (rare) pole-on orientation favors the observation of large shifts, then SDSS J1508+4847 might be an example of a pole-on source.

5. CONCLUSION

Mg II λ2800 should be used as a virial estimator with caution in high Eddington ratio sources. Under the simplest assumptions, virial line profile blueshift can be interpreted as the signature of emission from radiative acceleration of gas motion, therefore invalidating the virial broadening assumption for Mg II λ2800 in 20% of Pop. A sources (10% of all quasars). Conversely, further work has shown that the majority of quasars show unshifted Mg II λ2800 profiles that are more symmetric than Hβ (J. W. Sulentic et al. 2012, in preparation, and references therein). The width of Mg II λ2800 is probably a suitable virial broadening estimator for those sources.

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