Quasar Main Sequence in the UV Plane

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Abstract
Active galaxies form a clear pattern in the optical plane showing the correlation between the FWHM of the Hβ line and the ratio of the equivalent width (EW) of the optical Fe II emission and the broad EW(Hβ). This pattern is frequently referred to as the quasar main sequence. In this paper, we study the UV plane showing the FWHM of Mg II line against the ratio of the EW of UV Fe II emission to the broad EW(Mg II). We show that the UV plane trends are different, with the underlying strong correlation between the FWHM(Mg II) and the EW(Mg II). This correlation is entirely driven by the choice of the continuum used to measure the EW(Mg II). If instead of the observationally determined continuum, we use a theoretically motivated power law extrapolated from the wide wavelength range, the behavior of the FWHM versus EW for Mg II becomes similar to the behavior for Hβ. Such a similarity is expected since both the lines belong to the low-ionization group of emission lines and come from a similar region. We discuss the behavior of the lines in the context of the broad line region model based on the presence of dust in the accretion disk atmosphere.

Unified Astronomy Thesaurus concepts: Catalogs (205); Surveys (1671)

1. Introduction
Active galactic nuclei (AGNs) are complex sources. A variety of their observed properties have led to various classification schemes (for a recent review, see e.g., Padovani et al. 2017). Even if we limit ourselves to the radio-quiet unobscured AGNs with dusty, molecular torus not crossing our line of sight toward the nucleus, a considerable complexity shows up in the broadband spectra and the emission line properties. It is not surprising since, from the theoretical point of view, we expect that an active nucleus should be parameterized by the mass of the central supermassive black hole, its spin, the accretion rate, and the viewing angle. This last quantity is likely to be important even in unobscured objects since the key elements of an active nucleus, the accretion disk and the broad line region (BLR), are considerably flattened.

Nevertheless, the Principal Component Analysis (PCA) of Boroson & Green (1992) showed that by combining 13 measured AGN spectral properties it was possible to construct an Eigenvector 1 (EV1) relation that was responsible for a significant fraction (29.2%) of the dispersion present in their sample. Thus, AGNs also form a main sequence, although the correlations are by no means as tight as in the case of stellar main sequence.

The key quantity in EV1 was the parameter \( R_{\text{Fe}^{\text{opt}}} \), which is the ratio of the equivalent width (EW) of Fe II lines in the optical band (4434–4684 Å) to the EW of broad Hβ line. Later on, many studies specifically concentrated on the optical plane of EV1 made by \( R_{\text{Fe}^{\text{opt}}} \) and FWHM of broad Hβ line (e.g., Sulentic et al. 2000, 2002; Zamfir et al. 2010; Marziani et al. 2018; Panda et al. 2019b). In parallel, a full multi-parameter PCA approach also continued (e.g., Kuraszkiewicz et al. 2009; Marziani et al. 2018), and a spectral PCA approach started by Francis et al. (1992) was also further developed (Rochais et al. 2017; Davies et al. 2018). However, from the point of view of theoretical interpretation, simpler studies limited to a single plane are particularly attractive.

The existing correlations lead to a characteristic shape covered by the data points in the optical plane. This shape does not always look identical since various authors apply different criteria in selecting objects for plots to enhance the pattern. For example, Shen & Ho (2014) use a smoothing box of the size 0.2 in \( R_{\text{Fe}^{\text{opt}}} \) and of 1000 km s\(^{-1}\) in FWHM, and plot objects only if there are more than 50 objects in the smoothing box. On the other hand, Zamfir et al. (2008) have a relatively small number of objects when they introduce their division of the optical plane into several subclasses, and objects are included in the plot if they belong to these specific subclasses (e.g., Marziani et al. 2018; Panda et al. 2019b, 2020).

In this paper, we study the UV plane in a close analogy to the optical plane of EV1, by replacing the optical Fe II emission with the UV FeII emission, and the Hβ line with the Mg II line. In Section 2 we describe the data we use in the current work. The results for the optical and the UV planes are given in Section 3. Section 3 also includes the correlations of the line widths and the line EWs along with the respective Fe II pseudo-continua. In Section 4, we discuss the expected properties of the BLR at the basis of the assumed BLR model. We also show how the observed correlation between the line width and the line EW for Mg II changes if, instead of a continuum underneath the line, we measure the line EW using a theoretically motivated asymptotic power law. We summarize our results from this work in Section 5.

2. Method
We select a subsample of quasars with the parameters determined by the QSFit\(^5\) (Calderone et al. 2017), which contains 71,261 objects. We did not use the software ourselves

\(^5\)Quasar Spectral Fitting package. We use the parameters determined using their version 1.2.4 available through http://qsft.maf.it/.


but downloaded the QSFit catalog prepared by the authors using the spectroscopic measurements from the Sloan Digital Sky Survey (SDSS). The fitting method of Calderone et al. (2017) assumed a power-law model for the AGN continuum, a Balmer continuum component, and a host galaxy contamination based on an elliptical galaxy template. The Hβ and Mg II line profiles were measured assuming two Gaussians (one for the narrow component and the other for the broad component), and Fe II pseudo-continuum in the optical and UV bands were fitted using the appropriate templates. Additional Gaussian components were also added whenever necessary.

Our subsample contains all quasars from this catalog that have both Mg II and Hβ lines within the observed range. We limited ourselves to sources with the measurement errors of each of the following quantities smaller than 20%: the fraction of objects that satisfy each criterion are marked within parentheses: FWHM(Hβ) (15 179/71 261), FWHM(Mg II) (9215/71 261), EW(Mg II) (9155/71 261), EW(Hβ) (8947/71 261), EW(Fe IIUV) (6861/71 261), and EW(Fe IIopt) (3536/71 261). Next we add two more selection criteria. We request the EW(O III5007) measurement to be non-zero, which reduces the sample to 2967 objects, and we exclude for which the loudness parameter were moderately bright, the distribution of the radio to optical luminosity is satisfactory, with the median signal-to-noise ratio of the spectra in the sample is 45.8, typical for intermediate redshift quasars. Selected sources are moderately bright, the distribution of the radio-loudness parameter is quite different but this is due to the adopted wavelength range 2700–2900 Å region at 13.9, and the median S/N per pixel for the rest frame 2900–3090 Å region at 15.3. The typical relative measurement errors in the selected sample are reported as follows: for FWHM(Hβ) = 0.0603, FWHM(Mg II) = 0.0439, EW(Hβ) = 0.0578, EW(Mg II) = 0.0359, EW(Fe opt) = 0.0838, and, EW(Fe UV) = 0.0837.

The EW(Fe opt) in the QSFit catalog is measured in the wavelength range 3500–7200 Å (rest frame; Véron-Cetty et al. 2004), and the EW(Fe UV) is measured in the range 1250–3090 Å (rest frame; Vestergaard & Wilkes 2001). The optical range for the quoted Fe II emission is systematically different from the values given by Shen et al. (2011) and Shen & Ho (2014) who have used only the range from 4434 Å to 4684 Å, based on the Boroson & Green (1992) prescription. For each object we recalculate the EW(Fe IIopt) from 3500–7200 Å (rest frame) to 4434 Å - 4684 Å. We reconstruct the continuum for each object using the continuum luminosity and the spectral slopes computed and provided in the QSFit catalog. Smearing the iron template (Véron-Cetty et al. 2004) to v = 3000 km s⁻¹ for the broad component and v = 500 km s⁻¹ for the narrow component, and re-normalizing the flux, we compute the EW(Fe IIopt) for the new spectral window. This complex procedure is roughly equivalent to rescaling the EW(Fe IIopt) values obtained from the QSFit catalog by a factor of ~6 for the majority of the sample objects.

3. Results

For this subsample we construct the optical and the UV plane by plotting the FWHM(Hβ) versus the ratio R_Feopt = EW(Fe IIopt)/EW(Hβ), and the FWHM(Mg II) versus the ratio R_FeUV = EW(Fe IIUV)/EW(Mg II) (see Figure 3) and compare the properties of the two planes. The optical quasar main sequence (upper panel of Figure 3) is well visible as in the diagrams presented in the literature (Sulentic et al. 2000; Zamfir et al. 2010; Shen & Ho 2014; Marziani et al. 2018). It constitutes a general trend of decreasing FWHM(Hβ) with increasing strength of the Fe IIopt contribution measured with respect to the Hβ. The extension of the plot in R_Feopt is larger (we have values above 2.25) than the values shown by Shen & Ho (2014) since they limited their sample objects densely populating the diagram while we did the selection at the basis of the fit quality. We colored the objects with respect to the EW(O III) and we see a general trend of these values decreasing with the R_Feopt.

The UV plane looks topologically similar (lower panel of Figure 3). The range of the FWHM(Mg II) is slightly narrower, but the same general trend of decreasing line width, this time with the R_FeUV is visible. The range of the R_FeUV values is quite different but this is due to the adopted wavelength range.
involved in calculating the EW($\text{Fe_{UV}}$), which is very broad. The points colored with the EW($\text{Mg II}$) show the same pattern as in the optical plane, i.e., with respect to the EW($\text{[O III]}$).

Therefore, the UV plane seems equivalent to the optical plane at a first glance. In principle, this is not surprising since the Mg II line belongs to the low-ionization lines (LILs) together with the H$\beta$ (Collin-Souffrin et al. 1988). However, the connection between the optical and the UV emission of Fe II is not so clear (Kovačević-Dojčinović & Popović 2015). Therefore, we analyzed separately the dependence of the line width on the EW of the studied lines (H$\beta$ and Mg II) and on the corresponding Fe II emissions.

The dependence between the FWHM of the line and the EW of the corresponding line in the optical and in the UV plane are shown in Figure 4. To see more clearly the possible character of the dependence, we use logarithmic values instead of the traditional linear values reserved for the plots in the optical plane. We can do that since we selected only high-quality results from the QSFit and the errors for small values of the Fe II intensity do not distort the plot.

In order to study the presented relation quantitatively, we calculate the Pearson correlation coefficient, $r$, and the correlation significance measured through the $p$-value which tests the null hypothesis that the coefficient is equal to zero (no effect). If $P > 0.05$ the correlation is not significant, and if $P < 0.0027$ the correlation is significant at more than 3 sigma level. We then use the following approach: if $|r| > 0.5$, we determine the best-fit linear trend using the orthogonal regression fits, taking into account individual errors in each measurement. The method we apply is called the orthogonal distance regression (ODR) (Boggs et al. 1989). We use this approach with the data of Figure 4 and in the figures henceforth. However, when $r$ is below 0.5, then only a $r^2$ fraction ($<0.25$, or 25%) of the variance is due to correlated changes in the two studied variables. In such case the predictive power of the linear best fit is very limited, since the corresponding prediction interval is broad. Thus, we show the best fits only for the limiting values $|r| > 0.5$. We report the $p$-values ranging between 0.0027 and 0.05, and just give the upper limit for highly significant correlations.

The optical part of the plot (upper panel of Figure 4) shows an apparent anti-correlation between the H$\beta$ line width and the Fe II EW. The trend correlates well with the trend in the black-hole mass (see colors of points in Figure 4 (upper panel)). The dependence does not seem strictly linear in the logarithmic plot, rather suggesting some saturation at values of $\sim$80 Å when the H$\beta$ line becomes narrower. Pearson correlation coefficient (see Table 1) is relatively small ($r = -0.39, p$-value $< 0.0027$), which implies that the linear fit does not represent the data well.

However, the UV plot looks visually different (lower panel in Figure 4). The trend is negative in the optical plane but marginally positive in the UV plane. However, in both cases the correlation is weak ($r = -0.39$ and 0.13, respectively), so the conclusion is not firm. On the other hand, our determination of the correlation coefficient may not be accurate in the UV since the QSFit catalog contains results obtained apparently with the adoption of the firm lower and upper limit for the

**Figure 3.** Optical plane (top) and the UV plane (bottom) for the subsample of quasars from the QSFit catalog with errors for each value.

**Figure 4.** Dependence of the FWHM(H$\beta$) on the EW(Fe $\text{II}_{\text{opt}}$) (top), and the FWHM(Mg II) on the EW(Fe $\text{II}_{\text{UV}}$) (bottom) for the subsample of quasars from the QSFit.
EW(Fe II) of about 90 Å and 220 Å, respectively, and we cannot estimate the role of this potential outlier removal on our results. However, in our subsample, the objects do not pile strongly at these limits. The different behavior of the Fe II emission in the optical and in the UV was already stressed by Kovačević-Dojčinović & Popović (2015) on the basis of the subsample of 293 objects from the SDSS. They additionally noticed significant redshifts in the Fe IIUV not seen in the Fe IIopt.

Next we plot the dependence of the line widths against the corresponding line EWs, again in the logarithmic scale (see Figure 5).

The general rising trend in the FWHM(Hβ) with the rising EW is visible (upper panel), apparently correlated with the black-hole mass. The correlation is not very strong ($r = 0.33$) but suggestive. The correlation is consistent with the trend noticed already by Osterbrock & Pogge (1985) that objects with narrower lines, like the NLS1 galaxies, with line widths smaller than 2000 km s$^{-1}$ have lower-line EWs. In the case of Mg II line (lower panel), the correlation between the line width and the line strength itself is very clear as suggested by the high Pearson correlation coefficient, i.e., 0.61 (see Table 2). The slope of the relation is 0.95 ± 0.016, consistent with the linear dependence between the two quantities. On the bottom panel of Figure 5, the measurement of the outlying point with the smallest EW(Mg II) is affected by absorption present in this particular spectrum. This outlier can also be seen in the lower panel of Figure 6. The correlation between the FWHM and the EW of the Mg II line has been noticed before by Puchnarewicz et al. (1997) but the strictly linear dependence is only well visible in our relatively larger sample.

We tested whether the results for the Hβ line are closer to those for Mg II line if another method is used to establish the linear trends. We chose the relation FWHM(Hβ) versus EW(Hβ), since it showed small values of the coefficient $r$ in the log–log space while the analogous correlation in UV plane was strong. Apart from the orthogonal regression method with individual errors used throughout the paper we applied several other methods for the best-fit linear trend determination (Sen 1968; Feigelson & Babu 1992), listed in Table 3 for FWHM(Hβ) versus EW(Hβ) and Table 4 for FWHM(Mg II) versus EW(Mg II). These results do not include the individual measurement errors. Without errors, in the case of Hβ, the orthogonal regression returns the coefficient $b$ equal 0.94, instead of 0.83, when the latter is with errors included.

After applying the sigma-clipping method for ODR best fits, our sample reduces from 2962 (and $b = 0.83$) to 105 (and $b = 1.14$), which simply confirmed that the dispersion in the measurements is much larger than measurement errors, and correlation is too weak to obtain meaningful constraint for the slope. The standard least squared method gave us much shallower slope (0.32). Similar slopes were obtained by minimum absolute deviation and the Theil-Sen estimator (see Feigelson & Babu 2012). The ordinary least square (OLS) bisector and the geometrical mean of the OLS gave much steeper slopes.

So the results are method-dependent, and the slope is determined with relatively very high uncertainty, as expected in the case of a very weak correlation. We repeated similar analysis for the Mg II line, and in this case the slope of the linear fit determined using various methods shows much

### Table 1

|                      | log EW(Hβ) | log FWHM(Hβ) | log EW(Feopt) | EW(Hβ) |
|----------------------|------------|--------------|---------------|--------|
| log EW(Hβ)           | $r = 1$    | 0.33         | −0.22         | ...    |
|                      | $P = 0$    | <0.0027      | <0.0027       | ...    |
| log FWHM(Hβ)         | $r = 0.33$ | 1            | −0.39         | 0.36   |
|                      | $P < 0.0027$ | 0            | <0.0027       | <0.0027|
| log EW(Feopt)        | $r = −0.22$ | −0.39        | 1             | ...    |
|                      | $P < 0.0027$ | <0.0027      | 0             | ...    |
| EW(Hβ)               | $r = ...$  | 0.36         | ...           | 1      |
|                      | $P = ...$  | <0.0027      | ...           | 0      |

**Figure 5.** Dependence of the FWHM(Hβ) on the EW(Hβ) (top), and the FWHM(Mg II) on the EW(Mg II) (bottom) for the subsample of quasars from the QSFit. Line fitted using ODR method.
smaller dispersion. Thus, the trends observed in the optical and UV planes are different.

Some apparent similarity of the optical and UV planes in Figure 3 and a different behavior of the corresponding plots based on EWs motivated us to also check those correlations. In Figure 6 we show the correlation between EW of Hβ or MgII with EW of corresponding FeII emission. The various correlations are not very high but they suggest an opposite trend.

Additionally, we checked the correlation between the EW(FeII) in the optical and UV band and it is very weak ($r = 0.042$, $p$-value = 0.0207). The ratios $R_{\text{Feopt}}$ and $R_{\text{FeUV}}$ show a slightly higher correlation, although it is by no means a strong correlation ($r = 0.41$, $p$-value < 0.0027) (see Figure 7). This is why we also see the UV quasar main sequence in the lower panel of Figure 3, despite no correlations between EWs of the FeII lines in the two bands.

### 4. Discussion

We compared the optical and the UV plane of the quasar main sequence. The apparent similarity between the two plots (see Figure 3) is actually misleading, despite the fact that both Hβ and MgII lines belong to the same class of LILs, and their widths are plotted there against the corresponding FeII emission. The main sequence in the optical plane is driven both by the trends in FeII and Hβ intensities while in the UV plane the EW(FeII) does not correlate with the MgII line width.
and the main sequence is based just on the correlation between the Mg II line width and intensity.

The tight correlation between the EW and FWHM of Mg II was first noticed by Puchnarewicz et al. (1997) in their study of the optical and X-ray properties in a sample of 160 X-ray selected AGNs from the RIXOS survey. A similar correlation is observed for the Hβ (Osterbrock 1977; Gaskell 1985; Osterbrock & Pogge 1985; Goodrich 1989) in small samples of objects, but in a large sample of objects such as in the present paper, this correlation is much weaker.

The theoretical interpretation of the observational trends—strong correlation in the UV and weak correlation in the optical band between the leading line EW and the FWHM—is not obvious. We first start with common expectations for the optical and the UV emissions based on a specific model of the BLR, and then discuss the mechanisms that may lead to differentiation between the optical and the UV trends.

### 4.1. Comparison of the FWHM and the EW Line Trends with the BLR Model

Most of the BLR models are parametric, without specific predictions about the line properties. However, the Failed Radiatively Accelerated Dusty Outflow (FRADO) model proposed by Czerny & Hryniewicz (2011) predicts the formation of the emission lines from the LIL group. These lines generally do not show strong asymmetries and thus likely come from the medium with turbulence, but not strong outflow, and the failed wind scenario seems attractive for these lines. We thus compare the model prediction with the observed trend.

The kinematic width of the line (FWHM) is determined by the Keplerian velocity of the material located at a distance $R_{\text{BLR}}$ from the central black hole of mass $M_{\text{BH}}$:

$$\text{FWHM} \propto M_{\text{BH}}^{1/2} R_{\text{BLR}}^{-1/2}.$$  

where we drop constants as well as the geometrical factor related to the dynamics of the BLR and its extension (see e.g., Mejía-Restrepo et al. 2018).

The BLR location in the FRADO model depends only on the monochromatic flux from the disk, usually measured at 5100 Å. In the model it comes from the fixed effective temperature where the dust forms, and in the observations this is supported by the number of reverberation measurements for (mostly nearby) sources (Kaspi et al. 2000; Peterson et al. 2004; Bentz et al. 2013; Du et al. 2015, 2018). Thus, we have a relationship

$$R_{\text{BLR}} \propto L_{5100}^{1/2}.$$  

and in the FRADO model this slope is exactly 0.5. In the Hβ monitoring (e.g., Peterson et al. 2004) the continuum is measured at 5100 Å, in the case of Mg II monitoring (e.g., Średzińska 2017; Zhu et al. 2017, see also Koziol̆ski 2015) the continuum is measured at 3000 Å, which affects only the proportionality coefficient, but not the slope.

From the classical theory of accretion disks (Shakura & Sunyaev 1973) we know that the spectrum at longer wavelengths is well described by a single power-law shape, with the slope 1/3

$$L_\nu \propto \nu^{1/3},$$

where $L_\nu$ is the disk luminosity at a frequency $\nu$. The normalization of this power law at a given frequency (or wavelength) depends on the black-hole mass, the accretion rate (in dimensional units), and the inclination angle $i$. Thus, for the disk luminosity at 5100 Å we have

$$L_{5100} \propto \cos i (M\dot{M})^{2/3}.$$  

If we neglect the problem of the viewing angle $i$, which has a limited range of values for the Type 1 objects due to the presence of the dusty-molecular torus, we obtain the following relation of the FWHM on the black-hole mass and the accretion rate

$$\text{FWHM} \propto M^{1/3} \dot{M}^{-1/6}. $$

Now we can estimate the line EW as

$$\text{EW} \propto \frac{L_{\text{line}}}{L_{5100}}, $$

where the continuum flux is measured at 5100 Å or 3000 Å. The line intensity can be estimated roughly as a constant fraction of the incident radiation intercepted by the BLR, and this is linked to the source bolometric luminosity, $L_{\text{bol}} = \eta MC^2$, where $\eta$ is the accretion efficiency depending on the black-hole spin, and the solid angle $\Omega_{\text{BLR}}$ filled by the BLR

$$L_{\text{line}} \propto \Omega_{\text{BLR}} \eta \dot{M}.$$  

If we drop the spin-dependent term $\eta$ we obtain a relation

$$\text{EW} \propto \Omega_{\text{BLR}} \dot{M}^{1/3} \dot{M}^{-2/3}.$$  

If the BLR clouds fill the volume densely, the solid angle is given by the geometrical height of the BLR, $z_{\text{max}}$, and the distance:

$$\Omega_{\text{BLR}} = z_{\text{max}} / R_{\text{BLR}},$$

and combining this relation with the previous one we obtain

$$\text{EW} \propto z_{\text{max}} M^{-1}.$$  

Here we assume that the BLR has axial symmetry, so the solid angle depends linearly on the opening angle.

FRADO model actually predicts the cloud dynamics, so the value of $z_{\text{max}}$ as a function of the global parameters of an active nucleus (Czerny et al. 2015, 2017)

$$z_{\text{max}} \propto \dot{M}, $$

Thus, we have a relationship

$$\text{FWHM} \propto L_{5100}^{1/2} \dot{M}^{-1/2}.$$
which finally gives
\[ EW \propto \dot{M} M^{-1} . \]  
(12)

The predicted trend is not consistent with the strong trend observed in the UV plane. In the model, the FWHM should mostly depend on the black-hole mass, but the EW should strongly rise with an increase in the accretion rate. This is clearly seen if we express the accretion rate in Eddington (dimensionless) units as \( \dot{m} \):
\[ FWHM \propto M^{1/6} \dot{m}^{-1/6}; \quad EW \propto \dot{m}. \]  
(13)

The dependence on the dimensionless accretion rate in the model implies an expected anti-correlation instead of the observed correlation. Thus, some of the underlying assumptions of the model are apparently incorrect.

The rise of the cloud height with an increase of the Eddington ratio is really generic to the model, and convenient to explain the line profiles since a larger vertical velocity in proportion to the local Keplerian speed leads to less disk-like profiles. Higher vertical BLR extension is also seen in the data–Kollatschny & Zetzl (2011) noticed that when modeling the emission line shape with the disk and a turbulent velocity component.

Therefore, in our opinion a weak point in the derivation above is the assumption that the covering factor of the BLR is close to 1 in the area covered by the clouds, independently from the accretion rate and the vertical extension. Thus, Equation (9) in general should be replaced by
\[ \Omega_{\text{BLR}} = f_c \frac{c_{\text{max}}}{R_{\text{BLR}}}, \]  
(14)

and the covering factor \( f_c \) can decrease with the rise in the Eddington ratio. Physically, this is expected when the development of the thermal instability in the rising medium and the cloud formation is taken into account. Such an instability is well known for the irradiated media in the context of AGNs (see Krolik et al. 1981). If the material rises high above the disk there is more time for the development of dense compact clouds embedded in a hot fully ionized plasma out of the initial, moderately dense wind. The quantitative predictions of this phenomenon were not yet done in the context of the FRADO, but it was discussed in a number of papers (e.g., Różańska & Czerny 2000; Czerny et al. 2009; Różańska et al. 2014, 2017). The linear relation between the FWHM and the EW would require
\[ f_c \propto M^{1/6} \dot{m}^{-7/6}, \]  
(15)
i.e., a rapid decrease of the covering factor of the BLR with an increase in the Eddington ratio and an increase of the BLR vertical extension. This indeed can be expected if the integrated vertical optical surface density of the BLR zone is roughly constant, independent of the Eddington rate, as actually postulated in Czerny et al. (2015), and the rising clumpiness accounts for the drop in the covering factor and an actual increase in the local cloud density for high Eddington ratio sources, as discussed by Adhikari et al. (2016, 2018).

However, this still leaves an important question as to why the same relation is not seen between the FWHM and the EW for the H_β, while in the (simplified) model predictions both lines should show the same trend. We also analyzed the emissivity profiles of the H_β and the Mg II lines within the BLR clouds, and the properties of the two lines seemed comparable, with no clear systematic differences (see the Appendix).

The explanation might be in the theoretical aspect of the trend predictions. The expected trends between the different parameters characterizing the BLR were easy to formulate analytically since we used an asymptotic power law with a fixed slope (1/3) (see Equation (3)) and normalization depending on the black-hole mass and the accretion rate (see Equation (4)). However, the actual shape of the continuum is not that of an asymptotic power law, since the disk has the maximum temperature reached in the innermost part, which causes the continuum to curve down, and the difference between the asymptotic power law and the actual continuum systematically increases with the decrease in the wavelength. Since the Mg II is located at considerably shorter wavelength, the simplified prediction roughly appropriate for H_β and the 5100 Å band may not apply to the Mg II and the 3000 Å band. In order to test that, in the following section we modify the approach to the observational data.

4.2. Effects of the Choice of Continuum: The Observed Power Law versus the Asymptotic Power Law

As stressed by Goodrich (1989), the EW is essentially a combination of the two physical parameters, the line and the continuum luminosity. The two quantities may be physically unrelated since the continuum measured close to the line is not necessarily the driving continuum. This is the case for both the H_β and the Mg II. The H_β is basically driven by the photons close to 1 Rydberg, creating highly excited hydrogen atoms. Formation of the Fe II is even more complex. Therefore a question arises again—which among these two parameters is driving the correlation between line width and the line EW in the case of the Mg II line. The issue of the underlying power law is even more important for the Mg II line since the AGN continuum in the UV is subject to possible significant extinction, and also, for massive black holes, the true continuum, represented by the underlying accretion disk can start to bend in this region, showing a departure from the power-law continuum. Such a power-law extrapolation has been used for example in the previous section to derive the trends expected from the FRADO model.

The curvature of the predicted continuum shape is noticeable for larger black-hole masses and lower accretion rates. In Figure 8 we show a disk spectrum and an asymptotic power law for the average black-hole mass in our sample. We see a strong departure from the asymptotic power law in the Mg II line region. For objects with a higher mass and/or lower Eddington ratios the effect is stronger, while in objects with lower masses and/or higher Eddington ratios the asymptotic power law describes the disk spectrum relatively well. The position of the maximum in the disk spectrum depends on the ratio of \( \dot{m}/M \) for a nonrotating black hole considered here (Shakura & Sunyaev 1973).

We thus perform the following exercise: we calculate a family of accretion disk models using the simplest theory of Shakura & Sunyaev (1973) for a range of black-hole masses and accretion rates in our sample, and for each model we determine the ratio of the continuum measured at 5100 Å, and at 3000 Å to the power-law approximation specified by Equations (3) and (4). Next, for all 2962 objects in our sample we interpolate the results from the grid of the models and we
calculate the EWs of Hβ, Mg II, and iron in the optical and the UV range with respect to the power law instead of the actual continuum by multiplying the EW from the QSFit catalog by the ratio of the disk spectrum to the power-law approximation, appropriate for each object, according to its mass and Eddington ratio reported by the QSFit catalog. We find a relatively good analytical approximation for this factor as a function of the black-hole mass and the Eddington ratio, which allows us to apply it conveniently to the whole sample.

We call this procedure an exercise since this choice of a new continuum does not imply that the new continuum is a better representation of the observed continuum in the source. We illustrate that in Figure 9 for one of the objects, SDSS 000111.19–002011.5. The blue line taken from the QSFit catalog—a power law with the adjusted slope fits the source continuum in the best possible way. The fit with the use of the Shakura–Sunyaev disk model and a black-hole mass appropriate for this object is comparable, and it shows some curvature in the spectrum. A stronger effect is expected for a larger black-hole mass and a lower Eddington ratio. However, the power law that we use in this section is an asymptotic power law, with a fixed slope of $\beta/3$. It passes well above the whole spectrum, and our only motivation to use it here is purely theoretical. The model predictions for the line behavior discussed in Section 4.1 were based on this asymptotic power law, without the spectral curvature effect included. Such an approach has lead to the expected similar behavior of the Hβ and the Mg II, while the data shows clear differences in the observed properties of the two lines. The difference between the line behavior could reflect important differences between the physical properties of the regions where the two lines form, but may be simply related to the lower number of photons at 3000 Å continuum than expected from an asymptotic power-law model. It is thus important to stress that by using the asymptotic power law we do not test the actual curvature of the spectrum but the fact that real spectrum is much redder than suggested by the slope of the asymptotic power law. Thus, the accretion disk fit (curved spectrum) and the QSFit continuum (power law much redder than the asymptotic power law) are similar, and we use them in the computations performed in this section as equivalent, while the asymptotic power law is essentially different, and its adoption leads to strongly different values of the EW (see Table 5).

In this way we plot new FWHM—EW relations in the optical and in the UV plane with color coding with the black-hole mass (see Figure 10). In Tables 6 and 7 we show all correlation coefficients for the optical and the UV planes with the EWs measured using the asymptotic power law. We see that in this case the relation between the line width and the line EW in log–log scale for the Hβ shows again a weak linear correlation, the Pearson correlation coefficient is now $-0.12$, which implies an even weaker correlation than before ($r = 0.33$). However, for the Mg II line the change is substantial, in the case of FWHM(Mg II) the strong positive correlation (Pearson coefficient 0.61) is replaced with a very weak and negative correlation (Pearson coefficient $-0.24$). A significant change in correlations is also present in the case of iron (for both the optical and the UV). Particular changes are seen in the following correlations: FWHM(Hβ)–EW(Fe IIopt) changed from $-0.39$ to $-0.56$, FWHM(Mg II)–EW(Fe IIUV) changed from $0.13$ to $-0.60$, and EW(Mg II)–EW(Fe IIUV) from $0.38$ to $0.65$.

This result shows that the differences of EWs in the optical and the UV ranges are surprising and important. As it was stressed long ago by Green (1996), it is very important what continuum we use to calculate the line EWs before we draw physically motivated conclusions. In the case of the Hβ and the Mg II, the continuum normally used for computations is just a matter of convenience $-5100$ Å and 3000 Å are located close to the corresponding measured lines and are relatively free of

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**Table 5**

|        | Hβ (Å) | Mg II (Å) |
|--------|--------|-----------|
| QSFit  | 25.55  | 22.79     |
| DiskFit| 28.05  | 21.92     |
| AsymptoticPl | 20.85 | 13.26 |
Figure 10. Dependence (from the top left) of the EW(Mg II) on the EW(FeUV), the FWHM(Mg II) on the EW(FeUV), the EW(H β) on the EW(Fe II opt), the FWHM(H β) on the EW(Fe II opt), the FWHM(H β) on the EW(H β) and the FWHM(Mg II) on the EW(Mg II), when the line EW is measured with respect to the asymptotic power law. Best fits are shown using the ODR method.

Table 6

|                  | log EW(H β) | log FWHM(H β) | log EW(Fe II opt) | EW(H β) |
|------------------|-------------|---------------|-------------------|---------|
| log EW(H β)      | r           | −0.12         | 0.19              | ...     |
|                  | P           | <0.0027       | <0.0027           | <0.0027 |
| log FWHM(H β)    | r           | −0.12         | 1                 | −0.56   |
|                  | P           | <0.0027       | 0                 | <0.0027 |
| log EW(Fe II opt)| r           | 0.19          | −0.56             | 1       |
|                  | P           | <0.0027       | <0.0027           | 0       |
| EW(H β)          | r           | −0.08         | 1                 | ...     |
|                  | P           | <0.0027       | ...               | 0       |
other lines and pseudo-continua contributions. However, they do not represent the actual driving continuum for the two lines.

In this case, the computing line EWs with respect to the asymptotic power law is motivated by the theory—this is how the predicted line correlations in Section 4.1 were obtained. The artificially constructed trend in the FWHM—EW for the Mg II line—is roughly consistent with the theoretical expectation of a weak anti-correlation.

5. Conclusions

We show that the UV plane of the quasar main sequence based on the Mg II line and the FeII UV emission looks apparently similar to the optical plane based on the Hβ and the Fe II opt. The actual linear correlations behind the linear plots are not strong. However, the optical and the UV planes differ with respect to the trend with the FeII emission and with respect to the EW of the corresponding line.

The optical plane shows a well-known weak correlation between the FWHM of the leading line and both the FeII and the EW of the Hβ line, while the UV plane shows no coupling to the FeII UV emission and, instead, a strong correlation between the FWHM and the EW of the Mg II line. Our analysis shows, however, that this strong trend is entirely caused by the choice of the continuum used to measure the EW of the line. The spectral energy distribution (SED) of an accretion disk shows a curvature in the UV, and this systematic decrease in the continuum flux at 3000 Å coupled to the black-hole mass and the accretion rate causes the correlation. Standard continuum fitting methods account well for this curvature, for example, by adopting the spectral slope as a free parameter. If we artificially correct for this effect in order to have an insight into the physics of the difference between the optical and the UV quasar plane, and use an asymptotic power law as a reference for both lines, no strong coupling is predicted between the FWHM and the EW for both LILs.

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### Appendix

#### Comparing Emissivity Profiles of Fe II in UV and Optical

These quasars have the Fe II contamination spread throughout the span of their optical-UV spectra. Here, we compare the emissivity profiles of the UV Fe II (2700–2900 Å) with respect to the broad Mg II emission line (2798 Å) and to their optical counterparts (4434–4684 Å) with respect to the broad Hβ emission line (4861.33 Å). We perform a CLOUDY photoionization modeling (Ferland et al. 2017) assuming a constant density single cloud model. It is assumed that all the emission that is considered here (i.e., the optical-UV Fe II, the Mg II and the Hβ) come from the BLR. The SED of this BLR cloud is modeled by a two-power law based on the prescription given in Pandya et al. (2017, 2018, 2019a). We use the average properties derived from our catalog of 2962 objects that are listed in Table A1. The distance to the face of the BLR cloud is derived using the $R_{\text{BLR}} - L_{5100}$ relation using the coefficients from the Clean model of Bentz et al. (2013). The cloud’s mean density ($n_\text{eq}$) is assumed to be $10^{12}$ cm$^{-3}$. The depth of the cloud is constrained using the stop column density command in CLOUDY, which is kept at $10^{24}$ cm$^{-2}$. The emissivity profiles are shown in Figure A1.

As we can see in the profiles, both the Mg II and the Hβ emissions come from a significant fraction of the volume of the BLR cloud. At the face of the cloud, the Hβ has at least four orders of magnitude fainter emission as compared to the optical Fe II. This difference in the emission is a factor of 100 lower in the case of the Mg II and the Fe II in the UV. Nevertheless, both the profiles show a similar trend with increasing depth, with a peak in the emission (for both Hβ and Mg II) showing at $\sim10^7$ cm from the face of the cloud. While there is a slump in both these emission profiles after this peak, the Mg II is shown to recover at around $10^{12}$ cm i.e., the dark edge of the cloud. Throughout the cloud’s depth, both the optical and the UV Fe II emission show almost similar behavior. As a preliminary conclusion, it can be said that both the Mg II and the Hβ have an extended emitting region covering almost the bulk of the BLR cloud, yet the Mg II seems to span over a larger region than the Hβ.

### Table 7

|                  | log EW(Mg II) | log FWHM(Mg II) | log EW(FeUV) | EW(Mg II) |
|------------------|--------------|----------------|--------------|-----------|
|                  | $r$          | $P$            | $r$          | $P$       |
|                  | 1            | 0              | −0.24        | 0.65      |
|                  | −0.24        | <0.0027        | 1            | −0.60     |
|                  | 0.65         | <0.0027        | 1            | 0         |
|                  | <0.0027      | <0.0027        | 0            | 0         |

**Facility:** SDSS.  
**Software:** QSFit (Calderone et al. 2017), CLOUDY (Ferland et al. 2017).
Notes.

Mean 45.852 ± 0.314
Maximum 46.26 ± 0.311
Minimum 45.055 ± 0.311

Table A1
Catalog Statistics Used to Produce Emissivity Profiles

|                  | Intrinsic                  | Derived                  |
|------------------|----------------------------|--------------------------|
|                  | log $L_{bol}$ (erg s$^{-1}$) | log $L_{3100}$ (erg s$^{-1}$) | log $M_{bol}$ ($M_{\odot}$) | log $L_{3100}^\ast$ (erg s$^{-1}$) | log $L_X$ (erg s$^{-1}$) | log $R_m$ (cm) |
| Minimum          | 45.055                      | 44.088                   | 7.4                         | 44.107                        | 37.435                       | 17.016              |
| Maximum          | 47.16                       | 46.26                    | 9.83                        | 45.955                        | 38.899                       | 18.193              |
| Mean             | 45.852 ± 0.314              | 44.879 ± 0.311           | 8.537 ± 0.371               | 44.786 ± 0.408                | 38.040 ± 0.394             | 17.445 ± 0.169     |

Notes.

* At 2500 Å.

** At 2 keV.

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Figure A1. Emissivity profiles of the 10 most intense FeII emission lines in the optical (left panel) and the UV (right panel), with the Hβ and the MgII emission, respectively. The profiles show the emission across the depth of a constant density ($n_H = 10^{12}$ cm$^{-3}$) single BLR cloud.
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