More Variable Quasars Have Stronger Emission Lines

Wen-Yong Kang1,2 ⋆, Jun-Xian Wang1,2 ⋆, Zhen-Yi Cai1,2 ⋆, and Wen-Ke Ren1,2

1 CAS Key Laboratory for Researches in Galaxies and Cosmology, University of Science and Technology of China, Chinese Academy of Sciences, Hefei, Anhui 230026, People’s Republic of China; kwy0719@mail.ustc.edu.cn
2 School of Astronomy and Space Science, University of Science and Technology of China, Hefei 230026, People’s Republic of China; jxw@ustc.edu.cn

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Abstract

UV/optical variation, likely driven by accretion disk turbulence, is a defining characteristic of type I active galactic nuclei and quasars. In this work we investigate an interesting consequence of such turbulence using quasars in Sloan Digital Sky Survey Stripe 82 for which the measurements of the UV/optical variability amplitude are available from ~10 yr long light curves. We discover positive correlations between the UV/optical variability amplitude σrms and equivalent widths of C IV, Mg II, and [O III]5007 emission lines. Such correlations remain statistically robust through partial correlation analyses, i.e., after controlling the effects of other variables including bolometric luminosity, central supermassive black hole mass, Eddington ratio, and redshift. This, for the first time, indicates a causal link between disk turbulence and emission line production. We propose two potential underlying mechanisms, both of which may be involved: (1) quasars with stronger disk turbulence have on average a bluer/harder broadband spectral energy distribution, an expected effect of the disk thermal fluctuation model; (2) stronger disk turbulence could lead to the launch of emission line regions with larger covering factors.

Unified Astronomy Thesaurus concepts: Quasars (1319); Active galactic nuclei (16); Supermassive black holes (1663); Accretion (14)

1. Introduction

The presence of prominent optical/UV broad emission lines (BELs) is a defining characteristic of type I active galactic nuclei (AGNs) and quasars. It is widely accepted that BEL emitting clouds in the broad-line region (BLR) are photoionized by the central radiation, thus BELs are important probes of the ionizing continuum and subsequently the inner accretion disk where ionizing photons are produced. Meanwhile, the BLR clouds themselves may physically originate from the disk in the form of winds or failed winds driven by various potential mechanisms (e.g., Emmering et al. 1992; Konigl & Kartje 1994; Murray et al. 1995; Proga & Kallman 2004; Czerny & Hryniewicz 2011; Baskin & Laor 2018), though nondisk origin models also exist (e.g., Wang et al. 2017).

An intimately linked phenomenon is the well-known anticorrelation between the BEL equivalent width (EW) and continuum luminosity, the so-called “Baldwin effect” (Baldwin 1977). The Baldwin effect of various BELs has been extensively investigated for nearly four decades (e.g., Wampler et al. 1984; Baldwin et al. 1989; Netzer et al. 1992; Francis & Koratkar 1995; Dietrich et al. 2002; Xu et al. 2008; Dong et al. 2009; Wu et al. 2009a; Kovačević et al. 2010; Bian et al. 2012; Shemmer & Lieber 2015), however the physical origin of the anticorrelations and the notably large scatter in the line EW are still under debate. This is likely because the observed line EW could be influenced by many factors, including the broadband spectral energy distribution, metallicity, BLR covering factor and ionization, etc. Besides, the disk inclination effect (the limb darkening and projected disk surface area effects, e.g., Risaliti et al. 2011; Zhang et al. 2013) and the continuum variation (e.g., Jiang et al. 2006; Shu et al. 2012) may produce artificial anticorrelations between line EW and continuum luminosity in AGN samples. Searching for other such factor(s) may yield new clues to understanding the BEL production.

Aperiodic multiband flux variation is another notable characteristic of AGNs (e.g., Ulrich et al. 1997). In UV/optical, the variation is generally attributed to thermal fluctuations in the accretion disk, likely driven by magnetic turbulence (Kelly et al. 2009), a theoretically critical process but observationally hard to probe. Besides studying the correlations with physical parameters including the luminosity, wavelength, Eddington ratio, black hole mass, and redshift (Vanden Berk et al. 2004; Willhite et al. 2005; Wold et al. 2007; Willhite et al. 2008; Bauer et al. 2009; Ai et al. 2010; MacLeod et al. 2010; Meuslinger et al. 2011; Zuo et al. 2012; Meuslinger & Weiss 2013; Kozłowski 2016), exploring additional parameters correlating with variability could help to reveal the consequences of the magnetic turbulence (e.g., X-ray loudness in Kang et al. 2018).

It is intriguing to note that, similar to the BEL EW, the UV/optical variability amplitude in AGNs also anticorrelate with luminosity (e.g., Vanden Berk et al. 2004; Meuslinger & Weiss 2013; Kang et al. 2018). Is there any intrinsic and physical link between the two fundamental characteristics of AGNs? Considering that both BEL production and UV/optical variability are closely related to processes in the accretion disk, observationally revealing such a link would be useful to probe the currently vague underlying mechanisms.

In this work we present a first exploratory study of the potential intrinsic correlation between the BELs (as well as [O III]5007) and UV/optical variability. We focus on the intrinsic correlation between line EWs and UV/optical variability amplitudes, which could be precisely measured for a large sample of quasars. In Section 2 we present the quasar sample and the quantities utilized in this study. We perform partial correlation analyses in Section 3 to reveal the intrinsic correlations between the EW (of various lines) and UV/optical variability amplitude, controlling the effects of other variables.

3 There also exists a Baldwin effect for narrow emission lines (e.g., Boroson & Green 1992; Shields 2007; Shen & Ho 2014), as well as the X-ray Fe Kα line (e.g., Iwasawa & Taniguchi 1993; Jiang et al. 2006; Shu et al. 2012; Ricci et al. 2013).
including Eddington ratio, supermassive black hole mass, and redshift. In Section 4 we propose and discuss two potential mechanisms for the intrinsic link we discovered. Throughout this work, cosmological parameters of \( H_0 = 70 \text{ km s}^{-1} \text{Mpc}^{-1} \), \( \Omega_m = 0.3 \), and \( \Omega_\Lambda = 0.7 \) are adopted.

### 2. The Quasar Samples

Sloan Digital Sky Survey (SDSS) Stripe 82, which has been scanned over 60 times in five bands (ugriz) by the SDSS, is a 290 deg\(^2\) equatorial field of the sky (Sesar et al. 2007). Recalibrated 10 yr long SDSS light curves in ugriz for 9275 spectroscopically confirmed quasars in Stripe 82 were presented by MacLeod et al. (2012). Their physical parameters, including bolometric luminosity, black hole mass, redshift, and emission line properties (FWHM, flux, EW) could be extracted from Shen et al. (2011). Such a large sample of quasars is adopted in this work to explore the intrinsic relation between emission lines and UV/optical variation.

We note that many studies adopted the damped random walk process to model quasar light curves (Kelly et al. 2009; MacLeod et al. 2010; Zu et al. 2013; Kozłowski et al. 2010) with two parameters: \( \tau \) (the characteristic timescale) and \( S Fin \) (the structure function). However, due to the limited length and the sparse sampling, for many quasars these parameters are poorly constrained with SDSS Stripe 82 light curves (Kozłowski 2017). In this work, similar to Kang et al. (2018), we quantify the intrinsic variability amplitude of each source in each band with a single model-independent parameter, i.e., the excess variance \( \sigma_{\text{rms}} \) (Vaughan et al. 2003):

\[
\sigma_{\text{rms}}^2 = \frac{1}{N - 1} \sum (X_i - \bar{X})^2 - \frac{1}{N} \sum \sigma_i^2
\]

where \( X_i \) is observed magnitude, \( \bar{X} \) the average magnitude, \( \sigma_i \) the photometric uncertainty of each observation, and \( N \) the number of photometric measurements. If there is no intrinsic variation, the expected value of \( \sigma_{\text{rms}} \) is zero with a statistical uncertainty (Vaughan et al. 2003) of

\[
\text{err}(\sigma_{\text{rms}}^2) = \frac{2}{N} \times \frac{1}{N} \sum \sigma_i^2.
\]

We dropped the u and z bands in which the photometric uncertainties are significantly larger, thereby comparing with the other three bands.

In this work we focus on the most prominent lines in SDSS spectra, including broad Mg II, C IV, broad H/β, as well as the narrow emission line [O III]5007. We build samples for each line within a certain redshift range.

For the Mg II line, we select quasars from Shen et al. (2011) with broad Mg II measurements\(^4\) (0.35 < \( z < 2.25 \)) and median SDSS spectral signal-to-noise ratio (S/N) per pixel \( \geq 3 \) in the rest frame 2700–2900 Å. The Mg II sample includes 6553 quasars, for which we adopt the virial black hole mass based on Mg II (S10 in Shen et al. 2011) and bolometric luminosity derived from \( L_{\text{bol}} \).

The C IV sample\(^5\) contains 3313 quasars (1.50 < \( z < 3.69 \)) with median SDSS spectral S/N per pixel \( \geq 3 \) in the rest frame 1500–1600 Å. For this sample, the C IV virial black hole mass was derived as VP06 from Shen et al. (2011), and the bolometric luminosity based on \( L_{[1350]} \) is adopted. Note that the C IV line-based BH mass could be significantly biased (e.g., Coamatl et al. 2016, 2017).

Both broad H/β and [O III]5007 samples are required to have median SDSS spectral S/N per pixel \( \geq 3 \) in the rest frame 4750–4950 Å, including 1226 (0.08 < \( z < 0.89 \))\(^6\) and 1132 (0.08 < \( z < 0.84 \)) quasars, respectively. For both samples, which indeed largely overlap, the broad H/β based virial black hole mass (VP06 in Shen et al. 2011) and \( L_{[5100]} \)-based bolometric luminosity are adopted.

### 3. Correlation Analyses

#### 3.1. The Baldwin Effect

Before we look into the correlations between emission lines and UV/optical variations, we first examine the Baldwin effect in our quasar samples, an issue closely relevant to this study. In Table 1, we present the Pearson’s rank correlation coefficients \( r \) and linear regression slopes \( \beta \) between line EWs and parameters including bolometric luminosity, Eddington ratio \( L_{\text{bol}}/L_{\text{edd}} \), black hole mass \( M_{\text{bh}} \), and 1 + \( z \). We perform Monte Carlo simulations (e.g., Curran 2015; Timlin et al. 2020) to quantify the statistical errors of the correlation coefficient \( r \) and \( rcc \) due to uncertainties in the data. This was done through adding randomized Gaussian errors to the observed parameters of each source, and performing the Pearson’s rank correlation analysis on the simulated data set. We repeat this process 100 times and calculate the standard deviation of the derived coefficients.

In Figure 1, we plot the EW versus \( L_{\text{bol}} \) result of four samples, with the slopes of the best-fit linear regression given in the upper-left corner of each panel. Note that in this work, when performing linear regression, we adopt the standard approach simply using the x-axis as the independent variable. This is because (1) the best-fit standard linear regression slope is directly comparable with those derived from multiple linear regressions (before versus after correcting the effects of other parameters); and (2) the slope is directly comparable with literature studies which adopted the standard approach, particularly those that measured line EW from the composite spectra at different luminosity bins (e.g., Dietrich et al. 2002). The best-fit bisector regression is plotted as grey dash lines in Figures 1, 3 and 4.

Since the luminosity, supermassive black hole (SMBH) mass, and redshift in our samples are clearly degenerate, i.e., quasars at high redshifts tend to be more luminous and thus have more massive black holes, partial correlation analyses are required to reveal the intrinsic correlation between line EW and each physical parameter by controlling the effects of the other parameters. We further perform partial correlation analyses between EW and each of the three parameters (Eddington ratio \( L_{\text{bol}}/L_{\text{edd}} \), black hole mass \( M_{\text{bh}} \), and 1 + \( z \)) by controlling the other two (see Table 1). Note that since \( L_{\text{bol}} \) is simply the arithmetic product of the Eddington ratio and the black hole mass, we need to drop it during partial correlation analyses. We also adopt multiple linear regression analysis to quantify the relations between EW and these three physical parameters:

\[
\text{EW}_\text{line} \sim (L_{\text{bol}}/L_{\text{edd}})^\gamma M_{\text{bh}}^{\delta_1} (1 + z)^\delta_2.
\]

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\(^4\) Two sources with unphysically large values of Mg II EW (\( > 20,000 \) Å) are excluded.

\(^5\) Note Shen et al. (2011) did not subtract a narrow component while fitting the C IV line.

\(^6\) Four sources are dropped because of unreasonably large H/β EW (above 1000 Å).
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Table 1
Correlation Coefficients and Linear Regression Slopes between Line EW and Other Parameters (Named in the Left Column)

|                          | Broad Mg II | C IV | Broad H/β | [O III]5007 |
|--------------------------|-------------|------|------------|-------------|
| Pearson’s Rank Apparent Correlation Coefficients $r$, Confidence Levels $rcc$, and Linear Regression Slopes $s$ | | | | |
| $L_{bol}$                 | $r$         | $-0.259(0.014)$ | $-0.325(0.007)$ | $-0.017(0.018)$ | $-0.212(0.077)$ |
|                           | $rcc$       | $<16e(1<16$, $<16e)$ | $<16e(1<16$, $<16e)$ | $0.28(0.11, 0.49)$ | $3e<16e, 2e<6$ |
|                           | $s$         | $-0.111 \pm 0.005$ | $-0.239 \pm 0.012$ | $0.011 \pm 0.019$ | $-0.246 \pm 0.034$ |
| $\tilde{M}_{bh}$         | $r$         | $-0.416(0.018)$ | $-0.118(0.014)$ | $-0.215(0.024)$ | $-0.196(0.039)$ |
|                           | $rcc$       | $<16e(1<16$, $<16e)$ | $4e(1<14e, 1<14e)$ | $1e<14e(1<16, 8e<12)$ | $2e<116e, 5e<8$ |
|                           | $s$         | $-0.209 \pm 0.006$ | $-0.070 \pm 0.010$ | $-0.106 \pm 0.014$ | $-0.159 \pm 0.024$ |
| $1+z$                    | $r$         | $0.094(0.013)$ | $-0.132(0.012)$ | $0.197(0.029)$ | $0.046(0.042)$ |
|                           | $rcc$       | $1e<14(1<16, 2e<11)$ | $1e<14(1<16, 2e<12)$ | $2e<12e(16, 2e<9)$ | $0.06(2e<3, 1$ |
|                           | $s$         | $0.039 \pm 0.005$ | $-0.072 \pm 0.009$ | $0.094 \pm 0.013$ | $0.037 \pm 0.024$ |

Partial Correlation Coefficients $r$ and Confidence Levels $rcc$

| $\tilde{M}_{bh}$, $1+z$   | $r$         | $-0.454(0.020)$ | $-0.314(0.018)$ | $-0.141(0.030)$ | $-0.226(0.044)$ |
|                           | $rcc$       | $<16e(1<16$, $<16e)$ | $<16e(1<16$, $<16e)$ | $4e<7e10, 5e<5$ | $7e<15<16e, 4e<10$ |
|                           | $s$         | $-0.239(0.017)$ | $-0.317(0.017)$ | $-0.007(0.028)$ | $-0.140(0.041)$ |
| $1+z$                    | $r$         | $0.218(0.014)$ | $0.098(0.009)$ | $0.101(0.046)$ | $-0.001(0.032)$ |
|                           | $rcc$       | $<16<16e(1<16$, $<16e)$ | $9e<7e(10<16, 2e<7)$ | $2e<7e(10<1, 1e<16)$ | $0.48(0e<15, 1e<16)$ |

Multiple Linear Regression Slopes (See Equation (3))

| $\tilde{M}_{bh}$         | $a$         | $-0.327 \pm 0.008$ | $-0.283 \pm 0.015$ | $-0.114 \pm 0.023$ | $-0.310 \pm 0.040$ |
|                           | $b$         | $-0.152 \pm 0.008$ | $-0.266 \pm 0.014$ | $-0.006 \pm 0.024$ | $-0.193 \pm 0.041$ |
| $1+z$                    | $c$         | $0.666 \pm 0.037$ | $0.468 \pm 0.083$ | $0.647 \pm 0.182$ | $-0.014 \pm 0.321$ |

Note. Here $r$ and $rcc$ represent the correlation coefficient and confidence level of the correlation. In the left-most column, the single parameter name stands for the apparent Pearson’s rank correlation of EW$_{line}$ and this parameter, while $X(Y, Z)$ denotes a partial correlation between EW$_{line}$ and X by controlling Y and Z. Values in parentheses after $r$ and $rcc$ give the standard deviations to $r$ derived from Monte Carlo simulations (see text for details), and the 1σ confidence range of $rcc$, respectively. $s$ represents the best-fit apparent linear regression slope between EW$_{line}$ and other parameters, while $a$, $b$, and $c$ are slopes of the best-fit multiple linear regression in Equation (3).

The best-fit slopes, showing correlation patterns between those parameters consistent with the results from partial correlation analyses, are also presented in Table 1.

Our samples show significant Baldwin effects (the anticorrelation between line EW and bolometric luminosity) in broad Mg II, C IV, and [O III]5007, but no such effect in the Balmer line (broad H/β), consistent with literature studies (e.g., Wampler et al. 1984; Baldwin et al. 1989; Netzer et al. 1992; Sergeev et al. 1999; Dietrich et al. 2002; La Mura et al. 2007; Xu et al. 2008; Dong et al. 2009; Wu et al. 2009a; Bian et al. 2012; Rakić et al. 2017).

Negative correlations between EW and $L_{bol}/L_{Edd}$ are significant in all four emission lines, and remain evident after controlling the effects of $M_{bh}$ and $1+z$ (see Table 1). This reveals that the Eddington ratio has an intrinsic and dominant effect on EW, consistent with previous studies (e.g., Baskin & Laor 2004, 2005; Xu et al. 2008; Dong et al. 2009; Bian et al. 2012). Partial correlation analyses also reveal clear intrinsic anticorrelation between EW and $M_{bh}$ for all lines but H/β, showing $M_{bh}$ also plays a nonnegligible role.

Meanwhile, while we see no strong apparent anticorrelations between line EW and $z$, consistent with Dietrich et al. (2002), a significant positive partial correlation between line EW and $1+z$ is visible for all lines bar [O III]5007. This could primarily be due to a hidden selection bias of the quasar samples. SDSS quasars were primarily color selected and spectroskopically identified based on the detection of broad emission lines. At a given bolometric luminosity and SMBH mass (which means at a given continuum luminosity and broad-line width), quasars at higher redshifts have lower S/N in their SDSS spectra, thus sources with smaller broad emission line EWs may have not been spectroskopically identified. Such a selection effect has actually been noticed for a long time, and could strengthen the observed Baldwin effect for spectroskopically selected incomplete samples, since quasars with lower luminosities and lower line EWs are more likely to be missed from such samples (e.g., Osmer 1980; Steidel & Sargent 1991). To demonstrate this effect in our sample, we plot the Mg II sample in Figure 2, for instance. Within a narrow range of continuum luminosity we can clearly see that quasars at higher redshifts tend to have smaller broad Mg II line S/N, therefore the quasar sample could be significantly incomplete for low-line EW quasars at higher redshifts, yielding an artificial partial correlation between line EW and redshift. This scenario is also supported by the nondetection of the partial correlation between [O III]5007 EW and redshift, as spectroskopical
identification of quasars does not rely on significant detection of the narrow-line [O III]5007. An extensive study of the potential correlation between line EW and redshift is beyond the scope of this work. We stress that the aim of this work is to explore the intrinsic correlation between line EW and \( \sigma_{\text{rms}} \) (see Section 3.3) through partial correlation analyses, i.e., removing the effects of other parameters including redshift. Therefore, such an observational bias or the intrinsic correlation between line EW and redshift (if there is any) would not affect the main results of this work, as the effect of redshift has been excluded during the partial correlation analyses below.

Similarly, the sample completeness could be line-width dependent, as detecting a broader line requires a higher S/N or line EW, compared with a narrower line. Since the SMBH mass is derived from line width and luminosity, this effect may bias the correlation between line EW and SMBH mass (or Eddington ratio). Again, such an effect would not affect the main results of this work, as the effect of redshift has been excluded during the partial correlation analyses below.

3.2. The Dependence of \( \sigma_{\text{rms}} \) on Luminosity and Eddington Ratio

Following Section 3.2, we perform apparent correlation analyses between the UV/optical variability amplitude \( \sigma_{\text{rms}} \) and factors including bolometric luminosity, Eddington ratio \( L_{\text{bol}}/L_{\text{Edd}} \), black hole mass \( M_{\text{bh}} \), and \( 1+z \). The results are shown in Table 2 (and Tables 4 and 5 in the Appendix). We

\footnote{Such a study should not be limited to the quasars in SDSS Stripe 82.}
plot the results of the four samples in Figure 3. Clear negative
correlations between UV/optical variability and luminosity are
seen in all our samples, consistent with many other works (e.g.,
Vanden Berk et al. 2004; Wilhite et al. 2008; Ai et al. 2010;
Zuo et al. 2012; Meusinger & Weiss 2013). Besides, the
variability also anticorrelates with the Eddington ratio (see also
Vanden Berk et al. 2004; Wilhite et al. 2008; Ai et al. 2010;
Zuo et al. 2012; Meusinger & Weiss 2013). Apparent negative
correlations between \( \sigma_{\text{rms}} \) and redshift are also seen, primarily
because quasars at higher redshifts are generally more
luminous.

Again, to break the degeneracies between various param-
eters, partial correlation analyses are also performed (see
Table 2). The partial correlation analyses show that \( \sigma_{\text{rms}} \)
anticorrelates with both the Eddington ratio and SMBH mass.
The partial correlation between \( \sigma_{\text{rms}} \) and redshift is primarily
positive, because AGN variation is known to be stronger at
a shorter rest-frame wavelength (e.g., Vanden Berk et al. 2004;
Wilhite et al. 2005; Zuo et al. 2012; Sun et al. 2014; Meusinger
et al. 2011; Kang et al. 2018) and a given SDSS photometric
band probes a shorter rest-frame wavelength for quasars at
higher redshifts. The negative partial correlation between \( g \)
band \( \sigma_{\text{rms}} \) and redshift in the C IV sample might be due to the
fact that the strong Ly \( \alpha \) line (which is less variable than the
continuum) would be redshifted into the \( g \) band at redshift
\( \gtrsim 2.3 \), making \( g \) band variation weaker compared with quasars
at \( z \lesssim 2.3 \). Note that the \( \sigma_{\text{rms}} \) in this work measures the
variability amplitude at a certain timescale in the observed
frame, therefore the time dilation effect exists here in that for
quasars at higher redshifts we are actually probing the
variability at a shorter timescale in the rest frame (e.g.,
Hawkins 2010). Correcting the time dilation effect or the
wavelength dependence of the variability is hard, however, as
the exact relation between variability and timescale or wavelength
is poorly constrained and may depend on other
parameters. Fortunately, such effects would not affect the
partial correlations between other parameters when the effect of
redshift is controlled.

We also perform multiple linear regression to quantify the
relations between \( \sigma_{\text{rms}} \) and the three physical parameters (see
Equation (4) below), and the results in Table 2 (and Tables 4
and 5 in the Appendix).

\[
\sigma_{\text{rms,exp}} \sim (L_{\text{bol}} / L_{\text{Edd}})^a M_{\text{bh}}^b (1 + z)^c
\]  

(4)

The results are consistent with partial correlation analyses.
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3.3. The Intrinsic Correlation between EW and $\sigma_{\text{rms}}$

Since both line EWs and $\sigma_{\text{rms}}$ similarly anticorrelate with luminosity and $L_{\text{bol}}/L_{\text{Edd}}$, it is not surprising that the two quantities show apparent positive correlations (see Table 3 and Figure 4). Partial correlation analyses are thus essential to reveal the intrinsic correlation between the two quantities. In Table 3 we also present the partial correlation coefficients between line EW and $\sigma_{\text{rms}}$ by controlling the effects of $L_{\text{bol}}/L_{\text{Edd}}$, $M_{\text{bh}}$, and redshift. Again, as $L_{\text{bol}}/L_{\text{Edd}}$ is simply the ratio of $L_{\text{bol}}$ and $M_{\text{bh}}$, the effect of $L_{\text{bol}}$ is also simultaneously controlled during the analyses. Replacing $L_{\text{bol}}/L_{\text{Edd}}$ with $L_{\text{bol}}$ during the analyses does not alter the results.

Partial correlation analyses reveal strong intrinsic correlations between line EWs of broad Mg II, C IV, and $\sigma_{\text{rms}}$ (g, r, i), though with coefficients considerably smaller than the apparent correlations (see Figure 5). Such intrinsic correlations indicate that at a given Eddington ratio, black hole mass, and redshift, quasars with stronger variabilities in UV/optical have stronger broad Mg II and C IV emission lines. The intrinsic correlation coefficient $r$ between the [O III]5007 EW and $\sigma_{\text{rms}}$ is smaller but still statistically significant, and that between the broad H$\beta$ and $\sigma_{\text{rms}}$ is the weakest among the four lines.

Meanwhile, we also perform multiple linear regression analyses to quantify the relations between line EWs and

![Figure 4](https://example.com/image4.png)

**Figure 4.** Correlations between line EW and g band variability amplitude. Symbols and lines are the same as shown in Figure 1.
physical parameters including the Eddington ratio, black hole mass, redshift, and UV/optical variability amplitude \( \sigma_{\text{rms}} \).

\[
\text{EW} \sim \left( \frac{L_{\text{bol}}}{L_{\text{Edd}}} \right)^s M_{\text{bh}}^r (1 + z)^t \sigma_{\text{rms}}^u
\]  

The results of best-fit parameters are displayed in Table 3, showing intrinsic correlation patterns between line EWs and \( \sigma_{\text{rms}} \) consistent with those from partial correlation analyses.

To directly illustrate the intrinsic correlation between line EWs and \( \sigma_{\text{rms}} \), we derive the residual line EWs with respect to \( \sigma_{\text{rms}} \). In each panel, the blue markers represent the apparent Pearson’s correlation \( r \) and regression slope \( s \) between EW_{line} and \( \sigma_{\text{rms}} \). The red ones represent the partial correlation coefficient \( r \) (controlling Eddington ratio, black hole mass, and redshift) and regression slope \( s \) (Equation (5)), and the black ones plot the expected artificial correlations due to the uncertainties of the control variables if there is no intrinsic correlation between EW_{line} and \( \sigma_{\text{rms}} \). The inverted triangles, circles, and squares stand for \( g \), \( r \), and \( i \) observational bands, respectively.

It is well known that the measurements of black hole mass and bolometric luminosity of quasars suffer from considerable uncertainties. The large uncertainties in the control variables may lead to artificial partial correlations between two quantities that both correlate with the control variables. Following Kang et al. (2018), we perform simulations to examine possible artificial partial correlation due to the uncertainties of \( L_{\text{bol}}/L_{\text{Edd}} \) and \( M_{\text{bh}} \). Utilizing the observed \( L_{\text{bol}}/L_{\text{Edd}} \), \( M_{\text{bh}} \), and redshift for each quasar, we calculate the expected line EWs and \( \sigma_{\text{rms}} \) based on the best-fit Equations (3) and (4), respectively. Random Gaussian fluctuations are then added to the expected values to reproduce the observed scatters in Equations (3) and (4). The simulated line EWs and \( \sigma_{\text{rms}} \) we produced have no intrinsic correlation between each other. However, after we randomly fluctuate the values of \( L_{\text{bol}}/L_{\text{Edd}} \) and \( M_{\text{bh}} \) to mimic their measurement uncertainties, artificial partial correlation between line EWs and \( \sigma_{\text{rms}} \) could emerge. For \( L_{\text{bol}} \), we adopt a 0.08 dex uncertainty (20%), to take account of the uncertainty in bolometric correction; Richards et al. (2006), and add it quadratically to the direct measurement error from Shen et al. (2011). For mass measurement, both a conservative 0.4 dex calibration uncertainty (Shen et al. 2011) and the direct measurement error from Shen et al. (2011) are included. No fluctuation is added to the redshift as it has considerably small uncertainty. Partial correlation analyses using the simulated samples do show positive partial correlations between line EWs and \( \sigma_{\text{rms}} \), but they are too weak to explain the observed correlations for Mg II, C IV, and [O III]5007 (see Figure 5).

We finally note that in this work, the line EW, bolometric luminosity, and SMBH mass for each quasar (from Shen et al. 2011) are measured based on single-epoch SDSS spectra obtained at certain spectral MJD (sMJD), while \( \sigma_{\text{rms}} \) is measured over a period of \( \sim 10 \) yr. We show below that such a fact does not bias the results in this work. Comparing the sMJD with photometric observations for our sample, we find on average \( \sim 80\% \) of the photometric data points were obtained after the sMJD. We further compare the synthetic photometry measured from the spectra with the photometric data points,
and find \( \sim 15\% \) of our quasars have synthetic photometry fainter than the minimum brightness in the corresponding photometric light curve (but contrarily 4.7\% of quasars have synthetic photometry brighter than the maximum brightness in the light curve). These are likely due to the fiber-drop issue (e.g., Guo et al. 2020). Excluding those sources, however, does not alter the results of this work. Other than those sources with fiber dropping, we do not find systematic offset between the photometric and the synthetic photometry, i.e., the SDSS spectra could represent the properties of the quasars at a random epoch. Furthermore, around half of our quasars have repeated SDSS spectroscopy. Our results remain unchanged if we utilize spectra other than those used by Shen et al. (2011) and measure the corresponding line EW, bolometric luminosity, and SMBH mass following an approach similar to Shen et al. (W. K. Ren et al. 2021, in preparation).

### 4. Discussion

The intrinsic correlations we have revealed between the strong emission line (Mg II, C IV, and [O III]5007, but not H\(\beta\)) EWs of quasars and UV/optical variability amplitude indicate that more variable quasars have stronger emission lines.\(^8\) Note that Rumbaugh et al. (2018) found that extremely variable quasars (those with a maximum change in \(g\)-band magnitude of more than 1 mag) tend to have stronger emission lines (Mg II, C IV, and [O III]5007) compared with a control sample with matched luminosity and redshift (see also W. K. Ren et al. 2021, in preparation), nicely consistent with our findings.

The correlations show that the line production and disk turbulence are physically connected. Below, we first propose two interesting mechanisms behind such intrinsic correlations: (1) stronger disk turbulence yields a bluer/harder quasar SED, thus stronger emission lines; (2) disk magnetic turbulence launches outflowing wind which could elevate the covering factor of BLR and narrow-line region (NLR) clouds. We finally briefly discuss the puzzling different behavior of the H\(\beta\) line (compared with Mg II, C IV, and [O III]5007).

Theoretically, disk thermal-fluctuating models (Dexter & Agol 2011; Cai et al. 2016, 2018, 2019, 2020) associate the multiband variability with magnetic turbulence in the accretion disk. Note such fluctuation models indeed predict bluer averaged EUV SEDs than the standard thin-disk model without temperature fluctuation, and the stronger the turbulence the bluer the mean SED (see Figure 4 of Cai et al. 2016). This is qualitatively consistent with the discovery presented in this work that quasars with stronger UV/optical variability have stronger emission lines, albeit it yet to be observationally confirmed whether quasars that are more variable do have bluer extreme UV SEDs (Z. Y. Cai et al. 2021, in preparation). As reproducing the ionizing SED of AGNs is never straightforward, we would defer a quantitative comparison with predictions of a disk fluctuation model and our results to a future work. Meanwhile, we have previously found a positive correlation between the UV/optical variability and the X-ray loudness (Kang et al. 2018), showing the X-ray corona heating in AGNs could be also closely associated with magnetic turbulence, and suggesting that more variable quasars do have a relatively harder SED, which could produce stronger emission lines.

Alternatively, stronger disk magnetic turbulence might be able to launch disk winds with larger covering factors, thus yielding stronger emission lines. Please refer to Section 1 for references to theoretical models of disk winds. While it is extremely challenging to theoretically depict the role of magnetic turbulence in wind launch, this work brings up an interesting potential probe for it: comparing the observational properties of AGNs with stronger disk turbulence with quieter ones to probe the sequence of the disk turbulence. For instance, in additional to emission line EW, one may investigate the connection between disk turbulence and emission line profile (W. K. Ren et al. 2021, in preparation).

However, it is currently difficult to distinguish the two scenarios we proposed above, i.e., a bluer/harder SED or a larger covering factor of emission line clouds. We note that compared with broad Mg II and C IV lines, [O III]5007 shows a weaker intrinsic correlation (the partial correlation coefficient \( r \)) with \( \sigma_{\text{rms}} \) (see Table 3 and Figure 5). This is likely because compared with a BLR, the covering factor of NLR could be affected by additional factors such as the torus and the interstellar medium environment, thus showing a significantly larger scatter (see also Figure 6). Further note that the O III line comes from the narrow-line region, i.e., averaging variability over 1000 yr, while \( \sigma_{\text{rms}} \) in this paper is measured with a decadal timescale. This fact could also play a role in producing the large scatter and reducing the correlation coefficient \( r \) between the [O III]5007 EW and \( \sigma_{\text{rms}} \). Notably, comparing with Mg II and C IV, [O III]5007 exhibits a similar linear regression slope and \( \sigma_{\text{rms}} \) (Figure 5). Such a fact tends to favor the bluer/harder SED scenario, as both BLR and NLR are illuminated and expected to be ionized by the same central radiation. However, though NLR has a much large physical scale, the turbulence-driven disk wind scenario cannot be ruled out if such wind could eventually reach the NLR (e.g., Proga et al. 2008). For instance, Du et al. (2014) reported a strong correlation between BLR and NLR metallicities in AGNs, suggesting outflows from BLRs could carry metal-rich gas to NLRs.

Due to the lack of extreme UV coverage, it is hard to constrain the ionizing SED of quasars. As an experiment, below we adopt X-ray loudness as an approximate proxy of broadband SED to investigate whether a harder SED\(^9\) could fully account for the observed intrinsic correlation between line EW and \( \sigma_{\text{rms}} \). Note a caveat of this approach is that quasars with the same X-ray loudness do not necessarily have the same EUV SED. To derive the X-ray loudness of our quasars, following Kang et al. (2018), we cross-match our Mg II and C IV samples with the Stripe 82X X-ray source catalog (Ananna et al. 2017). The source numbers of X-ray-matched Mg II and C IV samples are 572 and 236, respectively. The significant reduction of the sample sizes is due to the limited coverage of Stripe 82X (31.3 versus 290 deg\(^2\)), and the X-ray detection completeness of the parent samples within the Stripe 82X footprint is considerably high (66\%–80\%).\(^{10}\) The [O III]

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\(^8\) Since during the partial correlation analyses the effects of bolometric luminosity (simply derived from continuum luminosity) and redshift have been removed, a partial correlation between line EW and variability also means a partial correlation between line flux (or luminosity) and variability. This is confirmed through replacing line EW with flux (or luminosity) during the analyses.

\(^9\) Note Wu et al. (2009b) did report a positive correlation between C IV line EW and the relative X-ray to UV brightness.

\(^{10}\) Following Kang et al. (2018) we estimate the effect of X-ray sample incompleteness and conclude that the incompleteness does not affect the results presented below.
5007 and Hβ samples are excluded because the final X-ray matched samples are too small. We then calculate the X-ray loudness (L_{0.5-10keV}/L_{bol}) for the X-ray-detected subsamples. In Figure 7, we plot the correlation coefficient $r$ between line EW and $\sigma_{\text{rms}}$ for the X-ray-detected subsamples. Similar to what we have seen in the parent samples, the partial correlations between EW and $\sigma_{\text{rms}}$ are evident for the X-ray subsamples, after controlling for the effect of Eddington ratio, black hole mass, and redshift, though they are considerably weaker than the apparent correlations. Further controlling the effect of X-ray loudness ulteriorly reduces the correlation coefficients (Figure 7), indicating that the first mechanism (more variable quasars have a harder SED) may have played a significant role.

We then examine whether the residual partial correlations between EW and $\sigma_{\text{rms}}$ could be artificial due to uncertainties in the control variables. Again, we adopt a 0.08 dex calibration uncertainty for $L_{\text{bol}}$ and 0.4 dex calibration uncertainty for $M_{\text{bh}}$ in addition to their statistical observational uncertainties from Shen et al. (2011). For X-ray luminosity used in the calculation of X-ray loudness, we employ 0.08 dex as the mean observational uncertainty (since not all X-ray sources have flux errors in the Stripe 82X catalog). Middei et al. (2017) provided the long term X-ray variation of SDSS quasars, and the structure function at $\sim 10$ yr is $\sim 0.3$ dex. We further include a $0.3/\sqrt{2}$ dex to represent the random long term variability of X-ray fluxes in SDSS quasars. The simulated artificial partial correlation coefficients (black data points in Figure 7) are smaller than, though statistically comparable to, the residual coefficients (green data points in Figure 7). This suggests the variation of SED alone might be insufficient to fully account for the intrinsic correlation between line EWs and $\sigma_{\text{rms}}$ we reported in this work. The second mechanism (stronger disk turbulence launches emission line clouds with larger sky coverage) may also be involved.

Finally, it is worth noting that the Hβ EW shows no (or at most slight) partial correlation with $\sigma_{\text{rms}}$, making it distinct from other lines (see Figure 5). Note Hβ also shows very weak or no Baldwin effect (see Table 1, and Sergeev et al. 1999; Dietrich et al. 2002; La Mura et al. 2007; Rakić et al. 2017). Considering the Baldwin effect is prominent for the Lyα line while it is missing for Balmer lines, Dietrich et al. (2002) proposed that the different behavior of Lyα and Balmer lines could be related to the complicated physical processes of Lyα and Hβ line emission (e.g., Netzer et al. 1995; Netzer 2020). The same mechanism may also account for the different behavior of Hβ in the EW $\sim \sigma_{\text{rms}}$ relation compared with other lines.

5. Conclusions

In this work, we investigate the correlation between emission line (broad Mg II, C IV, [O III]5007, and broad Hβ) EW and UV/optical variability amplitude $\sigma_{\text{rms}}$ for SDSS Stripe 82 quasars. We show that the two quantities show clear apparent correlations. Meanwhile, both quantities show apparent anticorrelations with bolometric luminosity and the Eddington ratio.

We perform partial correlation analyses and reveal intrinsic correlations between the line EWs (of Mg II, C IV, and [O III] 5007) and $\sigma_{\text{rms}}$, after controlling for the effect of luminosity, Eddington ratio, black hole mass, and redshift. Interestingly, broad Hβ, of which the Baldwin effect is known to be absent, does not show clear intrinsic correlation between EW and $\sigma_{\text{rms}}$.

The intrinsic correlations between line EWs (of Mg II, C IV, and [O III]5007) and UV/optical variability amplitude suggest that their underlying processes, i.e., line production and disk turbulence, are physically connected. We propose two possible mechanisms—both may be involved—for such a connection: 1) more variable quasars tend to have a bluer/harder SED, and 2) more variable quasars can launch emission line clouds with a larger covering factor.

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Appendix

Tables 4 and 5 and contain similar results to Table 2 but with different observational bands.
Table 4

Correlation Coefficients and Linear Regression Slopes between $\sigma_{\text{max}}$ (in the $r$ Band) and Other Parameters

| Broad Mg II | C IV | H $\beta$ | [O III]5007 |
|-------------|------|------------|--------------|
| Pearson’s Rank Apparent Correlation Coefficients $r$, Confidence Levels $rcc$, and Linear Regression Slopes $s$ |
| $L_{\text{bol}}$ | $r$ | $-0.342(0.002)$ | $-0.363(0.002)$ | $-0.199(0.006)$ | $-0.164(0.006)$ |
| | $rcc$ | $<1e-16(\text{<1e-16, 1e-16})$ | $<1e-16(\text{<1e-16, 1e-16})$ | $1e-12(2e-13, 5e-12)$ | $1e-8(4e-9, 4e-8)$ |
| | $s$ | $-0.158 \pm 0.005$ | $-0.230 \pm 0.010$ | $-0.118 \pm 0.017$ | $-0.101 \pm 0.018$ |
| $Z_{\text{gal}}$ | $r$ | $-0.322(0.008)$ | $-0.169(0.010)$ | $-0.265(0.016)$ | $-0.255(0.016)$ |
| | $rcc$ | $<1e-16(\text{<1e-16, 1e-16})$ | $<1e-16(\text{<1e-16, 2e-16})$ | $<1e-16(\text{<1e-16, 1e-16})$ | $<1e-16(\text{<1e-16, 2e-16})$ |
| | $s$ | $-0.173 \pm 0.006$ | $-0.087 \pm 0.009$ | $-0.116 \pm 0.012$ | $-0.110 \pm 0.012$ |
| $M_{\text{bh}}$ | $r$ | $-0.065(0.007)$ | $-0.114(0.008)$ | $0.116(0.017)$ | $0.137(0.015)$ |
| | $rcc$ | $7e-8(3e-9, 1e-6)$ | $2e-11(9e-13, 5e-10)$ | $2e-5(1e-6, 2e-4)$ | $2e-6(1e-7, 2e-5)$ |
| | $s$ | $-0.029 \pm 0.005$ | $-0.053 \pm 0.008$ | $0.049 \pm 0.012$ | $0.058 \pm 0.012$ |
| $I + z$ | $r$ | $-0.162(0.002)$ | $-0.119(0.001)$ | $-0.003(0.004)$ | $0.050(0.004)$ |
| | $rcc$ | $<1e-16(\text{<1e-16, 1e-16})$ | $3e-12(2e-12, 5e-12)$ | $0.460(0.40, 0.49)$ | $0.05(0.03, 0.06)$ |
| | $s$ | $-0.380 \pm 0.029$ | $-0.471 \pm 0.068$ | $-0.013 \pm 0.139$ | $0.255 \pm 0.153$ |

Partial Correlation Coefficients $r$ and Confidence Levels $rcc$

$Z_{\text{gal}} (M_{\text{bh}}, I + z) r$ | $-0.391(0.010)$ | $-0.344(0.014)$ | $-0.283(0.019)$ | $-0.261(0.021)$ |
| $rcc$ | $<1e-16(\text{<1e-16, 1e-16})$ | $<1e-16(\text{<1e-16, 1e-16})$ | $<1e-16(\text{<1e-16, 1e-16})$ | $<1e-16(\text{<1e-16, 1e-16})$ |
| $s$ | $-0.268(0.011)$ | $-0.322(0.014)$ | $-0.158(0.022)$ | $-0.138(0.022)$ |
| $M_{\text{bh}} (Z_{\text{gal}}, I + z) r$ | $0.140(0.010)$ | $0.043(0.005)$ | $0.101(0.009)$ | $0.119(0.008)$ |
| $rcc$ | $<1e-16(\text{<1e-16, 1e-16})$ | $6e-3(3e-3, 0.01)$ | $2e-4(6e-5, 6e-4)$ | $3e-5(9e-6, 9e-5)$ |

Multiple Linear Regression Slopes (See Equation (4))

$Z_{\text{gal}}$ | $a$ | $-0.301 \pm 0.009$ | $-0.267 \pm 0.013$ | $-0.207 \pm 0.020$ | $-0.189 \pm 0.021$ |
| $M_{\text{bh}}$ | $b$ | $-0.190 \pm 0.008$ | $-0.229 \pm 0.012$ | $-0.115 \pm 0.020$ | $-0.099 \pm 0.021$ |
| $I + z$ | $c$ | $0.466 \pm 0.041$ | $0.176 \pm 0.071$ | $0.565 \pm 0.159$ | $0.675 \pm 0.168$ |

Note. Similar to Table 2, but with $\sigma_{\text{max}}$ in the $r$ band. The results are similar to Table 2.
Table 5
Correlation Coefficients and Linear Regression Slopes between $\sigma_{\text{rad}}$ (in the $i$ Band) and Other Parameters

| Parameter | Broad Mg II | C IV | H/β | [O III]5007 |
|-----------|-------------|------|------|-------------|
| Pearson’s Rank | Apparent Correlation Coefficients $r$ | $r$ | $r$ | $r$ |
| $I_{\text{bol}}$ | $<1e-16(1e-16,1e-16)$ | $<1e-16(1e-16,1e-16)$ | $<1e-16(1e-16,1e-16)$ | $<1e-16(1e-16,1e-16)$ |
| $r$ | $-0.380(0.008)$ | $-0.332(0.003)$ | $-0.136(0.013)$ | $-0.113(0.010)$ |
| $M_{\text{bh}}$ | $<1e-16(1e-16,1e-16)$ | $<1e-16(1e-16,1e-16)$ | $<1e-16(1e-16,1e-16)$ | $<1e-16(1e-16,1e-16)$ |
| $r$ | $-0.108 (0.007)$ | $-0.107 (0.001)$ | $0.099 (0.022)$ | $0.116 (0.022)$ |
| $I + z$ | $<1e-16(1e-16,1e-16)$ | $<1e-16(1e-16,1e-16)$ | $<1e-16(1e-16,1e-16)$ | $<1e-16(1e-16,1e-16)$ |
| $r$ | $-0.232 (0.006)$ | $-0.045 (0.001)$ | $-0.007 (0.003)$ | $0.023 (0.005)$ |
| Multiple Linear Regression Slopes (see Equation (4)) | | | | |
| $a$ | $-0.283 \pm 0.009$ | $-0.264 \pm 0.013$ | $-0.134 \pm 0.019$ | $-0.122 \pm 0.020$ |
| $b$ | $-0.180 \pm 0.008$ | $-0.232 \pm 0.012$ | $-0.065 \pm 0.020$ | $-0.054 \pm 0.020$ |
| $c$ | $0.244 \pm 0.041$ | $0.472 \pm 0.071$ | $0.309 \pm 0.152$ | $0.344 \pm 0.161$ |

Note. Similar to Table 2, but with $\sigma_{\text{rad}}$ in the $i$ band. The results are similar to Table 2.

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ORCID iDs

Wen-Yong Kang © https://orcid.org/0000-0003-2573-8100
Jun-Xian Wang © https://orcid.org/0000-0002-4419-6434
Zhen-Yi Cai © https://orcid.org/0000-0002-4223-2198
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