THE VARIABILITY OF OPTICAL Fe ii EMISSION IN PG QSO 1700+518

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1. INTRODUCTION

Variability is a common phenomenon in quasi-stellar objects (QSOs) and provides a powerful constraint on their central engines. In the past two decades, optical variability research focused on spectral monitoring instead of pure photometric monitoring. With the active galactic nuclei (AGNs) and the Palomar-Green (PG) QSO spectrophotometrical monitoring projects, the reverberation mapping method, i.e., exploring the correlation between the emission lines and the continuum variations, is used to investigate the inner structure in AGNs. It is found that the correlation between the emission lines and the continuum variance and the continuum variance and the continuum time lag calculated from the empirical luminosity–size relation derived from the mapping method is used to calculate the masses of their central supermassive black holes (e.g., Kaspi et al. 2000, 2005; Peterson et al. 2004). With the line width of Hβ, Mg ii, and C iv from BLRs, the empirical size–luminosity relation derived from the mapping method is used to calculate the masses of their central supermassive black holes (SMBHs; e.g., Kaspi et al. 2000; McLure & Jarvis 2004; Bian & Zhao 2004; Peterson et al. 2004; Greene & Ho 2005).

It is found that the Fe ii emission contributes significantly to the optical and ultraviolet spectra of most AGNs. Thousands of UV Fe ii emission lines blend together to form a pseudocontinuum, resulting in the “small blue bump” around 3000 Å when they are combined with Balmer continuum emission (e.g., Wills et al. 1985). The optical Fe ii would lead to two bumps in two sides around the Hβ (λ4861) (e.g., Boroson & Green 1992). It is found that the flux ratio of Fe ii to Hβ, RFe ii, where the optical Fe ii flux is the flux of the Fe ii emission between λ4334 and λ4684, strongly correlates with the so-called eigenvector 1, which has been suggested to be driven by the accretion rate (e.g., Boroson & Green 1992; Marziani et al. 2003a).

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The origin of the photoionized BLRs cannot produce the observed shape and strength of the optical Fe ii emission and that the strength of UV Fe ii cannot be explained unless the micro-turbulence of hundreds of km s$^{-1}$ or the collisional excitation in warm, dense gas (Baldwin et al. 2004) is considered. However, Vestergaard & Peterson (2005) found the correlation between the optical Fe ii and the continuum variance and suggested that the optical Fe ii is due to the line fluorescent in a photoionized plasma. It suggests that the optical Fe ii line does not come from the same region as the UV Fe ii emission (e.g., Kuehn et al. 2008). Maoz et al. (1993) found that the reverberation time lag of UV Fe ii in NGC 5548 is about 10 days, similar to the C iv time lag, and smaller than the Hβ time lag. The reverberation measurement for the optical Fe ii emission has not fared so well. Some suggested that the optical emission is produced in the same region as the other broad emission lines, and some suggested that it is in the outer portion of the BLRs because of the narrower FWHM of Fe ii with respect to Hβ (e.g., Laor et al. 1997; Marziani et al. 2003a; Vestergaard & Peterson 2005; Kuehn et al. 2008). Recently, Hu et al. (2008a, 2008b) did a systematic analysis of Fe ii emission in QSOs from the Sloan Digital Sky Survey (SDSS) and found that the Fe ii emission is redshifted with respect to the rest frame defined by the [O iii] narrow emission line and the Hβ intermediate-width component is correlated with Fe ii, which is located at the outer portion of the BLRs.

Kaspi et al. (2000) gave the 7.5 yr spectroscopic monitoring data for 17 PG QSOs. There is one PG QSO, PG 1700+518, that has the strongest optical Fe ii emission and $R_{Fe} = 1.42$ (Turnshek et al. 1985; Boroson & Green 1992). Its Hβ FWHM is 1846 ± 682 km s$^{-1}$ (Peterson et al. 2004), and it is also called a narrow line Seyfert 1 galaxy (NLS1). Using the Fe ii template from one NLS1, I Zw 1, we model the Fe ii emission to investigate the Fe ii variability and its relation to the continuum variability in PG 1700+518. The data and analysis are described in Section 2, the results are given in Section 3, the discussion

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Online-only material: color figures
Figure 1. Mean spectrum (the red curve) and rms spectrum (the green curve; multiplied by 8) for PG 1700+518. (A color version of this figure is available in the online journal.)

is given in Section 4, and the conclusions are presented in Section 5. All of the cosmological calculations in this paper assume \( H_0 = 70 \text{ km s}^{-1} \text{ Mpc}^{-1}, \Omega_M = 0.3, \Omega_\Lambda = 0.7 \).

2. DATA AND ANALYSIS

The spectroscopic monitoring data of PG 1700+518 cover 7.5 yr from 1991 to 1998, and which were done every 1–4 months by using the 2.3 m telescope at the Steward Observatory and 1 m telescope at the Wise Observatory. The total number of optical spectra for PG 1700+518 is 39. The observational wavelength coverage is from \( \sim 4000 \) to \( \sim 8000 \) \( \AA \) with a spectral resolution of \( \sim 10 \) \( \AA \). Spectra were calibrated to an absolute flux scale using simultaneous observations of nearby standard stars (Kaspi et al. 2000). The 39 spectra of PG 1700+518 are available on the Web site.\(^3\)

In order to check its spectral variance, we calculate its mean and rms spectra (Kaspi et al. 2000; Peterson et al. 2004). In Figure 1, the mean spectrum (the red curve) shows strong optical Fe\(\text{II} \) emission, and the rms spectrum (the green curve) shows variable emission for H\(\beta\)\(\lambda\)4861, He\(\text{I} \)\(\lambda\)5878, and Fe\(\text{II} \) (blueward and redward of H\(\beta\)\(\lambda\)4861). In the rms spectrum, we can find Fe\(\text{II} \) features at \( \sim 4500 \), \( \sim 4924 \), and \( 5018 \) \( \AA \), suggesting variable Fe\(\text{II} \). The part of the Fe\(\text{II} \) emission between 4430 and 4770 \( \AA \) in the rms spectrum is more obvious than that between 5080 and 5550 \( \AA \). Because of more variability blueward of the spectrum, the blueward part of the rms spectrum would have a larger amplitude than the redward part. It is consistent with harder spectrum during bright phase (Figure 6; Pu et al. 2006). In the rms spectrum, we also find weak He\(\text{II} \)\(\lambda\)4686.

We use the following steps to do the spectral decomposition, which has been used to analyze the spectra for a large QSO sample from SDSS (Hu et al. 2008a; Bian et al. 2008).

1. First, the observed spectra are corrected for the Galactic extinction using \( A_V = 0.116 \) from the NASA/IPAC Extragalactic Database (NED), assuming an extinction curve of Cardelli et al. (1989; IR band) and O’Donnell (1994; optical band) with \( R_V = 3.1 \). Then the spectra are transformed into the rest frame by the redshift of 0.292.

2. The optical and ultraviolet Fe\(\text{II} \) template from the prototype NLS1 I ZW 1 is used to subtract the Fe\(\text{II} \) emission from the spectra (Boroson & Green 1992; Vestergaard & Wilkes 2001). The I ZW 1 template is broadened by convolving it with a Gaussian of various line widths, the centroid wavelength shifts, and fluxes. A power-law continuum is added in the fitting. The best modeling of Fe\(\text{II} \) and the power-law continuum is found when \( \chi^2 \) is minimized in the fitting windows 4430–4770 and 5080–5550 \( \AA \) (see an example fit in Figure 2). The monochromatic flux at 5100 \( \AA \), \( f_\lambda(5100 \text{ \AA}) \), is calculated from the power-law continuum.

3. Considering weak [O\(\text{III} \)\(\lambda\lambda\)4959, 5007 lines, two sets of one Gaussian are used to model them. We take the same line width for each component, and fix the flux ratio of [O\(\text{III} \)]\(\lambda\)4959 to [O\(\text{III} \)]\(\lambda\)5007 to be 1:3. For the asymmetric profile of the H\(\beta \) profile, a two-Gaussian is used to model the H\(\beta \) line, H\(\beta_b \) and H\(\beta_n \). The H\(\beta_b \) and H\(\beta_n \) fluxes are calculated by integrating the corresponding fitting components. The flux for total H\(\beta \), H\(\beta + b + n \), is the sum of the H\(\beta_b \) and H\(\beta_n \) fluxes.

3. RESULT

3.1. The Light Curves for the Continuum, Fe\(\text{II} \), and H\(\beta \)

By IRAF-splot, the signal-to-noise ratios (S/Ns) between 7400 \( \AA \) and 7600 \( \text{\AA} \) in the observational frame are measured

\(^3\) http://wise-obs.tau.ac.il/~shai/PG/
Figure 2. Example spectral decomposition for PG 1700+518. In the top panel, the black curve is the observed spectrum after the corrections of Galactic-extinction and the redshift; the red line is the sum of the power-law continuum and Fe II multiples (blue curves). The green ranges are our fitting windows. The bottom panel is the multi-Gaussian fits for the Hβ and [O III] lines. The red line is the sum of all multi-Gaussian fits (blue curves). The green curve is our fitting range for the pure Hβ and [O III] emissions after the subtraction of the power-law continuum and Fe II multiples.

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

for these 39 spectra. Two spectra (2nd and 35th spectra: pg1700910712.fits, pg1700980414.fits) are ignored in our next analysis due to their lower S/N, which is less than 10 (Kaspi et al. 2000). For the remaining 37 spectra, the S/N distribution is $25.3 \pm 9$. The goodness of modeling of the Fe II and continuum is tested by the elimina-
tion of Fe II features at λ4924 and λ5017 (see Figure 2). We calculate the Fe II flux by integrating the Fe II template fit between λ4434 and λ4684. In Figure 3, we show the light curves of Fe II, Hβ\textsuperscript{bb}, Hβ\textsuperscript{bb}, Hβ\textsuperscript{bb}, and f\textsubscript{β}(5100 Å) (from top to bottom).

We use the normalized variability measure defined by Kaspi et al. (2000) to compare the line variability to the continuum variability, σ\textsubscript{N} = 100(σ\textsuperscript{2} − δ\textsuperscript{2})\textsuperscript{1/2}/\bar{f}, where \overline{f} and σ are the average and the rms of the flux in a given light curve, and δ is the mean uncertainty in a given light curve. The σ\textsubscript{N} are 6.73, 2.58, 8.46, 8.38, and 3.65 for the light curves of f\textsubscript{β}(5100 Å), Fe II, Hβ\textsuperscript{bb}, Hβ\textsuperscript{bb}, and Hβ\textsuperscript{bb}, respectively, in Figure 3. Kaspi et al. (2000) showed that σ\textsubscript{N} for the light curves of f\textsubscript{β}(5100 Å) and Hβ are 6.8 and 3.2, respectively, which are consistent with our results. The σ\textsubscript{N} of Fe II is smaller than that for f\textsubscript{β}(5100 Å), Hβ\textsuperscript{bb}, Hβ\textsuperscript{bb}, and Hβ\textsuperscript{bb}.

### 3.2. Time Lag from CCCD

The measurement of the line time lag, τ, is made by cross-correlating the emission line and continuum light curves. In order to compare with the result of Peterson et al. (2004), we use their code to perform the line lag measurements. In Figure 4, we give the interpolated cross-correlation functions (CCF) for the continuum–Fe II (top left), the continuum–Hβ\textsuperscript{bb} (top right), the continuum–Hβ\textsuperscript{bb} (bottom left), and the continuum–Hβ\textsuperscript{bb} (bottom right) for PG 1700+518. We find a peak in the CCF for the Fe II light curve, which can be used to determine the time lag for the Fe II curve (Figures 4 and 5). Because of many peaks with positive lag times and/or peaks with negative lag times in the CCFs for the other curves, we cannot determine their time lags (Figures 4 and 5).

Through the Monte Carlo FR/RSS method, the uncertainty of τ can be determined (Peterson et al. 2004). In the code, we adopt a minimum correlation coefficient of 0.4 and a centroid threshold of 0.8 R\textsubscript{max}, and the number of trials is 3000 (Peterson et al. 2004). In Figure 5, we give the cross-correlation centroid distributions (CCCDs) for the continuum–Fe II cross-correlation (top left) and the continuum–Hβ\textsuperscript{bb} cross-correlation (top right) for PG 1700+518, as well as that for Hβ\textsuperscript{bb} and Hβ\textsuperscript{bb} (bottom panels). It is obvious that the CCCDs for Fe II have a narrow positive peak. Following the suggestion given by Peterson et al. (2004), we calculate the mean of the CCCD in all valid trials, as well as its upper and lower uncertainties, as the Fe II centroid time lag. We find that the Fe II time lag, τ\textsubscript{Fe II}, in PG 1700+518 is 270\textsuperscript{147} years. Its mean CCF R\textsubscript{max} is 0.54 ± 0.08. There are many positive peaks and/or strong negative peaks for Hβ, Hβ\textsuperscript{bb}, and Hβ\textsuperscript{bb}. Therefore, we cannot give the line lags for Hβ, Hβ\textsuperscript{bb}, and Hβ\textsuperscript{bb}. With the redshift of 0.292 for PG 1700+815 in the rest frame, the Fe II time lag in PG 1700+518 is 209\textsuperscript{147} years. Because the Hβ time lag cannot be determined, we do not know whether the region emitting Fe II is located outside of the region emitting the broad Hβ lines (Marziani et al. 2003b; Vestergaard & Peterson 2005; Popović et al. 2007; Hu et al. 2008b; Kuehn et al. 2008).

### 4. DISCUSSION

#### 4.1. The Fe II Fitting Method

In the analysis of the optical Fe II light curve for PG 1700+518, we fit the optical spectrum by the Fe II template instead of directly calculating the optical Fe II flux in the selected wavelength range (e.g., Kuehn et al. 2008). In modeling the Fe II emission, we simultaneously model the power-law continuum, which is different from Wang et al. (2005) in the Fe II analysis of the NLS1 NGC 4051. We also consider various FWHMs, centroid wavelength shifts, and fluxes in the convolving of the Fe II template. The accuracy of the measurement for the continuum shape depends on the wavelength coverage. For these 37 spectra of PG 1700+518, the wavelength coverage is mainly between 3500 Å and 6000 Å in the rest frame. Vestergaard & Peterson (2005) found that the optical Fe II feature blueward of Hβ is contaminated by He I λ4471 and He II λ4686 lines. For PG 1700+518, the He I λ4471 and He II λ4686 lines are not strong (Figure 1). Therefore, we use the fitting windows...
of 4430–4770 and 5080–5550 Å to exclude the emission lines of Hβ, Hγλ4340, and [O iii] λλ4959, 5007 (Figure 2). When we mask the region of He ii λ4686 in the fitting, the fitting result is almost the same. We tried the Fe ii template of V´eron-Cetty et al. (2004), and found that it is almost the same as that of I ZW 1.

4.2. The Optical Fe ii Emitting Region

Kuehn et al. (2008) presented the reverberation analysis of optical Fe ii for Ark 120. They gave the light curves of the blue/red side of Fe ii and Hβ, and the continuum by setting the measurement windows (Figure 1 in Kuehn et al. 2008). Although the Fe ii cross-correlation function is very broad and flat topped, they suggested that the optical Fe ii emitting region, ∼320 days, is several times larger than the Hβ zone (∼57 days). Kuehn et al. (2008) found that it is difficult to constrain the FWHM of optical Fe ii for Ark 120 because of its very smooth Fe ii emission (Figure 8 in Kuehn et al. 2008). Modeling the Fe ii emission in PG 1700+518, we find that the mean value of the Fe ii FWHM is 1554 ± 110 km s⁻¹. Because there is not a lot of change in the Hβ profile due to the Fe ii contribution (Figure 1), we adopted the Hβ FWHM value of 1846±682 km s⁻¹ by Peterson et al. (2004). We find that (FWHM$_{H\beta}$/FWHM$_{Fe\text{ ii}}$)$^2$ = 1.41. Assuming that the Fe ii and Hβ emission regions follow the virial relation between the time lag and the FWHM for the Hβ and Fe ii emission lines, we can derive the Hβ time lag to be 148±72 days. We also find that the new estimated Hβ time lag is consistent with the R$_{BLR}$–λL$_{λ}$ (5100 Å) relation by Bentz et al. (2009; see their Figure 5).

Considering the host contribution in $f_ν$(5100 Å), Bentz et al. (2009) suggested a new relation between BLR size and $\lambda L_{\lambda}$ (5100 Å), log $R_{BLR}$ = (−21.3$^{+2.9}_{-2.8}$) + (0.519$^{+0.063}_{-0.066}$) log $\lambda L_{\lambda}$ (5100 Å) (lt-days). Kaspi et al. (2000) gave the average flux of $f_ν$(5100 Å) at 5100 Å is (21.4 ± 1.5) × 10⁻¹⁶ erg s⁻¹ cm⁻² Å⁻¹. After excluding Fe ii contribution, we find that the mean value of $f_ν$(5100 Å) at 5100 Å is (21.4 ± 1.5) × 10⁻¹⁶ erg s⁻¹ cm⁻² Å⁻¹. Therefore, the Fe ii correction is very small for $f_ν$(5100 Å). Correcting for the contribution from starlight, Bentz et al. (2009) gave $f_ν$(5100 Å) as (18.5 ± 1.5) × 10⁻¹⁶ erg s⁻¹ cm⁻² Å⁻¹ and $\lambda L_{\lambda}$(5100 Å) as 3.63 × 10⁴⁵ erg s⁻¹ (the starlight contribution is about 16% in its total flux). The calculated $R_{BLR}$ from the $R_{BLR}$–$\lambda L_{\lambda}$(5100 Å) relation (Bentz et al. 2009) with a $\lambda L_{\lambda}$(5100 Å) of 3.63 × 10⁴⁵ erg s⁻¹ is 222 lt-days. Considering the larger uncertainty of the intercept in this relation (about 3 in log $R_{BLR}$), this result is consistent with our estimated Hβ time lag, 148±72 days (Figure 5 in Bentz et al. 2009).

If we take the FWHM/time lag uncertainties into consideration, we find that the Fe ii emission region is located near the
Figure 5. Cross-correlation centroid distributions (CCCDs) for the continuum–Fe II cross-correlation (top left), the continuum–H β cross-correlation (top right), the continuum–H β cross-correlation (bottom left), and the continuum–H β cross-correlation (bottom right) for PG 1700+518.

Figure 6. Spectral slope, α, vs. $f_\lambda$(5100 Å). $f_\nu \propto \nu^{-\alpha}$. Considering the error in α, the red line is the best linear fit. The green line is the best linear fit excluding two discrete red points. (A color version of this figure is available in the online journal.)

Hβ emission region, though not conclusively located outside of the Hβ emission region. Kuehn et al. (2008) suggested that optical Fe II emission is possibly produced at the dust sublimation radius, $R_{\text{dust}} = 476 \times [L_{\text{bol}}/10^{45} \text{ erg s}^{-1}]^{0.5}$ (lt-days) (Elitzur & Shlosman 2006). By $L_{\text{bol}} = 9\zeta L_\odot(5100 \text{ Å})$, for PG 1700+518, we find that the dust sublimation radius $R_{\text{dust}} \sim 2868$ (lt-days), which is much larger than the radius indicated by the Fe II emission lag time.

Kaspi et al. (2000) measured the Hβ flux between 6120 Å and 6410 Å in the observational frame (also in Peterson et al. 2004). Their Hβ fluxes include Fe II contribution. Kaspi et al. (2000) gave the Hβ flux as $(18.88 \pm 0.99) \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$. Removing Fe II contamination from this region, the Hβ flux is $(14.22 \pm 1.01) \times 10^{-14}$ erg s$^{-1}$ cm$^{-2}$. With our new light curve for Hβ, we cannot determine the time lag for the Hβ emission line, but we can determine the time lag for Fe II line. This is possible due to the following. (1) The Hβ line has an asymmetric profile (Figure 2; narrow and broad components), suggesting that Hβ is coming from the region with a very broad size and Fe II is coming from the region with a narrow size. Therefore, we can detect Fe II time lag. The Hβ flux in Kaspi et al. (2000) and Peterson et al. (2004) includes Fe II contribution. (2) Peterson et al. (2004) found two peaks in their CCCD (see their Figure 15) and suggested that the peak at zero is due to correlated error. The spectral S/Ns are not high and the time sampling in the light curves is not good. More data and higher S/N spectra are needed in the future.
With respect to the Hβ time lag of 252 days suggested by Peterson et al. (2004), the smaller estimated Hβ time lag of 148 days, which leads to a smaller black hole mass estimation in the logarithm, is decreased by 0.23 dex. However, considering the uncertainties of time lag and the mass calculation, our results are consistent with that from Peterson et al. (2004).

4.3. The Relation between the Spectral Index and $f_\lambda$ (5100 Å)

In our previous work (Pu et al. 2006), we investigated the relationship between the spectral index and $f_\lambda$ (5100 Å) and found that almost all (15/17) PG QSOs showed an anti-correlation between them, except for PG 1700+518 and PG 1229+204. For PG 1229+204, this is due to the system difference in the two telescopes used. For PG 1700+518, we suggested that the difference may be due to the Fe ii contribution (Pu et al. 2006). Here, we give the same relation for PG 1700+518 when Fe ii contribution is carefully removed. We find that there is a strong anti-correlation between the spectral index of $f_\lambda$ (5100 Å) (see Figure 6). The Spearman coefficient $R$ is $-0.33$, with a probability of $p_{null} < 0.05$ for rejecting the null hypothesis of no correlation. If two discrete red points are excluded, $R$ is 0.55, and $p_{null} < 5.8 \times 10^{-4}$. Therefore, after considering Fe ii contribution, we find that PG 1700+518 shares the same spectral slope variability characteristic, i.e., harder spectrum during brighter phase (Hubeny et al. 2000), as the other 15 PG QSOs in our previous paper (Pu et al. 2006).

5. CONCLUSION

With the spectral decomposition of 39 spectra of PG 1700+518 with strong Fe ii emission, we investigate the Fe ii variability and its time lag. The main conclusions can be summarized as follows. (1) We give the light curves of $f_\lambda$ (5100 Å), Fe ii, Hβ, Hα, and Hβ +Fe ii, as well as the mean and rms spectra for PG 1700+518. With the normalized variability measure, $\sigma_N$, we find that all components are variable. (2) With the code of Peterson et al. (2004), we find that the Fe ii time lag in PG 1700+518 is $209^{+100}_{-547}$ days, while the Hβ time lag cannot be determined. (3) Considering the uncertainties of time lags, the expected Hβ time lag from the empirical luminosity–size relation is 221.6 lt-days, consistent with our measured Fe ii time lag. If we take the FWHM/time lag uncertainties into consideration, we find that the Fe emission region is located near the Hβ emission region, but not conclusively located outside of the Hβ emission region. (4) Assuming that the Fe ii and Hβ emission regions follow the virial relation between the time lag and the FWHM for the Hβ and Fe ii emission lines, we can derive the Hβ time lag to be $148^{+72}_{-70}$ days. With respect to the Hβ time lag of 252 days suggested by Peterson et al. (2004), the smaller Hβ time lag, which leads to a smaller black hole mass estimation in the logarithm, is decreased by 0.23 dex. (5) After considering Fe ii contribution, PG 1700+518 shares the same spectral slope variability characteristic, i.e., harder spectrum during brighter phase, as the other 15 PG QSOs in our previous work (Pu et al. 2006).

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