Implications from the optical to UV flux ratio of FeII emission in quasars

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ABSTRACT
We investigate FeII emission in Broad Line Region (BLR) of AGNs by analyzing the FeII(UV), FeII(A4570) and MgII emission lines in 884 quasars in the Sloan Digital Sky Survey (SDSS) Quasar catalog in a redshift range of 0.727 < z < 0.804. FeII(A4570)/FeII(UV) is used to infer the column density of FeII-emitting clouds and explore the excitation mechanism of FeII emission lines. As suggested before in various works, the classical photoionization models fail to account for FeII(A4570)/FeII(UV) by a factor of 10, which may suggest anisotropy of UV FeII emission; otherwise, an alternative heating mechanism like shock is working. The column density distribution derived from FeII(A4570)/FeII(UV) indicates that radiation pressure plays an important role in BLR gas dynamics. We find a positive correlation between FeII(A4570)/FeII(UV) and the Eddington ratio. We also find that almost all FeII-emitting clouds are to be under super-Eddington conditions unless ionizing photon fraction is much smaller than that previously suggested. Finally we propose a physical interpretation of a striking set of correlations between various emission-line properties, known as “Eigenvector 1”.

Key words: galaxies: active – galaxies: nuclei – quasars: emission lines – line: formation – atomic processes – radiation mechanisms: general

1 INTRODUCTION
According to the models of nucleosynthesis, much of Fe comes from Type Ia supernovae (SNe Ia), while α elements such as O and Mg come from Type II supernovae (SNe II). Because of the difference in lifetime of the progenitors, Fe enrichment delays relative to α elements. Hence the abundance ratio of Fe to α elements [Fe/α] should have a sudden break at 1–2 Gyr after the initial burst of star formation (Hamann & Ferland 1993; Yoshii, Tsujimoto & Nomoto 1996; Yoshii, Tsujimoto & Kawara 1998, but see also recent studies, such as Matteucci et al. 2006 and Totani et al. 2008, indicating a significant number of SNe Ia on relatively short timescales). Under the assumption that the FeII/MgII flux ratio reflects [Fe/Mg], various groups have measured FeII/MgII in high-redshift quasars hoping to discover such a break (e.g., Elston, Thompson & Hill 1994; Kawara et al. 1996; Dietrich et al. 2002, 2003; Iwamuro et al. 2002, 2004; Freudling, Corbin & Korista 2003; Maiolino et al. 2003; Kurk et al. 2007; Sameshima et al. 2009). However, these efforts have ended up with finding a large scatter of FeII/MgII showing little evolution.

A doubt is, thus, cast on the assumption that FeII/MgII reflects [Fe/Mg]. For examples, Verner et al. (2003) suggested that FeII/MgII depends not only on the abundance but also on the microturbulence of FeII-emitting clouds. Tsuzuki et al. (2006) showed that FeII/MgII correlates with the X-ray photon index, the full width at half maximum (FWHM) of MgII, the black hole mass, etc. For these reasons, prior to deriving the abundance from FeII/MgII, we must first clarify these non-abundance effects on the FeII emission as well as the source of the FeII excitation.

Column densities of clouds, which are considered to be one of the non-abundance factors largely affecting the FeII emission, have lately attracted attention for their significance in determining whether or not the radiation pressure plays an important role in BLR gas dynamics. Marconi et al. (2008) considered the effect of radiation pressure from ionizing photons on estimating of the black hole mass, which is based on the application of the virial theorem to broad emission lines in AGN spectra, and suggested that the black hole mass can be severely underestimated if the effect of radiation pressure is ignored. Netzer (2009) then used the $M_{BH} - \sigma_*$ relation for a test of this suggestion, where $M_{BH}$ is the black hole mass and $\sigma_*$ is the velocity dispersion of host galaxies, concluding radiation pressure effect is unim-
Portant, while Marconi et al. (2009) found the importance of radiation pressure by taking into account the intrinsic dispersion associated with the related parameters, in particular, column densities of BLR clouds. However, there are no reliable column density estimates from observations up to date.

In this paper, we will estimate column densities of quasars selected from the SDSS using Fe II, for investigating the excitation mechanism of Fe II emission and the BLR gas dynamics. In section 2, we perform numerical calculations of Fe II emission lines to establish a method for estimating column densities. In section 3, Fe II emission lines in the UV and optical as well as Mg II emission lines are measured in the SDSS quasars. The results and discussion about Fe II emission mechanism, radiation pressure, and the variety of quasar spectra called as “Eigenvector 1” are given in section 4. Throughout this paper, we assume a cosmology with $\Omega_m = 0.3$, $\Omega \Lambda = 0.7$ and $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

2 METHODOLOGY

In the following, we use Fe II(λ4570) to denote the UV Fe II emission lines in 2000 < λ < 3000 Å, Fe II(λ4570) to the optical Fe II emission lines in 4435 < λ < 4685 Å, and Mg II to the Mg II λ2798 emission line.

2.1 Fe II(λ4570)/Fe II(λ4570) to measure column densities

Figure 1 shows a simplified Fe II Grotrian diagram. As can be seen, Level 3–Level 2 transitions give rise to optical Fe II emission lines such as the Fe II(λ4570) bump. Branching ratio of Level 3–Level 1 UV resonance transitions is significantly higher than that of Level 3–Level 2 optical transitions. Hence strong optical Fe II emission requires a large optical depth between Level 1 and Level 3 such as $\tau_{13} > 10^3$ in order to transform UV Fe II lines to optical Fe II lines through a large number of scatterings (cf. Collin & Joly 2000). Thus Fe II(λ4570)/Fe II(λ4570) flux ratio must strongly depend on $\tau_{13}$ and $\tau_{23}$, which are the optical depths for photons emitted through Level 3–Level 1 and Level 3–Level 2 transitions, respectively. If so, the Fe II(λ4570)/Fe II(λ4570) can be an indicator of the column density.

Here we use a quite simple model to indicate the dependence of Fe II(λ4570)/Fe II(λ4570) on the column density. First, we ignore the Level 4 in Figure 1 and consider the Fe II as three-level system. Second, we assume thermal equilibrium population between Level 1 and Level 2. Third, we assume an expression of the local escape probability given by Netzer & Wills (1983) as $\epsilon_{ij} = (1 - \tau_{ij})/\tau_{ij}$. Although the model adopting these assumptions is obviously too oversimplified, it is useful to qualitatively understand how the line ratio depends on the physical parameters. The flux ratio is then written as

$$\frac{\text{Fe II}(\lambda 4570)}{\text{Fe II}(\lambda 4570)} \approx \frac{n_3 A_{23} \epsilon_{23} h \nu_{23}}{n_3 A_{31} \epsilon_{31} h \nu_{31}}$$  \hspace{1cm} (1)

$$\propto \exp \left( \frac{2.9 \text{ eV}}{kT} \right) \frac{1 - e^{-\tau_{23}}}{1 - e^{-\tau_{13}}}$$  \hspace{1cm} (2)

where $n_3$ is the population of level 3, and $A_{ij}$ is the spontaneous emission rate from the level $i$ to the level $j$. Following the fact that $\tau_{13} \gg 1$, the ratio can be roughly reduced to $\text{Fe II}(\lambda 4570)/\text{Fe II}(\lambda 4570) \propto 1 - e^{-\tau_{23}}$. Since $\tau_{23}$ is proportional to the column density, the ratio is an increasing function of the column density. We will discuss further on this matter in the following.

2.2 Photoionization models in the LOC scenario

Here we will show more sophisticated model calculations of Fe II(λ4570)/Fe II(λ4570). We performed photoionization model calculations with version C06.02 of the spectral simulation code Cloudy, last described by Ferland et al. (1998), combined with a 371 level Fe II model (up to ~11.6 eV, Verner et al. 1999). The incident continuum is defined as $f_\nu \propto \nu^{\alpha_{\text{UV}}} \exp(-\nu/kT_{BB}) \exp(-kT_{IR}/\nu) + \nu^{\alpha_{\text{X}}}$

The first term in the right-hand side of the equation (3) expresses an accretion disk component, which is usually called Big Bump. The $kT_{BB}$ and the $kT_{IR}$ indicate the higher and the lower cut off energies, respectively. The second term expresses a power-law X-ray component, which is set to zero below 1.36 eV, while to fall off as $\nu^{-3}$ above 100 keV. The coefficient $a$ is set to produce the optical to X-ray spectral index $\alpha_{ox}$.

1 The optical to X-ray spectral index $\alpha_{ox}$ is defined as $f_\nu(2 \text{ keV})/f_\nu(2500 \text{ Å}) = 403.3^{\alpha_{ox}}$.

Figure 1. Simplified Fe II Grotrian diagram. Note that each Level represents a large number of levels that have nearly the same excitation energies. Solid arrow indicates UV Fe II emission lines, while dashed arrow indicates optical Fe II emission lines.
integrating these clouds with an appropriate covering fraction distribution. The observed emission line flux is, then, expressed as:

\[ L_{\text{line}} \propto \int r^2 F(r, n_H) f(r) g(n_H) dn_H dr \]

where \( F(r, n_H) \) is the emission line flux of a single cloud at a distance \( r \) from the central continuum source and with \( n_H \), \( f(r) \) is a cloud covering fraction with distance \( r \), and \( g(n_H) \) is a fraction of clouds with \( n_H \). Matsuoka et al. (2007) showed that \( \text{O} \text{I} \) and \( \text{Ca} \text{II} \) emission lines in quasars, which are likely to emerge from the same gas as the \( \text{Fe} \text{II} \) emission lines, are well reproduced by a LOC model with \( f(r) \propto r^{-1} \) and \( g(n_H) \propto n_H^{-1} \), hence we have adopted these covering distributions. Baldwin et al. (1995) suggested that since clouds at large distances from the continuum source will form graphite grains which heavily suppress the line emissivity, clouds with \( \Phi < 10^{18} \text{ s}^{-1} \text{ cm}^{-2} \) must be excluded from integration. Thus we have calculated equation (4) for clouds which correspond \( \Phi > 10^{18} \text{ s}^{-1} \text{ cm}^{-2} \).

Figure 2 illustrates \( \text{Fe} \text{II}(\lambda 4570)/\text{Fe} \text{II}(UV) \) as a function of the column density for photoionized clouds. \( \text{Fe} \text{II}(\lambda 4570)/\text{Fe} \text{II}(UV) \) increases as the column density increases. It also shows that \( \text{Fe} \text{II}(\lambda 4570)/\text{Fe} \text{II}(UV) \) decreases as the microturbulent velocity increases, consistent with Verner et al. (2003), and that \( \text{Fe} \text{II}(\lambda 4570)/\text{Fe} \text{II}(UV) \) is maximum when no microturbulence is assumed to exist. This is explained as follows. Increasing microturbulent velocities broadens the line absorption profile, resulting in enhancement of the continuum photoexcitation. This effect is relatively large for high energy levels where the collisional excitation is inefficient for their high excitation potential. Thus large microturbulent velocities relatively enhances the continuum photoexcitation to the Level 4 in Figure 1, leading to emit more fluxes in the UV \( \text{Fe} \text{I} \) emission lines, thus decreasing \( \text{Fe} \text{II}(\lambda 4570)/\text{Fe} \text{II}(UV) \). For photoionized clouds, \( \text{Fe} \text{II}(\lambda 4570)/\text{Fe} \text{II}(UV) \) can be used as a column density indicator unless microturbulent velocities vary much from cloud to cloud.

It is noted that calculations adopting the other shapes of the incident continuum\(^2\) show little changes for \( \text{Fe} \text{II}(\lambda 4570)/\text{Fe} \text{II}(UV) \), indicating little dependence on the spectral energy distribution (SED) of ionizing continuum.

### 2.3 Collisionally ionized models

As an alternative to photoionization models, we consider models in which a cloud is assumed to be in collisional equilibrium at a given electron temperature \( T_e \), and call them collisionally ionized models. In these models, the specific heating mechanism is not accounted and arbitrary electron temperatures are given. It is noted that \( \text{Fe} \text{II} \) is collisionally excited in either mechanically heated clouds such as through shocks or photoionized clouds. In the latter case, the heating mechanism is specified to be the heating of the incident UV and X-ray photons.

\(^2\) Two types of SED given by Nagao, Murayama & Taniguchi (2001) are adopted. One is set to reproduce the ordinary SED of broad-line Seyfert 1 galaxies, and the other is set to reproduce that of narrow-line Seyfert 1 galaxies.

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**Figure 2.** \( \text{Fe} \text{II}(\lambda 4570)/\text{Fe} \text{II}(UV) \) vs. column densities based on the photoionization models. \( V_{\text{turb}} \) is the microturbulence velocity of clouds. Note that, in the LOC, the calculation results are not dependent on \( n_H \) and \( U \) since clouds with different hydrogen density and distance from central continuum source are all integrated.

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Joly (1987) offers collisionally ionized model calculations. In her models, \( \text{Fe} \text{II} \) is approximated by a 14-level (up to \( \sim 5.7 \text{ eV} \)), and the emission region is assumed to be a homogeneous slab with constant hydrogen density \( n_H \), column density \( N_H \), electron temperature \( T_e \), and not to receive any external radiation. The electron temperature ranges from 6,000 K to 15,000 K, the density from \( 10^{16} \) to \( 10^{22} \text{ cm}^{-3} \) and the column density from \( 10^{19} \) to \( 10^{25} \text{ cm}^{-2} \).

Figure 3 shows \( \text{Fe} \text{II}(\lambda 4570)/\text{Fe} \text{II}(UV) \) as a function of the column density, taken from Joly (1987). As expected from equation (2), it can be seen that \( \text{Fe} \text{II}(\lambda 4570)/\text{Fe} \text{II}(UV) \) increases with the column density while decreases with temperature. However, Figure 3 shows that \( \text{Fe} \text{II}(\lambda 4570)/\text{Fe} \text{II}(UV) \) does not so much depend on the temperature in 6,000 < \( T_e \) < 10,000 K. It is noted that Collin et al. (1980) and Joly (1987) showed emission line ratios including \( \text{Fe} \text{II} \) in quasars are well accounted by cold clouds with 6,000 < \( T_e \) < 10,000 K. Thus it is reasonable to assume that \( \text{Fe} \text{II} \)-emitting clouds have the temperatures in a range of 6,000 < \( T_e \) < 10,000 K, and the \( \text{Fe} \text{II}(\lambda 4570)/\text{Fe} \text{II}(UV) \) depends little on the temperature while strongly varies with the column density. We fit the data of 6,000 < \( T_e \) < 10,000 K models by a 4th-order polynomial, and find

\[
y = -0.72 + 0.28x - 0.046x^2 + 0.031x^3 - 0.0089x^4
\]

where \( y = \log \text{Fe} \text{II}(\lambda 4570)/\text{Fe} \text{II}(UV) \) and \( x = \log N_H[\text{cm}^{-2}] - 23 \). We will use this relation to estimate the column density of quasars.

### 3 ANALYSIS OF QUASAR SPECTRA

#### 3.1 Sample selection

We have analyzed quasar spectra selected from the fourth edition of the SDSS Quasar catalog (Schneider et al. 2007). SDSS uses a dedicated 2.5 m telescope at the Apache Point...
The density ranges from $10^{10}$ to $10^{12}$ cm$^{-3}$ and the column density from $10^{21}$ to $10^{25}$ cm$^{-2}$. Circles indicate the models with $6000 < T_e < 10000$ K, triangles with $T_e = 12500$ K and diamonds with $T_e = 15000$ K. The solid line indicates the fitted 4th-order polynomial for samples with $6000 < T_e < 10000$ K. The dotted and the dashed lines connect the median values of Fe II($\lambda$4570)/Fe II(UV) at each column density for samples with $T_e = 12500$ K and $T_e = 15000$ K, respectively.

Observatory equipped with a CCD camera to image the sky in five optical bands, and two digital spectrographs, one covering a wavelength range of 3800 Å to 6150 Å and the other from 5800 Å to 9200 Å. The spectral resolution ranges from 1850 to 2200. The fourth edition of the SDSS QSO catalog consists of the objects in the Fifth Data Release, and contains 77,429 quasars.

In order to measure the Fe II(UV) and Fe II($\lambda$4570) emission lines simultaneously, we have selected spectra which cover the wavelength range of 2200 to 5100 Å in the rest frame, corresponding to the redshift range from 0.727 to 0.804. 2,189 objects meet this requirement. Then we have checked the signal to noise ratio (S/N) per pixel for each spectrum which fulfills median S/N $> 10$ per pixel at their continuum levels for accurate flux measurements. 946 objects meet this requirement. All the spectra were inspected by eyes and 62 spectra were rejected because of wavelength discontinuity, terrible contamination by host galaxy star light, etc. Our final sample thus consists of 884 spectra.

Prior to the measurements, the quasar spectra were dereddened for the Galactic extinction according to the dust map by Schlegel, Finkbeiner & Davis (1998) using the Milky Way extinction curve by Pei (1992).

Since SDSS quasars are flux-limited in the survey, low luminosity quasars are lost in the SDSS sample. Figure 4 shows luminosity versus redshift for our sample. Because of the narrow redshift coverage for our sample, the minimum luminosity is almost constant and roughly estimated to be $\lambda L_{5100} = 10^{44.7}$ erg/s.

3.2 Continuum and line fitting

In the UV to optical, the quasar continuum is composed of (i) the power-law continuum $F_{\lambda}^{PL}$, (ii) the Balmer continuum $F_{\lambda}^{BaC}$ and (iii) the Fe II pseudo-continuum $F_{\lambda}^{FeII}$. Thus we assumed a following formula as a model continuum $F_{\lambda}^{cont}$:

$$F_{\lambda}^{cont} = F_{\lambda}^{PL} + F_{\lambda}^{BaC} + F_{\lambda}^{FeII}$$

3.2.1 Power-Law continuum

The power-law continuum is simply written as follows:

$$F_{\lambda}^{PL} = F_{5100} \left( \frac{\lambda}{5100} \right)^{-\alpha}$$

The free parameters of this model are a scaling factor $F_{5100}$ and a power-law index $\alpha$. We chose three fitting ranges, 2200-2230 Å, 4180-4220 Å and 5050-5100 Å, as continuum windows, since these areas have little emission lines (see Figure 5). There are, however, the Balmer continuum and the Fe II pseudo-continuum underneath these regions, requiring some corrections.

Tsuzuki et al. (2006) gives 14 quasar spectra covering a wide wavelength range and measured accurately their continuum levels. We fitted power-law continuum models to their spectra in the continuum windows, and compared the continuum levels with those given by Tsuzuki et al. (2006). We found that our method systematically overestimates the continuum levels, 10.1% at 2200-2230 Å, 5.7% at 4180-4220 Å and 3.4% at 5050-5100 Å. According to these results, we first reduced the flux densities of the object by these amount at each continuum window, then fitted the power-law continuum. An example of the fitted power-law continuum is indicated as the dashed line in Figure 5. The measurement error of the continuum levels is estimated to be less than 10%.

3.2.2 Balmer continuum

Grandi (1982) gives a formula describing the Balmer continuum produced by a uniform temperature, partially optically thick cloud:
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\[ F_{\lambda}^{BaC} = F_{BaC}B_{\lambda}(T_e) \left[ 1 - \exp \left\{ -\tau_{BE} \left( \frac{\lambda}{\lambda_{BE}} \right)^3 \right\} \right] \]

where \( B_{\lambda}(T_e) \) is the Planck function at the electron temperature \( T_e \), and \( \tau_{BE} \) is the optical depth at the Balmer edge at \( \lambda \approx 3646 \, \text{Å} \). Kurk et al. (2007) assumed gas clouds of uniform temperature (\( T_e = 15,000 \, \text{K} \)) and the optical depth fixed to \( \tau_{BE} = 1 \), and fit equation (8) to their sample quasar spectra to estimate the strength of the Balmer continuum (see also Dietrich et al. 2003). We followed their method and assumed \( T_e = 15,000 \, \text{K}, \tau_{BE} = 1 \). The only one parameter, namely the scale factor \( F_{BaC} \), is set free and is decided by fitting equation (8) to the power-law subtracted spectrum at 3600–3645 Å. An example of the fitted Balmer continuum is indicated as the dotted line in Figure 5.

3.2.3 FeII pseudo-continuum

Since FeII has enormous energy levels, neighboring emission lines contaminate heavily with each other, which makes it difficult to measure the FeII emission lines. One approach to measure the FeII emission lines is to use FeII templates. So far, several FeII templates are derived from the narrow-line Seyfert 1 galaxy, I Zw 1.

In the UV, Vestergaard & Wilkes (2001) and Tsuzuki et al. (2006) give their FeII templates. The template given by Vestergaard & Wilkes (2001) do not cover around MgII line. Tsuzuki et al. (2006) used a synthetic spectrum calculated with the Cloudy photoionization code in order to separate the FeII emission from the MgII line, and derived semiempirically the FeII template which covers around the MgII line. Since we want to measure the MgII emission line, we decided to use the UV FeII template given by Tsuzuki et al. (2006).

In the optical, Véron-Cetty, Joly & Véron (2004) and Tsuzuki et al. (2006) open their FeII templates to the public. Véron-Cetty et al. (2004) carefully analyzed the FeII emission lines in I Zw 1, finding that the FeII lines are emitted from both BLR and Narrow Line Region (NLR). They succeeded to separate them and called the broad line system L1 and the narrow line system N3, respectively. Tsuzuki et al. (2006) also analyzed the spectrum of I Zw 1 and derived the optical FeII template, which was however not separated into the BLR and the NLR components. We applied both the broad line system L1 template given by Véron-Cetty et al. (2004) and the optical FeII template given by Tsuzuki et al. (2006) to all of our samples, finding that the latter has a slightly smaller average \( \chi^2_p \) value (median \( \chi^2_p \approx 1.48 \) for Tsuzuki et al. 2006, while median \( \chi^2_p \approx 1.58 \) for Véron-Cetty et al. 2004). Here we adopt to use the optical FeII template given by Tsuzuki et al. (2006).

Prior to applying the FeII template to each quasar, broadening of the template spectrum is needed. Thus we modeled the FeII flux density as follows:

\[ F_{\lambda}^{FeII}(x) = F_{FeII} \int_{-\infty}^{\infty} F_{\lambda}^{template}(x') \times \exp \left\{ \frac{-4c^2 \ln(2(x-x'))^2}{FWHM_{conv}^2} \right\} dx' \]

where \( x = \ln \lambda, c \) is the velocity of light and FWHM\(_{conv}\) represents the FWHM of the convolved Gaussian function. We first calculated the equation (9) for FWHM\(_{conv} = 0 - 5000 \, \text{km/s} \) stepped by 100 km/s, thus prepared 51 FeII emission line models. Then we flux-scaled each model to fit the continuum subtracted spectrum (i.e., the spectrum after subtracting the power-law and the Balmer continuum), and adopted the model which gives the smallest \( \chi^2_p \) value. We decided mask regions as follows; 2280-2380 Å for CIII] λ2326; 2400-2480 Å for [NeIV] λλ2423, and FeIII: 2750-2850 Å for MgII: 3647-4000 Å for high-order Balmer lines; 4050-4150 Å for Hδ; 4300-4400 Å for Hγ; 4600-5050 Å for HeII λλ4686, Hβ and [OIII] λλ4959,5009. An example of the fitted FeII pseudo-continuum is indicated as the dot-dashed line in Figure 5.

3.2.4 MgII lines

After subtracting the continuum components, we have measured the MgII emission line for estimating the black hole mass from its FWHM. We have fitted the MgII emission line profile by two gaussian components. Figure 6 shows an example of the MgII emission line fitting.
3.3 Black hole mass and Eddington luminosity

For the classical black hole mass estimate in which the radiation pressure effect is neglected, we use the following formula given by McLure & Jarvis (2002):

$$M_{BH,0} = 3.37 \left( \frac{\lambda L_{3000}}{10^{37} \, \text{W}} \right)^{0.47} \left[ \frac{\text{FWHM}(\text{MgII})}{\text{km} \, \text{s}^{-1}} \right]^2 M_\odot$$  \hspace{1cm} (10)

The classical Eddington luminosity is given as follows:

$$L_{Edd,0} = \frac{4\pi cGM_{BH,0} m_p}{\sigma_T} \sim 1.26 \times 10^{38} \frac{M_{BH,0}}{M_\odot} \, \text{ergs/s}$$  \hspace{1cm} (11)

where \( c \) is the velocity of light, \( m_p \) is the proton mass, and \( \sigma_T \) is the Thomson cross-section.

On the other hand, Marconi et al. (2008) suggested that the force of the radiation pressure should be corrected to derive the black hole mass. They give the radiation pressure corrected black hole mass \( M_{BH,rad} \) and Eddington luminosity \( L_{Edd,rad} \) as follows:

$$M_{BH,rad} = M_{BH,0} + \frac{L_{bol}}{L_{Edd,0}} \left( 1 - \frac{a}{\sigma_T N_H} \right) M_{BH,0}$$  \hspace{1cm} (12)

$$L_{Edd,rad} = \frac{L_{Edd,0}}{1 - \frac{a}{\sigma_T N_H}}$$  \hspace{1cm} (13)

$$a \equiv \frac{L_{ion}}{L_{bol}}$$  \hspace{1cm} (14)

where \( L_{bol} \) is the bolometric luminosity, \( L_{ion} \) is the total luminosity of the ionizing continuum (i.e., \( h\nu > 13.6 \, \text{eV} \)), and \( a \) is the ionizing photon fraction. The second term in the right hand side of equation (12) represents the correction term of the radiation pressure. We here adopt a bolometric correction \( L_{bol} = 9\lambda L_{5100} \) given by Kaspi et al. (2000).

3.4 Error estimate

We performed a Monte-Carlo simulation similar to those done in Hu et al. (2008) for estimating the measurement errors. The detail of the procedure is as follows.

(i) Generating a composite spectrum. Following Vanden Berk et al. (2001), we generated a composite spectrum using all of our samples. This composite spectrum represents a typical quasar spectrum for our samples. (ii) Obtaining typical emission line profiles. We applied the measurement methods written in §3.2 to the composite spectrum, and obtained typical emission line profiles for FeII(UV), FeII(\( \lambda 4570 \)) and MgII. (iii) Making artificial spectra. We combined these line profiles with the power-law continuum and the Balmer continuum. Thus the simulated spectrum is written as follows.

$$F_{\lambda}^{sim} = F_{\lambda}^{PL}(F_{5100}, \alpha) + F_{\lambda}^{BAC}(F_{BAC}) + F_{\lambda}^{FeII(UV)}(EW_{FeII(UV)}) + F_{\lambda}^{FeII(\lambda 4570)}(EW_{FeII(\lambda 4570)}) + F_{\lambda}^{MgII}(EW_{MgII}, FWHM_{MgII})$$  \hspace{1cm} (15)

Note that, for simplicity, we ignored the broadening of the pseudo-FeII continuum. Values of input parameters, which are given in the parentheses in equation (15), are randomly sampled from probability distributions that are made to reflect the observations. Thus, we generated 1,000 simulated spectra. (iv) Generating a noise template. Using all the noise spectra produced by the SDSS pipeline for our samples, we generated a composite spectrum following Vanden Berk et al. (2001) and named it a noise template. This noise template is scaled so that the resulting median S/N to be 10 per pixel at the continuum level for each simulated spectrum, and is treated as its noise.

Now we have the 1,000 simulated spectra with their noise. The measurement methods written in §3.2 are applied to these simulated spectra. We calculate the value \( \delta_{sim} = (P_{out} - P_{in})/P_{in} \) for each simulated spectrum where \( P_{in} \) represents the input parameters (i.e., the values given in the parentheses in equation (15)) and \( P_{out} \) represents the corresponding measured values for the simulated spectra.

We regard \( \sigma_{sim} \), a standard deviation of \( \delta_{sim} \), as 1σ error of the measurement. Thus we evaluate the measurement errors to be 16.4% for EW of FeII(UV), 22.9% for EW of FeII(\( \lambda 4570 \)) and 7.9% for FWHM(MgII). The simulation implies the measurement error to be 2.9% for the luminosity, which is less than 10% estimated in the power-law fitting. Therefore we decided to evaluate the measurement error to be 10% for \( \lambda L_{3000} \) and \( \lambda L_{5100} \).

4 RESULTS AND DISCUSSION

4.1 On the excitation mechanism of FeII emission

Figure 7 shows the observed FeII(\( \lambda 4570 \))/FeII(UV) distribution. As can be seen from the comparison between this and Figure 2, our photoionization models underpredict the FeII(\( \lambda 4570 \))/FeII(UV) by a factor of 10, failing to account for the observations. This result is consistent with the preceding study by Baldwin et al. (2004). Additional microturbulence to the photoionized clouds gets the situation even worse. Thus, Figure 7 seems to challenge classical photoionized pictures of FeII-emitting clouds. On the other hand, in the case of the collisionally ionized models shown in Figure 3, the observed FeII(\( \lambda 4570 \))/FeII(UV) flux ratios are well reproduced with \( 10^{22} < N_H < 10^{24} \, \text{cm}^{-2} \) and with \( 6,000 < T_e < 10,000 \, \text{K} \).

These results give two remarks: (1) the FeII-emitting
clouds in quasars are heated to \(6,000 < T_c < 10,000 \text{ K}\); (2) the UV and the X-ray photons, which are the heating source in our photoionization models, fail to heat the gas to such temperatures (probably heat the gas too hot!). One possible interpretation is that the FeII-emitting clouds are heated by an alternative mechanism such as through shocks. Here we note that there is a reverberation mapping study implying shock heating for FeII emission. Kuehn et al. (2008) analyzed optical FeII emission bands in the Ark 120, finding that they do not respond to the continuum variation. Thus the optical FeII-emitting region may be heated by other mechanism than photoionization. These results favor the shock heating for the optical FeII-emitting region, but there are also difficulties. First, the amount of shock-processed matter would probably be too large. Second, as Kuehn et al. (2008) showed, collisionally ionized models failed to match the shape of the optical FeII-emission band. Third, the fact that there is no response to the continuum variation for optical FeII emission bands can also be interpreted as that the emitting region is too large to vary optical FeII emission in observable timescales. Unless shocks are a viable solution, the failure of the photoionization model simply indicates that it is not predicting the correct heating rate, or that the radiative transport calculations are not correct.

One possible cause disturbing classical photoionization models to reproduce the observations may be the assumption that the FeII emission is isotropic. Ferland et al. (2009) recently suggested that UV FeII lines are beamed toward a central source while optical FeII lines are emitted isotropically. Then photoionization models can reproduce the observed UV to optical FeII flux ratio if the FeII-emitting clouds are distributed asymmetrically so that we mainly observe their shielded faces. However, this needs special geometrical distributions like Type II AGNs; a thick FeII-emitting gas surrounding the central source with a substantial covering factor, and intervening between the central region and our eyes. At the present time, it is not clear whether or not photoionization models can reproduce the emission line strengths other than FeII under such the situation. Much broader exploration of photoionization model calculations is certainly needed.

### 4.2 Column density distribution inferred from \(\text{FeII}(\lambda4570)/\text{FeII}(\lambda)\)

Now we can roughly estimate column densities from the observed \(\text{FeII}(\lambda4570)/\text{FeII}(\lambda)\) by using equation (5). The estimated column density distribution is shown in Figure 8. An average and a standard deviation of the distribution are found to be \((\log N_H, \sigma_{\log N_H}) = (22.8, 0.5)\). Marconi et al. (2009) has suggested that radiation pressure does play an important role in BLR gas dynamics if column densities of BLR clouds have intrinsic dispersion such as \((\log N_H, \sigma_{\log N_H}) = (23.0, 0.5)\). Our results support that the assumption adopted in Marconi et al. (2009) is appropriate and that the radiation pressure plays an important role in BLR clouds.

![Figure 7](image1.png)

**Figure 7.** Observed \(\text{FeII}(\lambda4570)/\text{FeII}(\lambda)\) flux ratio distribution. The average of \(\log \text{FeII}(\lambda4570)/\text{FeII}(\lambda)\) is \(-0.8\) and the standard deviation is 0.2 dex, in disagreement with the range that the photoionization models predict.

![Figure 8](image2.png)

**Figure 8.** Estimated column density distribution. The average and the standard deviation of the distribution are \((\log N_H, \sigma_{\log N_H}) = (22.8, 0.5)\), providing observational support for the assumption adopted in Marconi et al. (2009).

### 4.3 Correlation between Eddington ratio and \(\text{FeII}(\lambda4570)/\text{FeII}(\lambda)\)

Figure 9 shows the relation between \(\text{FeII}(\lambda4570)/\text{FeII}(\lambda)\) and the Eddington ratio. A positive correlation is seen. Linear regression analysis, using an IDL procedure “FITXY.pro” (cf. Press et al. 1992), gives the relation as:

\[
\log \frac{\text{FeII}(\lambda4570)}{\text{FeII}(\lambda) = -0.71 + 0.31 \log \frac{L_{bol}}{L_{Edd,0}}}
\]

The Spearman’s rank correlation coefficient\(^3\) for assessing the nonlinear correlation is \(r_s = 0.58\). This means the

\(^3\) Spearman’s rank correlation coefficient is non-parametric measure of correlation, that is, which assesses how well an arbitrary monotonic function could describe the relationship between two variables without making any other assumptions.
probability of the null hypothesis that there is no correlation is less than $10^{-11}$. Thus the correlation between \( \text{Fe}^{II}(\lambda 4570)/\text{Fe}^{II}(UV) \) and the Eddington ratio is real. This implies that the column density increases with the Eddington ratio, because \( \text{Fe}^{II}(\lambda 4570)/\text{Fe}^{II}(UV) \) increases with the column density.

As was recently suggested by Dong et al. (2009), under the condition where the BLR clouds are subject to the radiation pressure, low-column-density clouds would be blown away by relatively large radiation pressure at large \( L_{\text{bol}}/L_{\text{Edd},0} \), so that only high-column-density clouds would be able to be gravitationally bound. Figure 9 is a supportive evidence for their suggestion.

### 4.4 Super-Eddington problem

Figure 10 plots our samples on \( N_H - L_{\text{bol}}/L_{\text{Edd},0} \) plane. Each line represents \( L_{\text{bol}} = L_{\text{Edd},\text{rad}} \), so that the lower region of the line corresponds super-Eddington area. If we adopt ionizing photon fraction \( a = 0.6 \) (i.e., thick solid line in Figure 10), which is an average value for AGNs calculated by Marconi et al. (2008), almost all of our samples become super-Eddington. This result can be interpreted in two ways: (i) the conversion from \( \text{Fe}^{II}(\lambda 4570)/\text{Fe}^{II}(UV) \) to column densities (i.e., equation (5)) is wrong, or (ii) the adopted value of \( a \) is inappropriate.

In the case (i), since \( \text{Fe}^{II}(\lambda 4570)/\text{Fe}^{II}(UV) \) is a function of the column density and the temperature, the false in the conversion is attributed to the assumed temperature. If we assume hot clouds such as \( T_e > 10,000 \) K, the corresponding column densities would become large, resulting in the solution for this super-Eddington problem. However, as already discussed, the previous studies favor cold clouds such as \( 6,000 < T_e < 10,000 \) K for \( \text{Fe}^{II} \) emission (cf. Collin et al. 1980, Joly 1987). Thus this interpretation seems to be inappropriate.

In the case (ii), it can be seen from Figure 10, if we adopt small values for \( a \) such as 0.01, the majority of our samples becomes gravitationally bound. This means that the fraction of ionizing photons irradiating on \( \text{Fe}^{II} \) emitting clouds is much less than those on usual BLR clouds. Then it seems quite natural to conclude that the \( \text{Fe}^{II} \) emission does not originate in the region where usual emission lines such as \( \text{H}\beta \) originate, but originate in outer parts of BLR where the incident ionizing photon fraction becomes as low as \( a = 0.01 \). It is worth noting that from the studies of \( \text{O}^{I} \) and \( \text{Ca}^{II} \) emission lines, Matsuoka et al. (2008) also suggests that \( \text{Fe}^{II} \) emission originates in outer parts of BLR.

#### 4.5 Eigenvector 1 in terms of the column density

Boroson & Green (1992) applied a principal component analysis to low-redshift quasars and found that the principal component 1 (which is called “Eigenvector 1”) links the strength of optical \( \text{Fe}^{II} \) emission and the weakness of \( \text{[O III]} \) emission. After a while, Boroson (2002) showed that Eigenvector 1 is driven predominantly by an Eddington ratio. However, the physical causes making up the Eigenvector 1 has been left unknown.

Here we propose a physical interpretation of Eigenvector 1 in terms of the column density. As discussed in the previous section, small-column-density clouds would be driven away from the line-emitting region by the radiation pressure at large Eddington ratio, and only large-column-density clouds can be gravitationally bound. Radiative transfer effects make the optical \( \text{Fe}^{II} \) emission become large in such large-column-density clouds. On the other hand, ionizing photons emitted from the central object are intervened by these large-column-density clouds and thus have less probabilities of ionizing photons reaching to NLR clouds, resulting in weak \( \text{[O III]} \) emission. In fact, Figure 10(t) in Tsuzuki et al. (2006) shows a negative correlation between the \( \text{[O III]}/\text{H}\beta \) and \( \text{Fe}^{II}(O1)/\text{Fe}^{II}(U1) \), which is almost the same as our \( \text{Fe}^{II}(\lambda 4570)/\text{Fe}^{II}(UV) \), for 14 quasars.
5 SUMMARY

(i) Analysis of the Fe II(UV), Fe II(λ4570) and Mg II emission lines is performed for 884 SDSS quasars in a redshift range of 0.727 < z < 0.804.

(ii) We suggest that Fe II(λ4570)/Fe II(UV) can be an indicator of the column density of Fe II-emitting clouds regardless of the excitation mechanism, i.e., photoionized or collisionally ionized clouds. From model calculations, we have confirmed this suggestion.

(iii) Our photoionization models underpredict Fe II(λ4570)/Fe II(UV) by a factor of 10, consistent with the preceding studies. Unless shocks are a viable heating mechanism, the failure of the photoionization model simply indicates that it is not predicting the correct heating rate, or that the radiative transport calculations are not correct. Ignoring anisotropy of UV Fe II emission may be one of the causes.

(iv) The column density distribution estimated from Fe II(λ4570)/Fe II(UV) is almost the same as the one suggested by Marconi et al. (2009), supporting that the radiation pressure does work on Fe II-emitting clouds.

(v) We also find a positive correlation between Fe II(λ4570)/Fe II(UV) and the Eddington ratio, implying the links between the column density and the Eddington ratio.

(vi) We find that under the assumption of the ionization fraction $a = 0.6$, almost all of our samples become super-Eddington. This problem can be cleared if the Fe II emission originates in outer parts of BLR where the ionizing photon fraction becomes as low as 0.01.

(vii) We propose physical interpretation of 'Eigenvector 1' in terms of the column density. In the interpretation, the strength of the optical Fe II emission results in the radiative transfer effects, while the weakness of the [O III] emission results in the reduction of ionizing photons in NLR caused by intervening large column density BLR clouds.

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