The Correlation between Si III $\lambda_{1892}/$C III $\lambda_{1909}$ and Fe II $\lambda_{4500}/$H$\beta$ in low redshift QSOs

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Abstract. HST archival FOS spectra of 40 QSOs with $z \leq 0.5$ in the Bright Quasar Survey have been analyzed. The spectra cover the region $\lambda\lambda_{1800-2000}$ in the QSOs’ rest frames, including the Al III $\lambda_{1859}$, Si III $\lambda_{1892}$, C III $\lambda_{1909}$, and Fe III UV34 emission-lines. We measured the flux of these UV emission-lines, and analyzed the correlations among UV and optical (H$\beta$, Fe II, and [O III]) emission-line properties as well as soft X-ray photon indices. We found a significant correlation between Si III$/$C III and Fe II$/$H$\beta$.

Si III and C III have similar ionization potentials, but Si III has one order magnitude larger critical density than C III. Si III$/$C III is thus a density indicator and becomes larger when density is higher. The correlation between Si III$/$C III and Fe II$/$H$\beta$ indicates that optical Fe II becomes strong when the density of the broad line region becomes high.

Our correlation analysis shows that large Si III$/$C III associates with weak [O III] $\lambda_{5007}$, large soft X-ray photon index, and narrow H$\beta$ width as well as with large Fe II$/$H$\beta$. Our results support the previous suggestions that the density of the broad line region gas and the mass accretion rate govern this correlation.

1. INTRODUCTION

Fe II emission-lines are one of the prominent features in the (rest) optical spectra of QSOs. Numerous observational studies have investigated the optical Fe II emission, and several correlations between optical Fe II strength and other observational properties have been found (Boroson & Green 1992 (BG92); Wang, Zhou, and Gao 1996; Wang, Brinkmann, and Bergeron 1996 (WBB96); Laor et al. 1997a).

BG92 analyzed the spectral region including Fe II $\lambda_{4500}$, H$\beta$, and [O III] $\lambda_{5007}$ of all 87 QSOs with redshift less than 0.5 in the Bright Quasar Survey (BQS) (Schmidt & Green 1983). They found a strong anticorrelation between the strength of Fe II and [O III] $\lambda_{5007}$. They also found that the asymmetry and
width of the Hβ line are associated with this anticorrelation. The principal component analysis by BG92 revealed that the most significant eigenvector, which accounts for 29% of the variance, consists of this anticorrelation between optical Fe II and the [O III] emission-line. BG92 called it Eigenvector 1. They suggested that Eigenvector 1 was related to the fraction of the Eddington luminosity.

Wang, Zhou, and Gao (1996) found that optical Fe II/Hβ correlates with Si IV + O IV λ1400/C IV λ1549 and C IV λ1549/Lyα in UV spectra of active galactic nuclei (AGN) with z < 0.211 obtained with IUE. They proposed three possible causes of this correlation: the inclination of the accretion disk, the spectrum of ionizing continuum, and the density of broad-line region (BLR) gas.

WBB96 also found that the soft X-ray photon index measured with ROSAT PSPC strongly correlates with the optical Fe II/Hβ and Hβ line widths in 86 AGN. The AGNs with steep spectral slopes in the soft X-ray region have stronger optical Fe II and narrower Hβ broad lines. WBB96 interpreted this to mean that the black hole mass and mass accretion rate govern the correlation between Hβ width and the spectral slope of soft X-rays.

Laor et al. (1997a) analyzed ROSAT PSPC spectra of the complete sample of BQS QSOs with z ≤ 0.400 and N_HI < 1.9 × 10^{20} cm^{-2}. They found that the power law slope of the soft X-ray spectra correlates with optical Fe II/Hβ, Hβ width and L_{[OIII]} in their sample. The correlations they have found are similar to those found by WBB96. The optical Fe II strength is related to the various properties of QSOs such as the radiation from the accretion disk (soft X-ray spectral slope), the kinematical properties of BLR (Hβ FWHM), and the luminosity of the narrow line region ([O III] luminosity). These properties arise from different structures ranging over more than four orders of magnitude difference in scale in the nuclei, from the inner radius of the accretion disk to a few hundred parsecs in the narrow line region. Study of these correlations will give us further understanding of QSOs.

Another property recently has been found to correlate with the optical Fe II emission-line strength. I Zw 1 (= PG 0050+124), which is known as a strong optical Fe II emitter (Phillips 1976), shows extremely strong Si III] λ1892 relative to C III] λ1909 (Laor et al. 1997b). We therefore have begun to analyze the emission-feature around 1900 Å in UV spectra of low-redshift (z ≤ 0.5) QSOs in the BQS obtained with the Faint Object Spectrograph (FOS) of the Hubble Space Telescope (HST). The BQS is a UV-excess (U - B < −0.44) and magnitude limited (B < 16.16) survey. The advantages of BQS QSOs are that they have been extensively observed over almost the entire electromagnetic waveband: radio, near-infrared, optical, and X-ray. Especially, good S/N optical spectra of all 87 BQS QSOs with redshift less than 0.5 have been reduced in the same manner and published by BG92. The low redshift BQS sample includes only apparently bright QSOs, allowing good S/N UV spectra. Wills et al. also have analyzed FOS spectra of the complete sample of BQS QSOs. Their results are presented in these proceedings.

Data and measurements of emission-lines are described in Section 2. We present in Section 3 the correlations among our measurements of UV emission-lines and optical and soft X-ray properties from the literatures. In section 4
we discuss the results and give interpretations. We give concluding remarks in Section 5. More details will be presented elsewhere (Aoki & Yoshida 1998).

2. DATA AND REDUCTION

We have gathered HST archival FOS data of BQS QSOs with redshifts less than 0.5. Two objects are omitted from the original list in Schmidt & Green (1983), as described in BG92, due to misclassification or a wrong redshift. The spectra of 44 BQS QSOs with \( z \leq 0.5 \) cover \( \lambda \lambda 1800 - 2000 \text{ Å} \) in the QSOs’ rest frames. They have been obtained with the G190H or G270H gratings (R \( \sim 1300 \)). They were observed for various studies of intervening and intrinsic absorption-lines as well as emission-line properties of QSOs, so this sample is not complete. Five different FOS apertures were used to observe them, but the difference in resolution caused by different aperture size is less than 5%. If an object was observed more than twice within one or two days with similar exposure times, we combined data to improve S/N even if the aperture sizes are different. If observations of the same object were separated by several months or more, we chose the one with better S/N. PG 1535+547 was observed with the spectropolarimetry mode, so we used the total flux spectra of it. Two objects, PG 0043+039 and PG 1700+518, are broad absorption line QSOs, for which it is difficult to do decompose the complex of emission lines around 1900 Å. They are excluded from our analysis. The objects’ names and redshifts are tabulated in Table 1. The spectra of six objects with strong Si III\( \lambda \lambda 1892 \) are shown in Fig. 1. They have been deredshifted using the measured peak wavelength of C III\( \lambda \lambda 1909 \).

| PG      | \( z \) | PG      | \( z \) | PG      | \( z \) | PG      | \( z \) |
|---------|--------|---------|--------|---------|--------|---------|--------|
| 0003+158| 0.450  | 1115+407| 0.154  | 1351+640| 0.087  | 1444+407| 0.267  |
| 0003+199| 0.025  | 1116+215| 0.177  | 1352+183| 0.158  | 1512+370| 0.371  |
| 0026+129| 0.142  | 1202+281| 0.165  | 1402+261| 0.164  | 1535+547| 0.038  |
| 0050+124| 0.061  | 1211+143| 0.085  | 1404+226| 0.098  | 1545+210| 0.266  |
| 0052+251| 0.155  | 1216+069| 0.334  | 1411+442| 0.089  | 1612+261| 0.131  |
| 0947+396| 0.206  | 1226+023| 0.158  | 1415+451| 0.114  | 1626+554| 0.133  |
| 0953+414| 0.239  | 1259+593| 0.472  | 1416+129| 0.129  | 1704+608| 0.371  |
| 1001+054| 0.161  | 1302+102| 0.286  | 1425+267| 0.366  | 2112+059| 0.466  |
| 1049–005| 0.357  | 1307+085| 0.155  | 1427+480| 0.221  | 2251+113| 0.323  |
| 1100+772| 0.313  | 1309+355| 0.184  | 1440+356| 0.077  | 2308+098| 0.432  |
| 1114+445| 0.144  | 1322+659| 0.168  |
Figure 1. The 1900 Å feature of six BQS QSOs with strong Si III] λ1892. The ordinate is flux density (erg s\(^{-1}\) cm\(^{-2}\) Å\(^{-1}\)), the abscissa is rest wavelength (Å). Galactic absorption lines are marked.
The FOS data were pipeline processed at STScI, and flux and wavelength calibrated. The line profiles were fitted using SPECFIT (Kriss 1994) in IRAF. The 1900 Å feature is supposed to be a blend of C III λ1909, Si III λ1892, and Fe III UV34 triplets λ1895, 1914, and 1926 (see, for example, Baldwin et al. 1996; Laor et al. 1997b). The 1900 Å feature may consist of five emission-lines, and Al III λλ1895, 1863 are also near the 1900 Å feature. Limited S/N and overlapping Galactic interstellar absorption lines prevented automatic fitting of the spectra. We therefore adopted a manual approach. The acceptable fits were determined by eye rather than from $\chi^2$.

PG 0026+129 was fitted by the Fe III triplets and a gaussian, and cannot be fitted by including corresponding components to Si III λ1892 nor C III λ1909. PG 1259+593 is also excluded due to serious overlapping of a Galactic interstellar medium absorption line. Thus these objects are excluded from following results and discussions.

In addition to our measurements, other observed properties have been gathered from the literature. Our interests especially focus on the Fe II emission strength and the quantities which correlate with Fe II emission in the previous studies (BG92; WBB96). $R_{\text{Fe II}}$ is the ratio of the equivalent width of the Fe II complex between λ4434 and λ4684 Å to that of Hβ. Peak λ5007 is the ratio of the peak height of the [O III] λ5007 to that of Hβ. This quantity is difficult to understand, however, because it is strongly anticorrelated with the Fe II complex strength (BG92). Hβ FWHM is the full width at half maximum intensity of the Hβ emission line, in km sec$^{-1}$. $M_{[\text{OIII}]}$ is an [O III] λ5007 absolute magnitude defined as $M_V - 2.5 \log (\text{EW [O III] \lambda5007})$. $\Gamma_X$ is the photon index of the soft X-ray spectra observed with the ROSAT PSPC. They have been gathered from WBB96. WBB96 showed that this quantity correlates well with Fe II/Hβ.

3. CORRELATIONS AMONG PROPERTIES

Correlation coefficients ($r$) have been calculated among properties taken from the literature and the UV line ratios which we measured: Si III λ1892 / C III λ1909 (Si III/C III), Al III λ1859 / C III λ1909 (Al III/C III), and Fe III UV34 / C III λ1909 (Fe III/C III). We present the correlation matrix in Table 2. Each correlation coefficient is calculated using only the objects for which both values are given; all 40 objects are used except that correlations involving the photon index ($\Gamma_X$) used only the 34 objects for which that quantity was measured.

There are many strong correlations in Table 2. Five absolute values of correlation coefficients are larger than 0.7, and nine absolute values are between 0.6 and 0.7. The measurement of Fe II strength ($R_{\text{Fe II}}$) anticorrelates with [O III] strength (Peak λ5007 and $M_{[\text{OIII}]}$) and Hβ FWHM in our sample, as BG92 had already found. The correlation coefficients among them in our sample are

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The significant correlations between $\Gamma_X$ and $R$ Fe II and between $\Gamma_X$ and Hβ FWHM which exist in our sample previously have been reported in WBB96. $\Gamma_X$ correlates with $M_{[OIII]}$. Laor et al. (1997a) previously found a similar correlation between the power-law slope of soft X-ray spectra and [O III] luminosity in their BQS sample.

The correlation coefficient between $R$ Fe II and the UV line ratios we measured, Si III]/C III], Al III/C III], and Fe III/C III], are large (Table 2). The correlation coefficient between Si III]/C III] and $R$ Fe II is the largest one except for that between Peak $\lambda$5007 and $M_{[OIII]}$, which is between essentially the same properties. It is clearly seen that there are two “zone of avoidance” which are right lower half and left upper half in Fig. 2(a). Si III]/C III] does correlate with $R$ Fe II, although recognizing the uncertainty due to the small size of our sample. The correlations between Al III/C III] and $R$ Fe II (Fig. 2(b)) and between Fe III/C III] and $R$ Fe II (Fig. 2(c)) also have similar uncertainty due to the small size of the sample with $R$ Fe II $\geq$ 0.6.

Among UV line ratios, Al III/C III] correlates with Si III]/C III] (Fig. 2(d)) and Fe III/C III] (Fig. 2(e)). The scarcity of objects with Al III/C III] $\geq$ 0.4 weakens the confidence in these correlations.

The correlation coefficient between Fe III/C III] and $\Gamma_X$ is large ($r =$ 0.61) (Table 2). The distribution of data, however, indicates there are two groups (Fig. 2(f)). The average $\Gamma_X$ of objects with Fe III/C III] $>$ 0 and ones with Fe III/C III] = 0 are $3.3 \pm 0.47$ and $2.5 \pm 0.28$, respectively. Strong Fe III emitters have steep soft X-ray spectra.

4. DISCUSSION

4.1. The Intensity ratio Si III]/C III] as a density indicator

Si III] 1892 has one order of magnitude larger critical density ($n_{cr} = 1.1 \times 10^{11}$ cm$^{-3}$) than C III] 1909 ($n_{cr} = 5 \times 10^9$ cm$^{-3}$). The ionization potentials for making and destroying Si III and C III are 16.3 and 33.5, and 24.4 and 47.9 eV,
Figure 2. a) The intensity ratio of Si III λ1892 to C III λ1909 (Si III/C III) is plotted against the ratio of equivalent width of Fe II λ4500 to that of Hβ (R Fe II). b) The intensity ratio of Al III λ1859 to C III λ1909 (Al III/C III) is plotted against R Fe II. c) The intensity ratio of Fe III UV34 to C III λ1909 (Fe III/C III) is plotted against R Fe II. d) Si III/C III is plotted against Al III/C III. e) Fe III/C III is plotted against Al III/C III. f) The photon index of soft X-ray spectra (ΓX) is plotted against Fe II/C III.
respectively. This line intensity ratio, therefore, is sensitive to the density of the gas. Using the results of BLR photoionization calculations made by Korista et al. (1997), we investigated the dependence of Si III]/C III] on the hydrogen density, n(H), and the ionization parameter, U(H). This photoionization calculation assumes that the hydrogen column density is $10^{23}$ cm$^{-2}$, the continuum spectral energy distribution peaks around 44 eV, $\alpha_{OX}$ is -1.40, and the Solar abundance (Korista et al. 1997). Si III]/C III] is mainly a function of n(H) up to n(H)$\sim 10^{11}$ cm$^{-3}$ over a wide range of U(H) ($-1.5 > \log U(H) > -3.5$). When n(H) becomes denser than $10^{11}$ cm$^{-3}$, Si III]/C III] remains constant. These behaviors are understood to be the result of the critical densities of Si III and C III].

Si III]/C III] correlates with Al III/C III] although there is an uncertainty due to the small sample size as described in Section 3. Al III 1859 is a permitted line, and the ionization potentials for making and destroying Al III are 18.8 and 28.4 eV, respectively. According to the same photoionization calculations by Korista et al. (1997), Al III/C III] increases with increasing n(H) when log $U(H) < -1$. Al III/C III] and Si III]/C III] increase with the hydrogen density up to n(H)$\sim 10^{11}$ cm$^{-3}$. The density variation of the BLR is the prime mover of the correlations between Al III/C III] and Si III]/C III]. Laor et al. (1997b) also interpreted a large Si III]/C III] of I Zw 1 as being due to denser BLR gas.

Fe III/C III] also correlates with Al III/C III] ($r = 0.67$), and correlates with Si III]/C III] ($r = 0.57$). The ionization potential for making and destroying Fe III is 16.2 and 30.7 eV, which are similar to those of Si III and Al III. Fe III UV34 is a permitted line, thus its strength correlates more significantly with that of Al III 1859 than Si III] 1892 because of less collisional deexcitation. Larger Fe III]/C III] also indicates higher density.

### 4.2. Interpretations of Eigenvector 1

Si III]/C III] correlates significantly with $R$ Fe II ($r = 0.72$). It also correlates with $M_{\text{OIII}}$ ($r = 0.55$), Peak $\lambda$5007 ($r = -0.49$), and H$\beta$ FWHM ($r = -0.47$). Si III]/C III] therefore associates with Eigenvector 1 found by BG92. Si III]/C III] also correlates with $\Gamma_X$ ($r = 0.49$). $\Gamma_X$ has previously been found to correlate strongly with H$\beta$ width (WBB96; Laor et al. 1997a), with $R$ Fe II (WBB96; Laor et al. 1997a), with [O III] luminosity (Laor et al. 1997a) and with Peak $\lambda$5007 (Laor et al. 1997a). These same correlations with $\Gamma_X$ appear in our sample (Table 2). $\Gamma_X$ associates with Eigenvector 1 as well as with Si III]/C III] and Fe II.

The correlation of Si III]/C III] with $R$ Fe II is interpreted as being due to the existence of dense gas in the BLR. The ionizing potentials of Fe II and Fe III are 7.9 eV and 16.2 eV, respectively. Fe II is emitted from the partially ionized region of hydrogen. High density gas can guarantee large optical depth which is necessary for development of a partially ionized region. Models calculated with high density have reproduced strong optical Fe II emission (Wills, Netzer, & Wills 1985).

An additional hint that $R$ Fe II depends on the density of the BLR gas comes from the significant correlation of Si IV + O IV $\lambda$1400/C IV $\lambda$1549 with $R$ Fe II (Wang, Zhou & Gao 1996). Wang, Zhou & Gao (1996) proposed high
density gas as one of the causes. Si IV $\lambda_{1397}$ becomes even stronger at densities higher than $10^{11}$ cm$^{-3}$ where C IV $\lambda_{1549}$ is thermalized (Korista et al. 1997).

Laor et al. (1997a) interpreted the correlation of soft X-ray slope with H$\beta$ emission-line width as being due to a change in $L/L_{Edd}$, the ratio of luminosity to Eddington luminosity of given mass. One ground for that interpretation is that Galactic black hole candidates (GBHC) show steeper x-ray slopes when they become brighter, that is, when the mass accretion rate becomes larger (eg., Ebisawa et al. 1994) although the physical mechanism controlling both the luminosity and the spectrum has not been understood. The other ground is that $L/L_{Edd} \propto v^{-2}L^{1/2}$ ($v$: velocity of BLR gas) assuming that the BLR is virialized and that the size of the BLR is determined by the luminosity, $R \propto L^{1/2}$. This scaling is based on the results of reverberation mapping (Kaspi et al. 1996) and on theoretical predictions of the radius of dust sublimation (Laor & Draine 1993; Netzer & Laor 1994). Larger $L/L_{Edd}$ at a given black hole mass means a larger mass accretion rate which may reflect the availability of more fuel. More fuel may relate to a gas rich environment and dense BLR gas.

An alternative interpretation is that this is an inclination effect. Puchnarewicz et al. (1992) suggested that a face-on view of an accretion disk will produce a narrow H$\beta$ width and a strong soft x-ray excess if the BLR gas clouds are localized in a plane and coplanar with an accretion disk. They favored a geometrically thick disk which would produce a strong soft x-ray excess when viewed face-on. In PG 0050+124, however, a steep x-ray spectrum is produced without a strong soft x-ray excess. It is necessary to obtain x-ray spectra of more BQS QSOs.

Why is [O III] $\lambda_{5007}$ weak for the QSOs with narrow H$\beta$, steep soft x-ray spectra, and dense BLR gas? Two possible reasons can be considered. One is the possible lack of an appropriate gas ($10^2 - 10^6$ cm$^{-3}$ and 10$^4$ K) for producing the [O III] $\lambda_{5007}$ emission-line. A gas-rich environment which leads to a dense BLR may suppress forbidden emission-lines such as [O III] due to relatively high density. Or gas may be removed as the results of infall into the BLR or outflow driven by supernovae explosions. The other reason is that the excitation might be too low for very much [O III] to be emitted. In this case relatively strong [O II] emission will be expected, but [O II] $\lambda_{3727}$ was not detected in PG 0050+124 (Laor et al. 1997b).

## 5. CONCLUSION

We have analyzed 40 FOS spectra of BQS QSOs with redshift less than 0.5. The fluxes of the Al III, Si III, C III] and Fe III emission-lines around 1900 Å were measured. We calculated correlation coefficients among the intensity ratios of these lines, the soft x-ray photon index and several optical emission-line properties (such as the ratio of Fe II to H$\beta$) taken from the literature. A significant correlation of Si III]/C III] with $R$ Fe II is found. Si III]/C III] also is associated with Eigenvector 1 found by BG92. Si III]/C III] is a density indicator and positively correlates with density up to $10^{11}$ cm$^{-3}$. These results support the suggestion that the density variation relates with $L/L_{Edd}$, that is, with the mass accretion rate, and that this is one of the causes of Eigenvector 1 found by BG92.
Many observational grounds for our interpretation depend on only one BQS QSO, PG 0050+124. Observations of other QSOs are necessary to study relationships associated with Eigenvector 1 and the cause for it. X-ray spectroscopy is needed to study the radiation mechanism producing the x-rays. In the future we can hope to discuss the x-ray continuum not only in terms of slope but also of radiation mechanisms.

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