PROBING THE ORIGINS OF THE C IV AND Fe Kα BALDWIN EFFECTS

JIAN WU1, DANIEL E. VANDEN BERK1,2, W. N. BRANDY1, DONALD P. SCHNEIDER1, ROBERT R. GIBSON1,3, AND JIANFENG WU1
1 Department of Astronomy & Astrophysics, the Pennsylvania State University, 525 Davey Lab, University Park, PA 16802, USA; jwu@astro.psu.edu
2 Department of Physics, Saint Vincent College, 300 Fraser-Purchase Road, Latrobe, PA 15650, USA
3 Department of Astronomy, University of Washington, Box 351580, Seattle, WA 98195, USA
Received 2009 April 28; accepted 2009 July 9; published 2009 August 14

ABSTRACT

We use UV/optical and X-ray observations of 272 radio-quiet Type 1 active galactic nuclei and quasars to investigate the C IV Baldwin Effect (BEff). The UV/optical spectra are drawn from the Hubble Space Telescope, International Ultraviolet Explorer and Sloan Digital Sky Survey archives. The X-ray spectra are from the Chandra and XMM-Newton archives. We apply correlation and partial-correlation analyses to the equivalent widths (EWs), continuum monochromatic luminosities, and αox, which characterizes the relative X-ray to UV brightness. The EW of the C IV λ1549 emission line is correlated with both αox and luminosity. We find that by regressing lν(2500 Å) with EW(C IV) and αox, we can obtain tighter correlations than by regressing lν(2500 Å) with only EW(C IV). Both correlation and regression analyses imply that lν(2500 Å) is not the only factor controlling the changes of EW(C IV); αox (or, equivalently, the soft X-ray emission) plays a fundamental role in the formation and variation of C IV. Variability contributes at least 60% of the scatter of the EW(C IV)–lν(2500 Å) relation and at least 75% of the scatter of the of the EW(C IV)–αox relation. In our sample, narrow Fe Kα 6.4 keV emission lines are detected in 50 objects. Although narrow Fe Kα exhibits a BEff similar to that of C IV, its EW has almost no dependence on either αox or EW(C IV). This suggests that the majority of narrow Fe Kα emission is unlikely to be produced in the broad emission-line region. We do find suggestive correlations between the emission-line luminosities of C IV and Fe Kα, which could be potentially used to estimate the detectability of the Fe Kα line of quasars from rest-frame UV spectroscopic observations.

Key words: quasars: emission lines

Online-only material: color figure, machine-readable tables

1. INTRODUCTION

One of the important properties of active galactic nuclei (AGNs) is the relation between the emission-line strength, characterized by the equivalent width (EW), and continuum luminosity, because it reveals that the regions emitting these two spectral components are associated. Baldwin (1977a) found that the EW of C IV λ1549 (C IV) is inversely correlated with the quasar monochromatic luminosity at 1450 Å, lν(1450 Å), namely, log EW(C IV) = k log lν(1450 Å) + b, Carswell & Smith (1978) referred to this trend as the “Baldwin Effect” (BEff), a designation now widely used to describe line strength–luminosity relations. Baldwin (1977a) identified this relation using only 20 quasi-stellar objects with 29.8 ≤ log lν(1450 Å) ≤ 32.0 and 1.24 < z < 3.53. Subsequent UV/optical surveys have enabled investigation of this relation with wider luminosity and redshift ranges (e.g., Kinney et al. 1990; Zamorani et al. 1992). It has been found that the BEff exists for not only C IV but many other broad emission lines such as Lyα, [C iii] λ1908, Si iv λ1396, Mg ii λ2798 (Dietrich et al. 2002; D. E. Vanden Berk et al. 2009, in preparation), UV iron emission lines (Green et al. 2001), and even forbidden lines such as [O ii] λ3727 and [Ne v] λ3426 (Croom et al. 2002). Applying a spectral-composite technique (Vanden Berk et al. 2001) to the Sloan Digital Sky Survey (SDSS; York et al. 2000) Data Release Three (DR3) quasar catalog (Schneider et al. 2005), D. E. Vanden Berk et al. (2009, in preparation) found that the BEff evolves with redshift, which is a source of scatter in this relation for a sample with a wide range of redshift.

The X-ray BEff (or Fe Kα BEff), in which the EW of the narrow Fe Kα line at 6.4 keV (hereafter abbreviated to Fe Kα) is anti-correlated with X-ray luminosity, lν(2 keV), was discovered in the early 1990s from observations by the X-ray observatory Ginga (Iwasawa & Taniguchi 1993). This relation has been subsequently confirmed using data from ASCA (Tanaka et al. 1994; Nandra et al. 1997) and from Chandra and XMM-Newton (Page et al. 2004; Zhou & Wang 2005; Jiang et al. 2006; Bianchi et al. 2007). Possible sites of origin for narrow Fe Kα emission include the broad emission-line region (BELR), the outskirts of the accretion disk, and the molecular torus (e.g., Weaver et al. 1992; Antonucci 1993; Krolik et al. 1994).

Although it is well accepted that the BEff exists for many UV/optical emission lines (e.g., Osmer & Shields 1999; Shields 2007), there is currently no theoretical model that provides a compelling and complete explanation of this well known phenomenon. Several physical explanations have been proposed to account for the UV/optical BEff.

One promising explanation is that the continuum shape may be luminosity dependent. In this model, the UV/optical BEff is due to the softening of the spectral energy distribution (SED) at high luminosity, which lowers the ion populations having high ionization potentials (Netzer et al. 1992; Korista et al. 1998). It has been found, using Einstein Observatory data, that the quasar SED, parameterized by αox1/3 (Tananbaum et al. 1979), depends on UV luminosity (e.g., Zamorani et al. 1981). Later research using radio-quiet (RQ) optically selected quasar samples from the SDSS Early Data Release (Stoughton et al. 4 Defined as αox = log[lν(2 keV)/lν(2500 Å)]/log[ν(2 keV)/ν(2500 Å)] = 0.3838 log [lν(2 keV)/lν(2500 Å)], αox is used to characterize the spectral hardness in the UV to X-ray band (e.g., Avni & Tananbaum 1982, 1986; Anderson & Margon 1987; Wilkes et al. 1994; Vignali et al. 2003; Strateva et al. 2005; Steffen et al. 2006; Just et al. 2007).
confirmed and extended this result (e.g., Vignali et al. 2003). Using optically selected AGNs, Strateva et al. (2005) and Steffen et al. (2006) firmly established the correlation of $\alpha_{\text{ox}}$ with UV luminosity for these sources. The idea that the UV/optical BEff is attributable to SED-driven ionization effects is supported both observationally (Zheng & Malkan 1993; Green 1996, 1998) and theoretically (Netzer et al. 1992). Recent work on a sample of non-broad absorption line (BAL), RQ, optically selected quasars indicates that the EW of C iv depends both on UV and X-ray luminosity. The physics of the C iv BEff is apparently associated with both UV and X-ray emission (e.g., Gibson et al. 2008, hereafter GBS08, and references therein).

Other proposed BEff drivers include the Eddington ratio, $L/L_{\text{Edd}}$ (Baskin & Laor 2004; Bachev et al. 2004; Warner et al. 2004; Zhou & Wang 2005), the black hole mass (Netzer et al. 1992; Wandel et al. 1999; Shields 2007), and the luminosity dependence of metallicity (Warner et al. 2004).

In this paper, we investigate the origin of the BEff for the C iv emission line in a sample of 272 Type 1 AGNs and quasars. Although C iv is not the only UV/optical broad emission line that exhibits a BEff, we selected it to study this phenomenon not only because it is a representative and well accepted BEff emission line, but also because C iv resides in a relatively clean spectral region where the local continuum can be well approximated as a single power law, with few blends with other emission lines (in particular the iron emission forest) and limited contamination from the AGN host galaxy. These properties make it relatively straightforward to perform spectral fitting and obtain accurate emission-line parameters for C iv. We also use partial-correlation analysis (PCA) and linear-regression analysis to investigate the correlations between EW, monochromatic luminosity, and $\alpha_{\text{ox}}$ for C iv and narrow Fe Kα emission lines.

Over the past three decades, there have been a large number of studies of the BEff. Our work on the C iv/Fe Kα lines combines the following important features (1) a wide range in redshift (0.009 $\lesssim z \lesssim$ 4.720) and luminosity (27.81 $\lesssim$ log $l_\lambda(2500 \text{ Å})$ $\lesssim$ 33.04) that allows one to disentangle evolutionary versus luminosity, so that we are not narrowing our study for quasars with a particular luminosity or at a certain redshift; (2) a relatively large sample size (272 objects); (3) the use of PCA; (4) a high X-ray detection rate ($\sim$94%); and (5) estimates of the effects of observational errors and object variability.

We describe the sample selection in Section 2 and the methods used to process the data in Section 3. In Section 4, we perform PCA and linear-regression analysis to investigate the roles of $\alpha_{\text{ox}}$ in the C iv and Fe Kα BEffs. In Section 5, we probe the connections between C iv and Fe Kα relationships in EWs, fluxes, and luminosities. We present our conclusions in Section 6. Throughout this work, we adopt the following cosmology: $\Omega_M = 0.3$, $\Omega_{\Lambda} = 0.7$, $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$.

## 2. SAMPLE CONSTRUCTION

The quasar sample in our study is drawn from three sources: 50 objects from Jiang et al. (2006), which will be referred to as “Sample A”; 98 objects from GBS08, which will be referred to as “Sample B”; and 124 objects from Just et al. (2007), which is referred to as “Sample C.” We define our “combined sample” as the combination of these three data sets.

### 2.1. Sample A

Jiang et al. (2006) compiled a data set of 101 Type 1 AGNs with Fe Kα observations from both the Chandra and XMM-Newton archives. The detection fraction of the Fe Kα line in their combined sample is around 55%. The redshifts of the AGNs range from 0.003 to 3.366, but most of the objects (87%) are low-redshift ($z \lesssim 0.4$) AGNs. The monochromatic luminosities, $l_\lambda(2500 \text{ Å})$, range from $10^{25.6}$ to $10^{31.5}$ erg s$^{-1}$ Hz$^{-1}$. We chose this data set because it is the most complete Fe Kα BEff sample with high-quality data obtained from the most sensitive X-ray missions. However, because the number of AGNs observed in the X-ray band is much smaller than the number observed optically and not all X-ray observed AGNs present Fe Kα emission lines, the Fe Kα sample is significantly limited in size.

We searched for UV/optical spectra of all 101 objects from the archival databases for Hubble Space Telescope (HST) and International Ultraviolet Explorer (IUE). We found 82 spectra covering the wavelength region around the C iv emission line (containing at least the 1500–1600 Å band). If observations are available from both HST and IUE, we selected the HST observations due to their generally higher signal-to-noise ratio (S/N). For spectra with multiple observations using the same instrument, we preferentially use spectra with higher S/N.

Next, we excluded all the radio-loud (RL) objects from the core sample, because additional X-ray emission is produced by the radio jet (e.g., Brinkmann et al. 2000) and changes the value of $\alpha_{\text{ox}}$ as well as the slope of the Fe Kα BEff.

We further excluded three objects for the following reasons.

1. **MCG-06-30-15.** The Fe Kα profile of MCG-06-30-15 is well fitted using a broad disk line model (e.g., Tanaka et al. 1995). The narrow component is not well resolved or very weak. In this work, we only study the narrow component of Fe Kα, so this object is excluded.

2. **IC 4329a.** The spectrum has low S/N, and the C iv emission line is cannot be accurately measured (e.g., Crenshaw & Kraemer 2001).

3. **PG 1407 + 265.** This object was termed as an “unusual” quasar (McDowell et al. 1995) because it contains extremely weak Lyα and C iv lines. Because of its peculiarity, we exclude it from our sample.

We removed five objects with strong associated absorption lines (AAVs) of C iv λ1549: PG 1411 + 442 (Wise et al. 2004), NGC 4151 (Crenshaw et al. 1999), Ark 564 (Crenshaw et al. 1999), NGC 4051 (Collinge et al. 2001), and PG 1114 + 445 (Shang et al. 2007). These features prohibit reconstruction of the unabsorbed C iv λ1549 emission-line profile. The X-ray absorption associated with the UV line absorption (Brandt et al. 2000) might also lead to an underprediction of continuum flux at 2 keV and, therefore, an incorrect estimation of the intrinsic value of $\alpha_{\text{ox}}$.

Finally, we exclude eight objects that are classified as Seyfert 1.5 (Sy 1.5) and Sy 1.9$^5$ (Osterbrock 1981, 1989). These objects are intermediate between Sy 1 and Sy 2 galaxies and are often subjected to obscuration along the line of sight. Thus their UV, X-ray luminosities, and $\alpha_{\text{ox}}$ values are also potentially affected.

The final version of Sample A consists of 50 AGNs. Among these objects, 34 are found in the HST archive (FOS$^6$ or STIS$^7$), and 16 are found in the IUE archive (SWP$^8$ or LWP$^9$). The

---

5 Based on NASA/IPAC Extragalactic Database: http://nedwww.ipac.caltech.edu/

6 Faint Object Spectrograph.

7 Space Telescope Imaging Spectrograph.

8 Short Wavelength Prime.

9 Long Wavelength Prime.
Fe Kα detection rate is 55%, the same as in the entire Jiang et al. (2006) study.

2.2. Sample B

Objects in Sample B were selected from 536 SDSS DR5 (Adelman-McCarthy et al. 2007) quasars in GBS08. These quasars, taken from the DR5 Quasar Catalog (Schneider et al. 2007), are at redshift 1.7 ≤ z ≤ 2.7 and have been observed by Chandra or XMM-Newton. The lower redshift limit ensures that all SDSS spectra in this sample cover the C iv region; the upper redshift limit ensures that the rest-frame flux at 2500 Å is covered so that αox can be measured accurately.

We excluded the BAL quasars in Table 1 of GBS08. BAL quasars can have strong absorption features in the C iv spectral region that prohibit accurate fitting of the continuum and emission-line profiles. In addition, BALs are usually associated with relatively strong X-ray absorption (e.g., Brandt et al. 2000; Gallagher et al. 2006). We only retain objects with Chandra observations with angular offsets <10' to avoid large X-ray flux uncertainties caused by variations of the point-spread function. This restriction reduces our sample size to 149. In addition, we excluded RL objects and strong AAL objects. The final version of Sample B consists of 98 objects with lν(2500 Å) between 10^{30.53} and 10^{13.67} erg s^{-1} Hz^{-1}. This is a relatively narrow luminosity range; however, it does provide a significant extension of Sample A since the latter is mostly composed of low-luminosity and low-redshift AGNs.

2.3. Sample C

To examine the relations between αox, lν(2500 Å), and lν(2 keV), Just et al. (2007) compiled a sample of 372 objects, including 26 from their core sample, 332 from Steffen et al. (2006), and 14 from Shemmer et al. (2006). BAL quasars, RL quasars, and gravitationally lensed objects have already been excluded from this sample. The gravitationally lensed quasars are removed because their fluxes are strongly amplified and thus their luminosities are uncertain.

Among the 372 objects, 38 are already in Sample A. For the rest of the AGNs, we searched for existing spectra with C iv coverage preferentially from SDSS, then the HST and IUE archives. Finally, we removed five AGNs whose spectra contain strong AALs. These restrictions leave 124 objects in Sample C, in which 91 objects are from the SDSS DR5 quasar catalog, 13 from the HST archive, and 20 from the IUE archive. The redshift of this sample ranges from 0.015 to 4.720 and lν(2500 Å) ranges from 10^{26.53} to 10^{33.04} erg s^{-1} Hz^{-1}.

2.4. Combined Sample

The combined sample (Table 1) consists of a total of 272 objects: 189 (69.5%) have spectra from SDSS, 47 (17.3%) from HST, and 36 (13.2%) from IUE. The redshifts range from 0.009 to 4.720 (Figure 1). The gap between z ∼ 0.5 and z ∼ 1.5 is caused by instrumentation limitations. Because of the wavelength coverage of the SDSS spectrographs, the redshifts of SDSS quasars having C iv coverage must be greater than 1.5. Most intermediate-redshift AGNs (0.5 ≤ z ≤ 1.5) are too faint for their UV/optical spectra to be taken by IUE and HST. Our sample exhibits a strong redshift–luminosity correlation (Figure 1); we discuss this issue further in our analyses below.

The lν(2500 Å) of this combined sample ranges between 10^{26.53} and 10^{33.04} erg s^{-1} Hz^{-1}, including Seyfert galaxies to the most-luminous quasars in the universe. The X-ray detection rate is 94.9%. The UV properties of the combined sample as well as the UV and X-ray properties of Sample A are tabulated in Tables 2 and 3. The combined sample will be used to investigate the C iv BEff, while only Sample A will be used to study the Fe Kα BEff.

3. DATA PROCESSING

3.1. Bad Pixel Removal and Reddening Correction

To ensure that we use high-quality data to perform the continuum and emission-line fitting, we remove bad pixels in the SDSS spectra based on the mask column contained in the SDSS quasar spectral files. We removed all the bad pixels in the spectra of SDSS objects in Sample C. The excluded pixels cover less than 10% of the total pixels for over 98% of SDSS objects, and the maximum fraction of removed pixels for a single object is 15%.

We perform Galactic reddening corrections to all the spectra using the E(B − V) dependent extinction curve of Fitzpatrick (1999). Values of E(B − V) are calculated following Schlegel et al. (1998).

3.2. Spectral Fitting

3.2.1. Sample A

For each UV/optical spectrum from HST or IUE, we fit the local continuum in the vicinity of C iv (typically 1300–1700 Å) using a single power law. We do not expect our measurements to be significantly affected by host-galaxy components because (1) our sample contains only Type I AGNs and quasars in which emission from the nucleus dominates the light from host galaxies.

### Table 1

Summary of Samples

| Sample | SDSS | HST | IUE | Total | Redshift Range | lν(2500 Å) Range |
|--------|------|-----|-----|-------|---------------|-----------------|
| A      | 0    | 34  | 16  | 50    | 0.009–1.735   | 27.81–31.69     |
| B      | 98   | 0   | 0   | 98    | 1.7–2.7       | 30.53–31.67     |
| C      | 91   | 13  | 20  | 124   | 0.015–4.720   | 28.12–33.04     |
| Combined | 189 | 47  | 36  | 272   | 0.009–4.720   | 27.81–33.04     |

10 For data processing of Sample B, refer to GBS08.
p The emission-line spectrum is obtained after subtracting the emission-line flux, we further assume that the emission line. Assuming the continuum flux $f_c = C \cdot \nu^{-1}$, we can derive
\[
\text{EW}(\text{Fe K}\alpha) = \int_0^{\infty} \frac{f_\nu(v)}{f_c(v)} \, d\nu = \frac{A}{C} \left[ \sigma^2 e^{-v_\nu/2\sigma^2} + v_0 \left( \sqrt{2\pi}\sigma \right) - \int_{v_0}^{\infty} e^{-x^2/2\sigma^2} \, dx \right] \approx \frac{A}{C} \sqrt{2\pi} v_0 \sigma. \tag{2}
\]

The Fe K\alpha emission-line flux is
\[
F_1 = \int_0^{\infty} f_\nu(v) \, d\nu = A \left( \sqrt{2\pi}\sigma - \int_{v_0}^{\infty} e^{-x^2/2\sigma^2} \, dx \right) \approx A \sqrt{2\pi}\sigma. \tag{3}
\]

The approximations are valid because generally $v_0 \gg \sigma$ so $v_\nu/2\sigma^2 \gg 1$. For instance, $v_0(\text{Fe K}\alpha) = 6.4$ keV while the width, $\sigma(\text{Fe K}\alpha)$, is usually $<0.1$ keV; as a result, $e^{-v_\nu/2\sigma^2} \approx 0$. We can therefore calculate the Fe K\alpha line flux by
\[
F_1 = \frac{\text{EW}(\text{Fe K}\alpha)}{\epsilon_0} \frac{F(2-10 \text{ keV})}{\ln 5}. \tag{4}
\]

The Fe K\alpha EWs, emission-line luminosities, and 2 keV monochromatic luminosities of Sample A are tabulated in Table 3.
3.2.2. Sample B

For objects in Sample B, we directly adopt the fitting results from GBS08. In their paper, the SDSS spectral continua were fit with polynomials, and the C\textsc{iv} emission lines were fit with Voigt profiles. The different model in GBS08 from our work used to fit the C\textsc{iv} spectral region will not cause significant differences; because the continuum around C\textsc{iv} is not contaminated with other emission/absorption lines, the polynomial fit will produce almost the same result as the simple power-law fit. In addition, since both multiple Gaussian and Voigt profiles produce acceptable fits to the emission line, they will give nearly the same line flux. The X-ray spectral continua were fit using a broken power law with the power-law break fixed at 2 keV in the rest frame in order to obtain $L_{\nu}(2 \text{ keV})$.

3.2.3. Sample C

We fit the UV/optical spectra from the SDSS using a routine, described by D. E. Vanden Berk et al. (2009, in preparation), developed for SDSS quasar spectra. This routine fits the “underlying continuum” using three components simultaneously: a power law, the iron emission forest, and the small blue bump. We adopt the UV iron emission template (1075–3090 Å) from Vestergaard & Wilkes (2001) and the optical template (3535–7534 Å) from Véron-Cetty et al. (2004). We first make a preliminary estimate of the power-law component by connecting two “line-free” points in the spectra. This provides initial estimates of the power-law parameters for the subsequent comprehensive processing in which the spectra are fit by considering all three components mentioned above. We evaluate the fitting quality by calculating $\chi^2$ values within some “line-free” windows. Finally, the continuum fit is subtracted from the original spectrum and the residuals are used to conduct emission-line fitting. For Sample C, the C\textsc{iv} emission lines are fit by superpositions of two Gaussian profiles, which always yields acceptable fits for the data. We then calculate the C\textsc{iv} EW, emission-line luminosity, and monochromatic luminosity at 2500 Å (Table 2). We adopt the values of $\alpha_{\text{ox}}$ and 2 keV monochromatic luminosity from Just et al. (2007).

Examples of continuum and emission-line fits of the HST, IUE, and SDSS spectra are presented in Figure 2.

3.3. Error Analysis

In order to estimate the uncertainties in the measured quantities for objects in Samples A and C, we ran Monte Carlo simulations assuming a model with a perfect correlation between $\text{EW}(\text{C\textsc{iv}})$, $f(\text{C\textsc{iv}})$, and $f_{\nu}(2500 \text{ Å})$. For each spectrum, we add random noise to the original best fit to produce artificial spectra. The random noise follows a Gaussian distribution, and its amplitude is determined in one of two ways. For a spectrum from the HST or IUE database, we apply a low bandpass filter, filtering out low-frequency signals via fast Fourier transformation.\textsuperscript{11} The residual signal is mostly noise. We then calculate the root mean square (rms) of the noise and take this value as the random noise amplitude to be added onto the model spectrum. For a spectrum from the SDSS database, we simply use the uncertainty level associated with each pixel as the noise amplitude. For each spectrum, we produce 100 artificial spectra and fit them in exactly the same way as the observed spectrum. The error bar of a spectral parameter is then calculated as the rms of 100 fitting results. The typical error bar shown in each plot (e.g., Figure 3) is the median of all the error bars of points in that plot.

Figure 2. Continuum and C\textsc{iv} emission-line fits examples. In each panel, the upper spectrum is the original and the lower spectrum is continuum subtracted; blue solid curves are the fits to the spectra. The cyan dotted curves are emission-line components. For PG 0947 + 396 and 3C 120, these components include the power-law continua and two Gaussian profiles for C\textsc{iv}. For SDSS J100129.64 + 545438.0, we also plot the iron emission forest and small Balmer bump components, although they are so weak that they are almost invisible. The rest-frame spectral resolutions of these spectra are, from top to bottom, $\sim 1.6 \text{ Å}$, $\sim 5 \text{ Å}$, $\sim 0.8 \text{ Å}$.

(\textsuperscript{11} http://www.msi.umn.edu/software/idl/tutorial/idl-signal.html)
shift and their uncertainties from the NASA Monte Carlo method. We adopt the most accurate values of redshift into the gross uncertainty calculation for all the objects to be added to the redshift values. The luminosity uncertainties after considering distance errors ($\delta f_d$) for objects in low-redshift objects. To validate this, we calculate the ratio of luminosity uncertainties without considering distance errors ($\delta f$; the error in the flux measurement) to luminosity uncertainties after considering distance errors ($\delta f_d$) for objects in Sample A, and denote it as $\delta f/\delta f_d$, in which $f$ stands for flux and $d$ stands for distance. Assuming that the square of total uncertainty can be expressed as the quadratic summation of the uncertainties of flux and distance individually, the square of the ratio, $(\delta f/\delta f_d)^2$, is more relevant than the ratio itself. We find that there are five out of 50 objects (in Sample A) whose ratios are above 0.1; three of them are even greater than 0.5. These objects have very low redshifts but large redshift uncertainties ($\delta z > 0.001$). For consistency, it is necessary to include the distance into the gross uncertainty calculation for all the objects in our samples. These uncertainties are also estimated using a Monte Carlo method. We adopt the most accurate values of redshift and their uncertainties from the NASA/IPAC Extragalactic Database. These uncertainties are treated as noise amplitudes to be added to the redshift values. The luminosity uncertainties are calculated using the following error-propagation equation:

$$\delta L = 4\pi d_L \sqrt{(d_L \delta f)^2 + 4 f^2 (\delta d_L)^2}.$$ 

We adopt a 20% uncertainty for each X-ray continuum luminosity, e.g., $L_x(2\text{ keV})$; their measurement errors are not available in the literature. The relative uncertainty varies considerably depending on the number of X-ray counts. For Sample A, when the Fe Kα emission lines are detected, the total number of counts is at least $\sim 500$. The Fe Kα emission-line luminosity and flux errors are calculated using the maximum error estimates. For instance, the upper bound of $L(\text{Fe Kα})$ is calculated using the upper bounds of both EW(Fe Kα) and $L(2\text{–}10\text{ keV})$; the upper bound of $f(\text{Fe Kα})$ is calculated using the upper bound of $L(\text{Fe Kα})$ and the lower bound of luminosity distance $d_L \sim \delta d_L$. This uncertainty ignores any systematic uncertainty produced by errors in the cosmological model.

For Sample B, because the parameter uncertainties are not given in GBS08, we simply apply a 20% uncertainty for all luminosity values as a first-order approximation.

4. DRIVERS OF THE C iv BALDWIN EFFECT

4.1. Comparison with Previous Work

We will first examine some important relations to determine if our measurements are consistent with previous work. It has been argued that $\alpha_{\alpha}$ has no detectable redshift dependence (e.g., Strateva et al. 2005; Steffen et al. 2006; but see Kelly et al. 2007), so in this paper we neglect any redshift evolution of $\alpha_{\alpha}$.

Figure 3 displays the plot of EW(C iv) against $l_x(2500\ \AA)$ for the combined sample, distinguished by luminosity. We use the monochromatic luminosity at 2500 Å rather than the traditional BEff wavelength (1450 Å) because our choice is more convenient to compare the BEff with the correlation between C iv and $\alpha_{\alpha}$. The luminosities at these two wavelengths are well correlated. The quantity $f_{1400}/f_{3500}$ is Gaussian distributed with a dispersion of $\delta = 0.15$ (Figure 3 in Gibson et al. 2009), so using $l_x(2500\ \AA)$ instead of $l_x(1450\ \AA)$ should only add a small dispersion to the data points but will not significantly affect the slope of the BEff. We fit the data points linearly in logarithmic space using the Expectation-Maximization (EM) method (Dempster et al. 1977; Table 4). It is clear that EW(C iv) decreases with $l_x(2500\ \AA)$ (Figure 3).

It has been reported that the slope of the BEff becomes steeper for high-luminosity quasars. For example, Dietrich et al. (2002) obtained a C iv BEff slope ($-0.14 \pm 0.02$), which was shallower than the value reported in previous studies ($-0.22 \pm 0.05$; Green 1996; also see Osmer et al. 1994; Laor et al. 1995). Using only the EW(C iv) measurements for their high-luminosity subsample with $\lambda L_\lambda(1450\ \AA) \gtrsim 10^{44}\ \text{erg s}^{-1}$, Dietrich et al. (2002) obtained a steeper slope of the BEff of $-0.20 \pm 0.03$ for C iv. To investigate the slope change with luminosity, we fit our data points with $l_x(2500\ \AA) < 30.5$. We find that the slope of the low-luminosity sample is consistent with the slope of the entire sample within $1\sigma$ (Table 4). Therefore, although our data set exhibits a suggestive trend which disagrees with Dietrich
et al. (2002), we do not find significant changes of slope over luminosity.

The large scatter in the BEff could have several causes, including observational error, intrinsic variation of the BEff (Osmer & Shields 1999; Shields 2007, and references therein), luminosity dependence of the BEff slope, and the redshift dependence of the BEff. D. E. Vanden Berk et al. (2009, in preparation) found that the slope of the BEff does not change across redshift, but its scaling factor (or equivalently, the EW of a broad emission line at a fixed monochromatic luminosity) exhibits a significant change our BEff slope is an overall average across the redshift and luminosity range we covered; remember that there is a strong redshift–luminosity correlation in our sample.

We examined the \( l_\alpha \) (2500 Å)–\( l_\alpha \) (2 keV) and \( l_\alpha \) (2500 Å)–\( \alpha_{ox} \) relations for both Sample A and the combined sample using survival analysis (ASURV; Lavalley et al. 1992) if censored data are involved, and find that all the results are consistent with previous work. When we calculate the slope of the Fe Kα BEff, we apply the Buckley–James fitting produces a slope of \( 0.046 \pm 0.001 \) in Jiang et al. (2006).

4.2. The Effects of \( \alpha_{ox} \) on the \( \text{C} \text{iv} \) and Fe Kα BEffs

Figure 4 shows the plot of EW(\( \text{C} \text{iv} \)) against \( \alpha_{ox} \) for the combined sample; the regression result from the EM algorithm for the linear relation is

\[
\log \text{EW(}\text{C} \text{iv}) = (1.035 \pm 0.075) \alpha_{ox} + (3.301 \pm 0.119)
\]

and the Spearman correlation coefficient is 0.607 (\( P_0 < 0.001 \)).13 Because \( \alpha_{ox} \) is an indicator of the hardness of the SED which controls the ionization level of \( \text{C} \text{iv} \) surrounding the central engine, Figure 4 demonstrates that as the ionizing flux becomes harder (\( \alpha_{ox} \) increases), the \( \text{C} \text{iv} \) emission has a strong positive response to \( \alpha_{ox} \).

13 \( P_0 \) is the confidence level of the null hypothesis. Therefore, the smaller \( P_0 \) is the more likely the correlation exists.

Both \( \alpha_{ox} \) and \( l_\alpha \) (2500 Å) are correlated with EW(\( \text{C} \text{iv} \)); which is a more fundamental driver? To investigate this issue, we applied PCA to EW(\( \text{C} \text{iv} \)), \( l_\alpha \) (2500 Å), and \( \alpha_{ox} \) using the combined sample, Sample A, and a reduced sample. Table 5 presents Pearson, Spearman, and Kendall’s correlation and partial-correlation coefficients (if available), along with significance levels for these three samples. We present the statistical results of Sample A for comparing the correlation results of \( \text{C} \text{iv} \) and Fe Kα. Because the combined sample contains censored data for the \( \alpha_{ox} \) values, we must use survival analysis to calculate the correlation coefficients. However, algorithms are not available for calculating all the correlation and partial-correlation coefficients for censored data. For example, the empty entries in Table 5 are due to the unavailability of corresponding algorithms. In order to compare the changes of correlation strength when the third parameter is controlled, we construct a reduced sample with the censored data removed, considering that this only excludes a small fraction (~6%) of the entire data set and should not affect the statistical properties of the sample. We can see that the \( \text{C} \text{iv} \) BEff is significantly weakened when \( \alpha_{ox} \) is held fixed; the correlation coefficient drops from \( -0.580 \) to \( -0.224 \) (Spearman). On the other hand, the correlation coefficient between EW(\( \text{C} \text{iv} \)) and \( \alpha_{ox} \) also drops significantly when \( l_\alpha \) (2500 Å) is held fixed, from 0.615 to 0.332. This implies that both \( \alpha_{ox} \) and \( l_\alpha \) (2500 Å) are driving the change of EW(\( \text{C} \text{iv} \)).

The Fe Kα BEff plot (not shown) of our sample (Sample A) is very similar to the correlation shown of Figure 4 in Jiang et al. (2006) except that our sample size is smaller. Figure 5 shows EW(Fe Kα) plotted against \( \alpha_{ox} \). The Spearman test gives a much weaker correlation coefficient (~0.230 with \( P_0 = 0.111 \)) than that for \( \text{C} \text{iv} \) (~0.304 with \( P_0 < 0.001 \)). In addition, simple \( \chi^2 \) fitting produces a slope of 0.046 ± 0.154, consistent with zero. The consistency between the correlation analysis and regression result provides strong evidence that EW(Fe Kα) is not correlated with \( \alpha_{ox} \).

4.3. Effects of AGN Variability on BEff Relation Scatter

Because of the ubiquity of AGN variability, combined with the different times of the optical and X-ray observations, our values of \( \alpha_{ox} \) do not reflect the spectral hardness at a specific time but are randomly distributed around their mean values. The deviation of \( \alpha_{ox} \) from its mean value would be ~0.083, assuming
that the variation amplitudes are 30\% for \( l_{\nu}(2500 \text{ Å}) \) and 40\% for \( l_{\nu}(2 \text{ keV}) \) (e.g., Strateva et al. 2005; GBS08).

To check how much of the scatter of our correlations could be attributed to variability, we performed two simple tests on our combined sample. We follow the method used in Section 3.1 of GBS08 and introduce \( \Delta \log \text{EW} \), which is the difference between the observed \( \text{EW}(\text{C}\text{iv}) \) and the \( \text{EW} \) calculated from linear regression (Equation (7)), i.e., \( \Delta \log \text{EW} = \log \text{EW} - \log \text{EW}(\text{C}\text{iv}) \). We define \( \mu \) and \( \sigma \) as the mean and dispersion of the distribution of \( \Delta \log \text{EW} \). To calculate \( \mu \) and \( \sigma \), we maximize the likelihood function (Maccarone et al. 1988):

\[
L = \prod_{i} \frac{1}{\sqrt{2\pi (\sigma_i^2 + \sigma^2)}} \exp \left\{ -\frac{\left( \log \text{EW}_i - \mu \right)^2}{2(\sigma_i^2 + \sigma^2)} \right\}
\]

in which the subscript \( i \) represents each object and \( \sigma_i \) is the uncertainty of \( \Delta \log \text{EW} \) associated with \( \log \text{EW}_i \). The maximization of \( L \) requires \( \mu = 0.01 \) and \( \sigma = 0.23 \).

Next, we estimate the potential scatter of \( \Delta \log \text{EW} \) due to variability. We need to consider two terms: \( \log \text{EW} \) and \( \log \text{EW}(\text{C}\text{iv}) \). To first approximation, \( \text{EW} \sim f_{\text{line}}/f_{\text{cont}} \) in which \( f_{\text{line}} \) is the emission-line flux and \( f_{\text{cont}} \) is the continuum flux. The emission-line variability of six luminous quasars at \( z = 2.2–3.2 \) was recently reported by Kaspi et al. (2007). The mean fractional variation \( F_{\text{var}} \) is \( \approx 0.096 \) by averaging the fractional variation of \( \text{C}\text{iv} \) \( \approx 0.549 \) of all six quasars. The \( \text{C}\text{iv} \) emission-line variability of a number of Seyfert galaxies has been studied, including Fairall 9 (Rodriguez-Pascual et al. 1997), NGC 5548 (Clavel et al. 1991), NGC 7469 (Wanders et al. 1997), NGC 3783 (Reichert et al. 1994), and 3C 390.3 (O’Brien et al. 1998). By averaging the fractional variations of Seyferts and quasars above, we obtain an average emission-line variation \( (F_{\text{var}}) = 0.130 \). The typical variation of \( l_{\nu}(2500 \text{ Å}) \) is \( \sim 30\% \) (e.g., Strateva et al. 2005). Therefore, the scattering of \( \log \text{EW} \) contributed from variability is \( \text{estimated} \) (assuming all independent variables are Gaussian distributed) as

\[
\sigma (\Delta \log \text{EW}) = \frac{1}{\ln 10} \sqrt{\left( \frac{\delta \text{EW}_{\text{line}}}{\text{EW}_{\text{line}}} \right)^2 + \left( \frac{\delta \text{EW}_{\text{cont}}}{\text{EW}_{\text{cont}}} \right)^2 + \alpha^2 \left( \frac{\delta \text{EW}(\text{C}\text{iv})}{\text{EW}(\text{C}\text{iv})} \right)^2} \approx 0.144.
\]

In the calculation above, \( \alpha = 0.198 \) (Equation (7)). This exercise indicates that at least 60\% of the scatter around the BEff in our sample can be attributed to AGN variability.

We performed a similar test for the \( \alpha_{\text{ox}} = \text{EW}(\text{C}\text{iv}) \) relation. Because the set of \( \alpha_{\text{ox}} \) contains censored data, we can only use the reduced data set (258 objects). The maximization of \( L \) (Equation (6)) yields \( \mu = 0.01 \) and \( \sigma = 0.22 \). The potential dispersion of this relation assuming all scatter comes from variability is \( \text{estimated} \) (assuming Gaussian distributions) as

\[
\sigma (\Delta \log \text{EW}) = \frac{1}{\ln 10} \sqrt{\left( \frac{\delta \text{EW}_{\text{line}}}{\text{EW}_{\text{line}}} \right)^2 + \left( \frac{\delta \text{EW}_{\text{cont}}}{\text{EW}_{\text{cont}}} \right)^2 + (0.3838\alpha)^2 \left( \frac{\delta \text{EW}(\text{C}\text{iv})}{\text{EW}(\text{C}\text{iv})} \right)^2} \approx 0.163.
\]
To consistently compare the rms values, we compute them using the combined sample without the censored data.

In the calculation above, $a = 1.035$ (Equation (5)). This indicates that variability produces at least 75% of the scatter around the $\alpha_{ox}$–EW(C iv) relationship.

In summary, the above two tests demonstrate that a substantial fraction, if not the majority, of the scatter in the correlations above can be attributed to X-ray and UV/optical variability. It should be possible to make the correlations tighter if the UV/optical and X-ray data are observed simultaneously.

### 4.4. Regressions of EW and Luminosity

The BEff provides a potential avenue to infer the luminosity of a quasar from emission-line observations. Type Ia supernovae (SNe) are treated as classical standard candles (e.g., Phillips 1993; Burrows 2000), but only a few are observed beyond $z \sim 1.5$. If quasars, which are much easier to detect than SNe and can be observed to much a higher redshift, can be used as standard candles, they would be an important tool for cosmological studies. Soon after the discovery of the BEff, many investigations considered the possibility of treating emission-line EW as a luminosity indicator (e.g., Baldwin 1977a; Wampler 1980). Unfortunately, the C iv BEff usually has a large scatter (Osmer & Shields 1999; Shields 2007); given the small slope in the log EW–log $l_\nu$ plot (on the order of $-0.2$), the predicted luminosities are very inaccurate. It has also been shown that the C iv BEff is redshift dependent (Francis & Koratkar 1995; D. E. Vanden Berk et al. 2009, in preparation), making it a less valuable probe of cosmology.

Because we are focusing on the influence of $\alpha_{ox}$ at the moment, and will put the redshift factor aside, we will concentrate on the issue of whether the scatter can be reduced if we regress EW(C iv) with $l_\nu(2500 \, \text{Å})$ and/or $\alpha_{ox}$, and if the prediction of luminosity can be made more accurate with this approach. The linear-regression results of EW(C iv) with $\alpha_{ox}$ are already shown in Equation (5).

Similar regressions from $l_\nu(2500 \, \text{Å})$ and both of $l_\nu(2500 \, \text{Å})$ and $\alpha_{ox}$, using the fully parametric EM algorithm, are

$$\log \text{EW(C iv)} = (-0.198 \pm 0.015) \log l_\nu(2500 \, \text{Å})$$

$$+ (7.764 \pm 0.461),$$

$$\log \text{EW(C iv)} = (-0.107 \pm 0.021) \log l_\nu(2500 \, \text{Å})$$

$$+ (0.615 \pm 0.106)\alpha_{ox} + (5.944 \pm 0.536),$$

in which EW(C iv) is in Å and $l_\nu(2500 \, \text{Å})$ is in erg s$^{-1}$ Hz$^{-1}$. The last regression was performed on the combined sample without the censored data (258 objects) because the EM algorithm in ASURV does not allow both independent variables to contain censored data points.

The last regression was performed on the censored-data-excluded sample. We then calculate the rms values of the residuals after subtracting the predictions from the equations above (Table 6). The rms value shrinks by 18% using EW(C iv) and $\alpha_{ox}$, compared to using EW(C iv) alone. We use the standard F-test to check if the two sets of residuals have consistent variance. The testing gives an $F$-statistic of 1.48 with a significance 0.002, indicating that these two sets of residuals have significantly different variances and 18% is a statistically significant improvement. To use quasars as standard candles via the BEff, we should at least confine the luminosity within an uncertainty of 30%, or, equivalently, rms $< 0.1$. This cannot be achieved using our current data set and controlled parameters.

### 5. RELATION BETWEEN Fe Kα AND C iv

Fe Kα is important in AGN studies because it is the strongest emission line appearing in the X-ray band. However, the strength of this emission line varies significantly from object to object, and the line is not detected in most X-ray observations of quasars. Given this lack of direct observational measurement, it would be useful to develop a way to predict the expected strength of the line empirically.

The EW(C iv) and EW(Fe Kα) do not exhibit a significant correlation (Figure 6) in Sample A; the correlation has a low

---

**Table 6**

| Independent Variable | Dependent Variable | rms Value |
|----------------------|-------------------|-----------|
| $l_\nu(2500 \, \text{Å})$ | EW(C iv) | 0.231 |
| $\alpha_{ox}$ | EW(C iv) | 0.228 |
| $l_\nu(2500 \, \text{Å})$ | EW(C iv)+$\alpha_{ox}$ | 0.217 |
| EW(C iv) | $l_\nu(2500 \, \text{Å})$ | 0.747 |
| $\alpha_{ox}$ | $l_\nu(2500 \, \text{Å})$ | 0.645 |
| EW(C iv) | $l_\nu(2500 \, \text{Å})$ | 0.615 |

**Note.** To consistently compare the rms values, we compute them using the combined sample without the censored data.
Spearman rank-correlation coefficient ($0.319$ with $P_0 = 0.027$). Although the EWs of the two lines are not well correlated, their luminosities and fluxes are strongly correlated (Figure 7), with Spearman correlation coefficients $0.529$ ($P_0 < 0.001$) and $0.551$ ($P_0 < 0.001$), respectively (Table 7). The linear correlations regressed in Figure 7 are

$$\log L(\text{Fe K}\alpha) = (0.588 \pm 0.079) \log L(\text{C}\,\text{iv}) + (16.164 \pm 3.416),$$

(11)

$$\log f(\text{Fe K}\alpha) = (0.978 \pm 0.188) \log f(\text{C}\,\text{iv}) - (2.082 \pm 2.228).$$

(12)

One must always question the significance of relations such as Equation (11) because even if there is no correlation between the observed fluxes of the lines, the fact that the line luminosities for a given object contain the same distance factor will introduce an apparent correlation in the luminosities. To investigate whether this effect is important for our study, we perform a test in which we conduct correlation and regression analysis for a subsample of Sample A. Objects in this subsample have similar redshifts, and thus they have approximately the same distances. First, we use objects with $0.06 < z < 0.09$ because this redshift bin contains a large number of objects. This subsample contains 10 objects. The correlation coefficient of $f(\text{Fe K}\alpha) - f(\text{C}\,\text{iv})$ is $0.624$ ($P_0 = 0.061$) and of $L(\text{Fe K}\alpha) - L(\text{C}\,\text{iv})$ is $0.709$ ($P_0 = 0.033$). The regression results are

$$\log L(\text{Fe K}\alpha) = (0.748 \pm 0.200) \log L(\text{C}\,\text{iv}) + (9.330 \pm 8.702),$$

(13)

$$\log f(\text{Fe K}\alpha) = (0.771 \pm 0.241) \log f(\text{C}\,\text{iv}) - (4.280 \pm 2.819).$$

(14)

Both the correlation and regression results of this subsample are consistent with the results of the entire sample within uncertainties, suggesting that the luminosity correlation of the C\text{iv} and Fe K\alpha lines may be real and is not a consequence of multiplying the two fluxes of a given object by the same large distance factor. The luminosity of C\text{iv} emission line increases faster than the luminosity of Fe K\alpha.

One might be concerned that the correlation between $L(\text{Fe K}\alpha)$ and $L(\text{C}\,\text{iv})$ is artificial because the calculation of the Fe K\alpha measurements involves $L(2–10 \text{ keV})$ (Equation (4)), which is proportional to $l_{\text{C}}(2 \text{ keV})$ (Equation (1)), and $l_{\text{C}}(2 \text{ keV})$ is correlated with $l_{\text{C}}(2500 \text{ Å})$, which is correlated with EW(C\text{iv}), i.e., the C\text{iv} BEff. EW(C\text{iv}) is calculated from continuum and emission-line luminosity, so apparently, the $L(\text{Fe K}\alpha)$ and $L(\text{C}\,\text{iv})$ are not independent before we perform the correlation. However, our calculation of Fe K\alpha is simply reversing the $F(2–10 \text{ keV})/\text{EW calculation of Jiang et al. (2006)}, so F(Fe K\alpha) is not actually dependent of $F(2–10 \text{ keV})$ and hence $l_{\text{C}}(2500 \text{ Å})$. In essence, we have the values of $F(\text{Fe K}\alpha)$ independent of $F(\text{C}\,\text{iv})$. Therefore, our $L(\text{Fe K}\alpha)$ and $L(\text{C}\,\text{iv})$ correlation, which is expected from existing relations, is not an artifact correlation.

That the EWs of C\text{iv} and Fe K\alpha are uncorrelated is consistent with the result by Page et al. (2004) and further demonstrates that the C\text{iv} and Fe K\alpha emission lines are unlikely to have the same origin. This result is not surprising because Fe K\alpha and C\text{iv} are produced in different processes. The correlation between their luminosities is probably a combination of effects between their EWs (uncorrelated) and continuum (strongly correlated). The flux correlation, although empirical and not very tight, is a useful first-order estimation of the Fe K\alpha line flux given the UV spectra in the rest frame of an AGN.

### 6. DISCUSSIONS AND CONCLUSIONS

We have compiled a sample of 272 Type 1 AGNs and quasars that have UV and X-ray measurements, among which Fe K\alpha emission lines are detected in 50 objects. The sample covers a wide range of redshift ($0.009 < z < 4.720$), and a wide range of luminosity from Seyfert galaxies to the most-luminous quasars.

| Relations | $\rho(P)^a$ | $k^b$ |
|-----------|-------------|-------|
| EW        | $0.319(0.027)$ | $0.291 \pm 0.131$ |
| $L(\text{line})$ | $0.529(<0.001)$ | $0.588 \pm 0.079$ |
| $f(\text{line})$ | $0.551(<0.001)$ | $0.978 \pm 0.188$ |

Notes.

- $^a$ Correlations are tested using Spearman’s $\rho$ and the significance level ($P$) is evaluated against the null hypothesis.
- $^b$ We use the Buckley–James method to do linear regression and $k$ is the slope.

The computation is done using the ASURV software package (Lavalley et al. 1992).

![Figure 7. Plot of log $L(\text{Fe K}\alpha)$ vs. log $L(\text{C}\,\text{iv})$ (upper panel) and log $f(\text{Fe K}\alpha)$ vs. log $f(\text{C}\,\text{iv})$ (lower panel) for the core sample. Upper limits are denoted as downward arrows. The solid lines are the best linear fits to the data using ASURV. For comparison, we show the best linear fits with a unity slope in dotted lines. The data symbols and typical error bars are labeled at the bottom right corners.](image)

![Figure 7. Plot of log $L(\text{Fe K}\alpha)$ vs. log $L(\text{C}\,\text{iv})$ (upper panel) and log $f(\text{Fe K}\alpha)$ vs. log $f(\text{C}\,\text{iv})$ (lower panel) for the core sample. Upper limits are denoted as downward arrows. The solid lines are the best linear fits to the data using ASURV. For comparison, we show the best linear fits with a unity slope in dotted lines. The data symbols and typical error bars are labeled at the bottom right corners.](image)
(27.81 \leq \log l_\nu(2500 \, \text{Å}) \leq 33.04). These properties allow us to study the overall properties of AGNs rather than focusing on a particular redshift or luminosity. It also has a high X-ray detection rate (\sim 96\%), which lets us obtain robust statistics. We have performed correlation and regression analyses using this sample and draw the following conclusions.

1. The C IV BEff is driven by both \( \alpha_{\text{ox}} \) and \( l_\nu(2500 \, \text{Å}) \), or equivalently, by \( l_\nu(2 \, \text{keV}) \) and \( l_\nu(2500 \, \text{Å}) \). This implies that changes in the ionizing flux induce changes in the ionization state of the BELR, producing more C IV ions when the SED becomes harder and vice versa. This is supported both by correlation and regression analyses.

   a) The partial correlation between EW(C IV) and \( l_\nu(2500 \, \text{Å}) \) when \( \alpha_{\text{ox}} \) is controlled is weaker than the regular correlation between EW(C IV) and \( l_\nu(2500 \, \text{Å}) \).

   b) The scatter in the linear regression decreases when we regress EW with \( \alpha_{\text{ox}} + l_\nu(2500 \, \text{Å}) \) compared with \( l_\nu(2500 \, \text{Å}) \) alone.

   Although the reduction of the scatter due to adding another regression parameter is not sufficiently large to treat quasars as standard candles, it demonstrates that a significant fraction of the scatter attributes to \( \alpha_{\text{ox}} \), and can be reduced by including it in regression analysis.

2. EW(Fe Kα) exhibits no strong correlation with either \( \alpha_{\text{ox}} \) or EW(C IV). This implies that Fe Kα is not likely to have the same origin as C IV.

3. There may be a correlation between the luminosities of Fe Kα and C IV with a logarithmic slope of 0.588 \pm 0.07. This correlation is possibly because both of these two quantities involve a factor related to the scale of the line emitting regions and the slope indicates that the C IV emission-line luminosity increases faster than the Fe Kα.

   Although \( \alpha_{\text{ox}} \) is a fundamental influence on EW(C IV), there is still a significant scatter in the EW(C IV)–\( \alpha_{\text{ox}} \) diagram. As we have demonstrated, most of the scatter is contributed by variability, but another likely contribution source is the nature of \( \alpha_{\text{ox}} \) which only connects the flux points at 2500 Å and 2 keV but misses the big blue bump, which is expected to play an important role in the photoionization process. The shape of an AGN SED can be very different depending on Eddington ratio (\( L_{\text{bol}}/L_{\text{Edd}} \)) but still have a fairly constant \( \alpha_{\text{ox}} \) (Vasudevan & Fabian 2007). It is perhaps more appropriate to use a point near 250 Å instead of 2500 Å to calculate a revised \( \alpha_{\text{ox}} \) (Shemmer & Koratkar 1995). This new \( \alpha_{\text{ox}} \) might be more strongly correlated with EW(C IV). However, this requires challenging observations that cannot be achieved at present for most AGNs.

We thank Jane Charlton for providing a number of HST/FOS spectra of the core sample AGNs, Eric Feigelson for useful suggestions and advice on statistics, Ohad Shemmer and Dennis Just for discussions on linear regression, and Lanyu Mi for help with the statistical computations.

This work was partially supported by NSF grant AST-0607634 and NASA LTSA grant NAG5-13035.

Funding for the SDSS and SDSS-II has been provided by the Alfred P. Sloan Foundation, the Participating Institutions, the National Science Foundation, the U.S. Department of Energy, the National Aeronautics and Space Administration, the Japanese Monbukagakusho, the Max Planck Society, and the Higher Education Funding Council for England. The SDSS Web site is http://www.sdss.org/.
