On the origin of the C IV Baldwin effect in active galactic nuclei

Alexei Baskin* and Ari Laor*
Physics Department, Technion, Haifa 32000, Israel

Accepted 2004 March 12. Received 2004 March 3; in original form 2004 January 16

ABSTRACT
The origin of the luminosity dependence of the equivalent width (EW) of broad emission lines in active galactic nuclei (AGN) — the Baldwin effect — is not firmly established yet. We explore this question for the broad C IV λ1549 line using the Boroson & Green sample of the 87 \( z \leq 0.5 \) Bright Quasar Survey (BQS) quasars. Useful UV spectra of the C IV region are available for 81 of the objects, which are used to explore the dependence of the C IV EW on various emission properties. We confirm earlier results on the strong correlations of the C IV EW with some of the emission parameters which define the Boroson & Green Eigenvector 1, and with the optical to X-ray slope \( \alpha_{\text{ox}} \). In addition, we find a strong correlation of the C IV EW with the relative accretion rate, \( L/L_{\text{Edd}} \). Since \( L/L_{\text{Edd}} \) drives some of the Eigenvector 1 correlations, it may be the primary physical parameter which drives the Baldwin effect for C IV.

Key words: galaxies: active – quasars: emission lines – quasars: general – ultraviolet: galaxies.

1 INTRODUCTION
The inverse correlation of the broad emission line equivalent width (EW) with luminosity in active galactic nuclei (AGN), discovered by Baldwin (1977) for the C IV λ1549 line, was intensively explored over the past 20 years (see a comprehensive review by Osmer & Shields 1999; and more recent studies by Wilkes et al. 1999; Green, Forster & Kuraszkiewicz 2001; Croom et al. 2002; Dietrich et al. 2002; Kuraszkiewicz et al. 2002; Shang et al. 2003). The physical origin for this effect is not clearly established yet, but a plausible explanation is softening of the ionizing continuum shape, and increasing gas metallicity with increasing luminosity (Korista, Baldwin & Ferland 1998). The softening of the ionizing continuum shape with luminosity is supported by: (1) some observed correlations of the emission-line strength with the ionizing spectral shape (Green 1998; Wang, Lu & Zhou 1998), (2) predictions of simple accretion disc models for the ionizing spectral shape dependence on luminosity (Netzer, Laor & Gondhalekar 1992), and (3) the dependence of the slope of the Baldwin effect on the ionization potential of the emitting ions (Espey & Andreadis 1999; Green et al. 2001; Dietrich et al. 2002; Kuraszkiewicz et al. 2002). Non-isotropic continuum emission (Netzer 1987), and the intrinsic Baldwin effect (Pogge & Peterson 1992; also review in Osmer & Shields 1999, section 5) can produce some of the observed scatter in the Baldwin effect for the various lines.

Significant correlations also exist among various optical emission-line properties in AGN, including the [O iii] and Fe ii strength, and the H\( \beta \) FWHM, which form part of Eigenvector 1 (EV1) in the comprehensive study of Boroson & Green (1992, hereafter BG92). Boroson, Persson & Oke (1985) speculated that the underlying physical parameter which drives these correlations is the relative accretion rate, \( L/L_{\text{Edd}} \), a speculation which received strong support through recent observations (see review in Laor 2000). Furthermore, Wills et al. (1999) found that various UV emission properties, including the C IV EW, are correlated with the optical EV1 parameters, which suggests that the C IV EW may also be largely driven by \( L/L_{\text{Edd}} \). The Baldwin effect may then just be a secondary correlation induced by the tendency of more luminous AGN to have a higher \( L/L_{\text{Edd}} \). The possible role of \( L/L_{\text{Edd}} \) in the Baldwin effect was already mentioned by Brotherton & Francis (1999). Later, Wilkes et al. (1999) noted that narrow-line AGN are outliers to the Baldwin effect, but the meaning of this result was not interpreted at that time (see Section 4 here). Most recently Shang et al. (2003) suggested an indirect indication, based on spectral principle component analysis, that \( L/L_{\text{Edd}} \) may contribute to the scatter in the Baldwin effect.

Recent studies established that reasonably accurate estimates of the black hole mass (\( M_{\text{BH}} \)) can be obtained in AGN based on the continuum luminosity and H\( \beta \) FWHM \( [M_{\text{BH}} \propto L^{1/2} \text{(H}\beta \text{ FWHM)}^2] \), and thus \( L/L_{\text{Edd}} \propto L^{1/2} \text{(H}\beta \text{ FWHM)}^{-2} \), e.g. Laor 1998. This opens up the possibility to test directly whether the Baldwin effect is driven by \( L/L_{\text{Edd}} \), which is the main point of this paper. The data set and measurement procedure are described in Section 2, the correlation analysis is presented in Section 3, and the main results are summarized in Section 4.

2 THE MEASUREMENTS
For the purpose of this analysis we use the BG92 sample which includes the 87 \( z < 0.5 \) AGN from the Bright Quasars Survey (BQS; Schmidt & Green 1983). This sample extends in luminosity from...
Seyfert galaxies with $v_L = 3.3 \times 10^{43}$ erg s$^{-1}$ (calculated using the continuum fluxes in Neugebauer et al. 1987, assuming $H_0 = 80$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 1.0$), to luminous quasars at $v_L = 1.4 \times 10^{46}$ erg s$^{-1}$, where $v_L$ is calculated at 3000 Å. This is a complete and well-defined sample, selected based on (blue) colour and (point-like) morphology, independently of the emission-line strengths. It is also the most thoroughly explored sample of AGN, with a wealth of high quality data at most wave bands. The EV1 correlations were established by BG92 using this sample, and the ability to obtain reasonably accurate estimates of $M_{BH}$ (and thus $L_{Edd}$) was demonstrated for this sample (Laor 1998), thus making it an optimal sample to explore the possible origin of the Baldwin effect.

Archival UV spectra of the C IV region are available for 85 of the 87 BG92 objects. The $HST$ archives contain UV spectra of 47 of the objects, which were obtained by the Faint Object Spectrograph (FOS); the UV spectra for the remaining 38 objects with no $HST$ spectra were obtained from the IUE archives (see Table 1). An average spectrum, weighted by the S/N ratio, was calculated when more than one archival spectrum was available. This averaging should decrease the scatter in the Baldwin effect induced by variability, as demonstrated in the intrinsic Baldwin effect.

Three of the archival spectra (PG 0934+013, PG 1004+130 and PG 1448+273) did not have a sufficient S/N to measure the C IV EW, and in one object (PG 1700+518) C IV is heavily absorbed (e.g. Laor & Brandt 2002), leaving a sample of 81 objects with a measurable C IV EW. The C IV region of PG 0934+013 is also rather heavily absorbed, and its measured C IV EW is probably just a lower limit. The continuum flux uncertainty of the $HST$ spectra, which were obtained without the flux density uncertainty from the $HST$ archives, was estimated using the average standard deviation of the flux at two windows: 1450–1470 Å, and 1710–1730 Å (rest frame). The rest-frame wavelengths were calculated using redshifts determined from the peak of the [O III] $\lambda$ 5007 line (kindly provided by T. Boroson, private communication). The wavelength dependence of the flux density uncertainty (of the $HST$ spectra) was assumed to scale with the square root of the ratio of the flux density to continuum flux density. The IUE spectra were obtained with the flux density uncertainty from the IUE archives.

The spectra were corrected for Galactic reddening using the $E(B-V)$ values from Schlegel, Finkbeiner & Davis (1998, as listed in the NASA/IPAC Extragalactic Database), and the reddening law of Seaton (1979). A local power-law continuum was fitted to each spectrum between $\sim$1470 Å and $\sim$1620 Å, and the C IV line emission was fit as a sum of three Gaussians, using the procedure described in Laor et al. (1994, section 3 and the appendix there). Wavelength regions suspected to be affected by intrinsic or Galactic absorption were excluded from the fit (Laor & Brandt 2002). The purpose of the line fit is not to decompose the line to possible origins.
components, but rather to obtain a smooth realization of the line profile, which is likely to yield more accurate values for the linewidth and EW.

Table 1 presents our measured rest-frame EW of the best-fitting models to the C IV profile, together with the estimated errors. The errors were estimated by repeating the model fits with the power-law continuum displaced upward and downward by 1σ. As expected, the typical errors associated with IUE spectra are significantly higher than those of the HST spectra. One should note that larger systematic errors could be associated with the placement of the continuum windows. In particular, the presence of very broad weak wings is difficult to detect, although they may have a non-negligible EW. Table 1 also lists υL☉ calculated at 3000 Å for each object, and the estimated L/LEdd.

3 THE CORRELATION ANALYSIS

Fig. 1 (top panel) presents the Baldwin effect for the 81 BQS quasars measured above. The C IV EW are taken from Table 1, and for the luminosity we use υL☉ at 3000 Å (see Section 2). To verify that our sample is not biased in any way, we also present in Fig. 1 data from two other studies, 454 Large Bright Quasar Survey objects analysed by Forster et al. (2001), and 125 pre-COSTAR AGN observations analysed by Kuraszkiewicz et al. (2002) (which overlap some of our objects). These data are available in public electronic form. The luminosities of these objects were derived from the specified flux densities using the same cosmology assumed for the BQS quasars. The trend and scatter of the Baldwin effect for the BQS quasars appears to be very similar to those displayed by the Forster et al. (2001) and Kuraszkiewicz et al. (2002) samples. The Spearman rank-order correlation coefficient for the BQS Baldwin effect is rS = −0.154. The flattening of the Baldwin relation at low luminosity is clearly seen in Fig. 1 (see discussion in section 4.2 of Osmer & Shields 1999). The non-linearity of the Baldwin effect (on a log-log scale) suggests that the Spearman rank-order correlation coefficient, which tests for a monotonic relation, is a more suitable statistical test here, compared with the Pearson correlation coefficient, which tests the significance of a linear relation.

Table 2 presents the results of a correlation analysis of the C IV EW reported in Table 1 with all the optical emission-line parameters from BG92 (table 2 there), supplemented by αox from Brandt, Laor & Wills (2000), and L/LEdd and Mbh as estimated from the optical luminosity and the Hβ FWHM (equation 3 in Laor 1998). For the sake of brevity we present only the most significant correlations (those where Pr < 5 × 10⁻⁵). To explore the effect of the generally lower S/N IUE spectra on the strength of the correlations, we also present in Table 2 the correlations obtained based only on the 46 objects with the generally higher S/N HST spectra. The correlations for the HST sample are similar, which suggests that the C IV EW measurement uncertainty is not a major source error.

The strongest correlations of the C IV EW are with αox, and with parameters related to the strength of the [O iii] and Fe II lines, and with the Hβ FWHM, which are part of the BG92 EV1 correlations. These correlations confirm earlier results on the inverse relation of the C IV EW and the Fe II strength (Marziani et al. 1996; Wang, Zhou & Gao 1996), the C IV EW EV1 correlations found by Wills et al. (1999, table 1 there) for a smaller sample of 22 BQS quasars (part of our sample), and the earlier results on the C IV EW correlation with αox (see Section 1). The correlation with αox is consistent with the suggestions that the Baldwin effect is driven by a softening of the ionizing continuum (which decreases αox), with increasing luminosity (Korista et al. 1998). The inverse correlation of the

2 We have ignored two upper limits in the tabulation of Forster et al. (2001), and several obvious typographical flux errors, in their total list of 488 objects.
C IV EW and the Fe II strength may be due to optical depth effects. A large optical depth in the Fe II emitting region strengthens the optical Fe II emission by converting UV Fe II emission to optical Fe II emission (Netzer & Wills 1983; Shang et al. 2003). In contrast, a large optical depth in the C IV emitting region results in collisional suppression of this line (Ferland et al. 1992). Thus, the observed inverse correlation could be produced if the optical depths of the Fe II and C IV emitting regions are related.

Objects with $\alpha_{\text{ox}} < -2$, or ‘Soft X-Ray Weak’ AGN, generally show intrinsic broad C IV absorption (Brandt et al. 2000), whose strength is correlated with luminosity (Laor & Brandt 2002). Incomplete correction for this absorption may induce the observed trend of decreasing C IV EW with decreasing $\alpha_{\text{ox}}$. To avoid absorption biases, we repeated the C IV EW versus $\alpha_{\text{ox}}$ correlation excluding the 12 objects with $\alpha_{\text{ox}} < -1.75$ where there is potentially significant absorption. This gave essentially the same result ($r_S = 0.498$, versus $r_S = 0.525$ for the complete sample), indicating there is no significant absorption bias.

The interesting new result in Table 2 (Fig. 1, middle panel) is the strong correlation of the C IV EW with the $L/L_{\text{Edd}}$ indicator (i.e. $L^{1/2} (\text{H} \beta \text{ FWHM})^{-2}$), where $r_S = -0.581$ (null probability of $P_r = 1.3 \times 10^{-9}$). This is not a simple consequence of the separate correlations of the C IV EW with $L$ and with the H$\beta$ FWHM, as for example, the correlation with $M_{\text{BH}}$ (i.e. $L^{1/2} (\text{H} \beta \text{ FWHM})^2$) is insignificant ($r_S = 0.21$, $P_r = 0.05$). However, does the combination of $L$ and H$\beta$ FWHM in the form $L^{1/2} (\text{H} \beta \text{ FWHM})^{-2}$ produces the tightest correlation? To answer that we searched for the largest $r_S$ in a correlation of log C IV EW with the linear combination log $L + a \log (\text{H} \beta \text{ FWHM})$, where $a$ is a free parameter. We found a maximum correlation of $r_S = -0.588$ at $a = -5.3$, close to the combination of $L$ and H$\beta$ FWHM which provides $L/L_{\text{Edd}}$ ($a = -4$). Thus, $L/L_{\text{Edd}}$ may be the primary parameter which drives the Baldwin effect for C IV. This implies that the large scatter in the Baldwin effect is produced by the range of $L/L_{\text{Edd}}$ at a given $L$, as suggested by Shang et al. (2003). However, our results disagree with the suggestion of Shang et al. that the C IV EW is primarily dependent on $L$, rather than $L/L_{\text{Edd}}$.

Is $L/L_{\text{Edd}}$ the only parameter that controls the C IV EW? Since the EV1 correlations also appear to be driven by $L/L_{\text{Edd}}$ (BG92; Boroson 2002), their correlation with the C IV EW could be interpreted as secondary correlations. This can be tested with a partial correlation analysis, which yields an average $r_S = 0.42$ for the correlation of C IV EW with $\alpha_{\text{ox}}$ and the EV1 parameters, keeping $L/L_{\text{Edd}}$ fixed, and also for the correlation of C IV EW with $L/L_{\text{Edd}}$ keeping EV1 and $\alpha_{\text{ox}}$ fixed. Although these correlations are weaker than the original ones (Table 2), they are still significant ($P_r \sim 10^{-4}$). The significance of the partial correlations suggests there is a true scatter in the BLR properties at a fixed $L/L_{\text{Edd}}$, though it may also be induced by the inaccuracy of our $L/L_{\text{Edd}}$ indicator.

The significance of the partial correlations implies that the scatter in the C IV EW versus $L/L_{\text{Edd}}$ relation can be reduced by including a third parameter (in addition to $L$ and the H$\beta$ FWHM, which form $L/L_{\text{Edd}}$). The parameter which most significantly improves this correlation is the [O III] $\lambda 5007$ EW (Fig. 1, lower panel), which yields $r_S = -0.722$ (using $\alpha_{\text{ox}}$ instead of [O III] $\lambda 5007$ EW as a third parameter yields $r_S = -0.667$, and using the Fe II/H$\beta$ flux ratio yields $r_S = -0.674$). Similarly, the most significant fourth parameter is $\alpha_{\text{ox}}$ (i.e. correlating log C IV EW versus a linear combination of log $L/L_{\text{Edd}}$, log [O III] $\lambda 5007$ EW, and $\alpha_{\text{ox}}$), which yields a small improvement to $r_S = -0.753$. Finally, the inclusion of the Fe II/H$\beta$ flux ratio as a fifth parameter yields a slight improvement to $r_S = -0.767$.

Some of the scatter in the C IV EW correlations may be induced by a spread in the BLR covering factors among AGN. A plausible way to overcome such a spread is to use the C IV EW/H$\beta$ EW ratio in the above correlations, instead of the C IV EW. This yields significantly lower correlations (e.g. the correlations with $L/L_{\text{Edd}}$ and $\alpha_{\text{ox}}$ go down to $-0.391$ and $0.391$ from $-0.581$ and $0.525$, respectively). This may suggest that the H$\beta$ EW is not a good indicator of the BLR covering factor, but is rather modulated by other BLR properties which do not modulate the C IV EW.

### Table 2. The main C IV EW correlations.

<table>
<thead>
<tr>
<th>Variable Name</th>
<th>$r_S^b$</th>
<th>$P_r^b$</th>
</tr>
</thead>
<tbody>
<tr>
<td>$\nu L_\nu$ (3000 Å)</td>
<td>-0.154</td>
<td>$1.71 \times 10^{-01}$</td>
</tr>
<tr>
<td>$L/L_{\text{Edd}}$</td>
<td>-0.581</td>
<td>$1.31 \times 10^{-08}$</td>
</tr>
<tr>
<td>$\alpha_{\text{ox}}$</td>
<td>-0.642</td>
<td>$1.53 \times 10^{-06}$</td>
</tr>
<tr>
<td>$\alpha_{\text{ox}}$</td>
<td>0.525</td>
<td>$8.47 \times 10^{-07}$</td>
</tr>
<tr>
<td>$\alpha_{\text{ox}}$</td>
<td>0.463</td>
<td>$1.18 \times 10^{-03}$</td>
</tr>
<tr>
<td>[O III] $\lambda 5007$ EW</td>
<td>0.624</td>
<td>$4.71 \times 10^{-10}$</td>
</tr>
<tr>
<td>Fe II EW</td>
<td>0.708</td>
<td>$3.67 \times 10^{-08}$</td>
</tr>
<tr>
<td>R [O III] $\lambda 5007$ peak height</td>
<td>0.624</td>
<td>$4.78 \times 10^{-10}$</td>
</tr>
<tr>
<td>R Fe II EW</td>
<td>0.647</td>
<td>$1.20 \times 10^{-06}$</td>
</tr>
<tr>
<td>R [O III] $\lambda 5007$ EW</td>
<td>0.471</td>
<td>$9.23 \times 10^{-06}$</td>
</tr>
<tr>
<td>FE II EW</td>
<td>0.494</td>
<td>$4.89 \times 10^{-04}$</td>
</tr>
</tbody>
</table>

Notes: $^a$The prefix ‘R’ indicates the ratio of the variable to that of H$\beta$ (BG92), e.g. R Fe II EW corresponds to Fe II EW/H$\beta$ EW. $^b$The top value for each variable is obtained for the complete sample of 81 objects, the bottom value corresponds to the sub-sample of 46 objects with HST spectra.

The physical mechanism implied by the correlation with the [O iii] EW remains to be understood. At least some of the remaining scatter can be produced by a non-isotropic, or a time variable continuum source.

The results presented here can be tested with larger samples of AGN. In particular, it will be interesting to explore the extension to high z AGN, where the Hβ region is observable in the IR (e.g. McIntosh et al. 1999; Yuan & Wills 2003; Shemmer et al. 2004). In addition, different lines show different slopes for the Baldwin effect, and it will be interesting to explore what are the primary physical parameters which drive other emission lines.

ACKNOWLEDGMENTS

We thank the referee for some very helpful remarks. This research has made use of the NASA/IPAC Extragalactic Data base (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

REFERENCES


This paper has been typeset from a \TeX/Xe\TeX file prepared by the author.