The PG X-ray QSO sample: Links between the UV-X-ray Continuum and Emission Lines

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Abstract.

The UV to soft X-rays of luminous AGNs dominate their bolometric luminosity, driven by an accretion-powered dynamo at the center. These photons ionize the surrounding gas, thereby providing clues to fueling and exhaust. Two sets of important relationships – neither of them understood – link the continuum and gas properties.

(i) Boroson & Green’s ‘eigenvector 1’ relationships: Steeper soft X-ray spectra are clearly related to narrower H\textbeta emission and stronger optical Fe II emission from the BLR, and weaker [O III] $\lambda$5007 from the NLR. We show that these relationships extend to UV spectra: narrower C III] $\lambda$1909, stronger low ionization lines, larger Si III] $\lambda$1892/C III] $\lambda$1909 (a density indicator), weaker CIV$\lambda$1549 but stronger higher-ionization NV$\lambda$1240. We speculate that high accretion rates are linked to high columns of dense ($10^{10} - 10^{11} \text{ cm}^{-3}$), nitrogen-enhanced, low-ionization gas from nuclear starbursts. Linewidth, inverse Fe II–[O III] and inverse Fe II–C IV relationships hint at the geometrical arrangement of this gas.

(ii) The Baldwin effect (inverse equivalent width – luminosity relationships): Our correlation analyses suggest that these are independent of the above eigenvector 1 relationships. The eigenvector 1 relationships can therefore be used in future work, to reduce scatter in the Baldwin relationships, perhaps fulfilling the dream of using the Baldwin effect for cosmological studies.

1. Introduction

The UV to soft X-rays of luminous AGNs dominate their bolometric luminosity, driven by an accretion-powered dynamo at the center. Reprocessing of energy within a few gravitational radii determines the spectral energy distribution at

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optical photon energies and above. These photons illuminate and ionize the surrounding gas on sub-parsec to kiloparsec scales – the fuel and exhaust of the central engine – enabling us to investigate its structure, dynamics and physical conditions.

Echo-mapping and photoionization modeling shows that luminous QSOs’ strong broad emission lines arise within 1 pc of the ionizing continuum, from gas with a range of distances, velocities (1000 km s\(^{-1}\) – 10,000 km s\(^{-1}\)), densities (at least 10\(^9\) cm\(^{-3}\) – 10\(^{12}\) cm\(^{-3}\)), and optical depths. This is the broad line region (BLR). Its average line strengths can be reproduced quite well (the “locally optimally emitting cloud” model of Baldwin et al. 1995; see Korista’s discussion in this volume). Beyond the BLR, at distances up to many kiloparsecs, is lower density and lower velocity (∼ 500 km s\(^{-1}\)) gas of the narrow line region (NLR).

Because QSO spectra are similar, the emphasis until recently, has been on explaining the average QSO spectrum. However, investigating relationships among QSO spectral parameters (absorption and emission) as a function of the properties of the ionizing continuum is a powerful way to further explore how the central dynamo works (Francis et al. 1992).

There are two important sets of relationships linking central engine properties with the surrounding gas – the Baldwin effect in the UV (Baldwin et al. 1978), and the optical–X-ray “eigenvector 1” relationships first clearly presented by Boroson & Green (1992).

The Baldwin effect is an inverse relationship between QSO luminosity and the equivalent width (EW) of C IV\(\lambda 1549\) (Baldwin et al. 1978), and other broad emission lines (Kinney et al. 1990). Because QSOs are exceedingly luminous and therefore visible at high redshifts, EWs could serve to determine luminosity distances. QSOs could then be a tool for cosmology. This hope has not been fulfilled because there is too much scatter in the Baldwin relationships.

In optical QSO samples, much of the spectrum-to-spectrum variation is explained by the strong eigenvector 1 relationships (hereafter called principal component 1 or PC1): As H\(\beta\) from the BLR becomes narrower, the strength of BLR Fe II (optical) emission increases, [O III] NLR emission decreases, and the optical–X-ray spectra steepen (increasing \(\alpha_{ox}\) and \(\alpha_x\), where \(F_{\nu} \propto \nu^{-\alpha}\)) (Boroson & Green 1992, Laor et al. 1994, 1997a, Grupe et al. 1998). These relationships link the emission-line properties to the central engine:

- The UV to soft X-ray region dominates the radiated power and ionizes the BLR.
- In principle, line widths (profiles), together with BLR distances based on echo-mapping time-delays or dust-sublimation radii, may be used to infer the virial central masses, hence \(L_{\text{Edd}}\) (Peterson et al. 1998, Laor 1998). QSO luminosities often appear to be significant compared with \(L_{\text{Edd}}\), suggesting that accretion onto a central Black Hole could be an unstable process, giving rise to winds.
- Line widths are also related to \(\alpha_x\), linking kinematics directly to a central engine property. By analogy with Galactic Black Hole Candidates in their “high” states, steep X-ray spectra may be related to high accretion rates (Pounds, Done, & Osborne 1995).
- The structure of the BLR must be linked to \(\alpha_x\) and hence probably to accretion and outflowing winds. One possible explanation for the inverse Fe II-[OIII] relation is that the smaller the effective covering of the central engine by opti-
ally thick BLR gas, the more photons are available to ionize the more distant NLR (Boroson & Green 1992, Brotherton, this volume).

- Clues to the geometry may also come from the fact that the BLR appears to see more continuum power than we infer from the observed continuum; there are too few ionizing photons to explain the line strengths – especially low ionization lines like Fe II, but also He IIλ1640 (Netzer 1985, Korista et al. 1997).

Here we present new UV relationships linking QSOs’ spectral energy distribution and the kinematics, structure and physical properties of the emitting gas. We show how these relationships could be used to reduce the scatter in the Baldwin relationship and lead to understanding of the effect itself.

We have investigated the UV spectra of 22 QSOs from the complete, optically selected sample of 23 QSOs with complete and high quality ROSAT (0.15 - 2 keV) spectroscopy (Laor et al. 1994). This is the same sample for which Laor et al. (1994, 1997a) showed striking X-ray-optical PC1 relationships. A brief report of the present work appeared in Wills et al. (1998a).

2. Observations & Measurements

We have obtained HST FOS spectrophotometry from wavelengths below Lyα to beyond the atmospheric cut-off, and McDonald Observatory spectrophotometry from the atmospheric cut-off to beyond Hα. Instrumental resolutions range from 230 – 350 km s\(^{-1}\) (FWHM). Here we emphasize the new results from UV spectroscopy, with most optical data taken from Boroson & Green (1992). In Figure 1 we show sample UV spectra, with QSOs arranged from the bottom in order of increasing optical PC1, in the sense of steeper soft X-ray spectrum and increasing strength of Fe II(optical).

We have measured strengths, ratios and widths (FWHM) for the following emission lines of the BLR: We have deblended Lyα and N Vλ1240 from each other and from Si IIλ1260, O Iλ1304 and C IIλ1335. We measured C IVλ1549 with N IVλ1486, He IIλ1640 and [O III]λ1663 removed, and we have deblended Al IIIλ1860, Si IIIλ1892 and C IIIλ1909. In most cases we used our McDonald spectra to define a ‘rest frame’ wavelength scale referred to [O III]λ5007 from the NLR. The λ1909 feature is a blend of Si IIIλ1892, C IIIλ1909 and Fe III lines. For our sample Fe III is a minor contributor. Evidence for this is that the wavelength of the peak corresponds to within 0.5-1Å rms of the expected wavelength of C IIIλ1909. An exception is Mkn 478, where Fe III is a clearly present. We have deblended the Lyα–N V emission lines in several ways, some assuming the N V components to have the same width as Lyα, and others assuming the same width as the components of C IVλ1549, with qualitatively similar results. The greatest uncertainties in line measurements arise from uncertainties in continuum placement, and in removal of associated and Galactic interstellar absorption. Details will be presented by Wills et al. (1998b). Some actual line measurements are tabulated by Francis & Wills (this volume).

\(^1\)One object was omitted for non-scientific reasons, so this omission does not bias the sample.
Figure 1. HST-FOS spectra of PG QSOs, plotted on a logarithmic flux density scale to emphasize the weaker features. They are plotted in order of PC1, with the 3 lower QSOs having amongst the flattest X-ray spectra (smaller $\alpha_x$) and weakest Fe II(optical)), and the 3 top spectra being those QSOs with softest X-ray spectra, strongest optical Fe II(optical), weaker [OIII]λ5007, and narrowest (BLR) Hβ. Increasing upwards, notice the increasing prominence of Al IIIλ1860, Si III]λ1892, O Iλ1304, C II λ1335. The λ1400 blend of O IV and Si IV, as well as the apparent strength of NV λ1240 increase relative to CIV and Lyα. The strength of the optical and UV Fe II blends (not shown) also increases.
3. Correlation Results

3.1. Direct Correlations

Table 1. Some Correlation Coefficients

| UV Parameters       | Optical First Principal Component Parameters | L_{1216} |
|---------------------|-----------------------------------------------|----------|
|                     | $\alpha_x$  | log FW H$\beta$ | log EW Fe II | Fe II/ H$\beta$ | log EW [O III] | opt-Xray PC1 |
| log FW C III]      | -0.60      | +0.78            | -0.49       | -0.52          | +0.21        | -0.57       | +0.18       |
| log EW L$\alpha$   | -0.13      | +0.27            | -0.02       | -0.16          | +0.34        | -0.17       | -0.77       |
| log EW C IV        | -0.49      | +0.69            | -0.53       | -0.62          | +0.67        | -0.68       | -0.39       |
| C IV/L$\alpha$     | -0.61      | +0.68            | -0.67       | -0.67          | +0.59        | -0.77       | +0.08       |
| log EW C III]      | -0.32      | +0.42            | -0.18       | -0.36          | +0.41        | -0.34       | -0.68       |
| Si III]/C III]     | +0.52      | -0.56            | +0.52       | +0.89          | -0.62        | +0.62       | -0.10       |
| Si III/L$\alpha$   | +0.39      | -0.59            | +0.57       | +0.83          | -0.70        | +0.72       | -0.22       |
| NV/C III]          | +0.71      | -0.53            | +0.47       | +0.65          | -0.51        | +0.73       | +0.08       |
| NV/L$\alpha$       | +0.53      | -0.48            | +0.41       | +0.45          | -0.57        | +0.66       | -0.01       |
| A1400/L$\alpha$    | +0.69      | -0.60            | +0.60       | +0.58          | -0.57        | +0.71       | -0.31       |

The usual Pearson correlation coefficients are given.

For 22 QSOs, a correlation coefficient of 0.4 corresponds to 1 chance in 15 of arising from uncorrelated variables (two tailed), 0.5 corresponds to 1 chance in 50, 0.6 to 1 chance in 300, and 0.7 to 1 chance in 2000 of arising from uncorrelated variables. FW $\equiv$ FWHM.

Some of the most important correlation results are summarized in Table 1 and Figure 2. Column (1) of Table 1 lists emission-line parameters of the ultraviolet spectrum: line ratios, logarithms of rest-frame equivalent widths (EW) and line widths (full width at half maximum, FWHM or FW). Columns (2) – (6) give correlation coefficients for the ultraviolet parameters vs. the well-known PC1 parameters, $\alpha_x$ derived from a fit between 0.2 keV and 2 keV, and parameters of the optical spectrum as given by Boroson & Green (1992). Column (7) gives correlation coefficients between the UV parameters of col. (1) and a linear combination of X-ray–optical PC1 parameters derived from a principal components analysis of our sample (See §3.2 and Francis & Wills, this volume). The table notes give two-tailed significance levels for the correlation coefficients. Where the probability of a correlation arising by chance from unrelated variables is $<1$ in 50, the coefficients are given in bold type. However, because such a large fraction of our observationally-independent parameters are significantly correlated, the assumption that the variables are unrelated breaks down, so the significance of our correlations is actually higher than indicated in the table. Figure 2 plots some of the correlations of Table 1, the four columns representing X-ray–optical PC1 observables: the steepness of the X-ray spectrum, the width of the broad H$\beta$ line, the strength of Fe II(optical), and the strength of NLR emission ([O III]$\lambda$5007). Optical PC1, in the sense of softer X-ray spec-
Figure 2. UV observables vs. $\alpha_x$ and optical Eigenvector 1 observables. Many line ratios are consistent with these trends – lower ionization, higher densities, in addition to (not shown) weaker $[\text{O III}]\lambda5007$ from the narrow line region (NLR) – all corresponding to steeper soft X-ray spectra. The 2-tailed probability of these correlations arising by chance from unrelated variables is between 1 in 50 to 1 in $>1000$. 

$[\text{O III}]\lambda5007$
trum, clearly extends to the UV: narrower C III] emission, stronger N Vλ1240, Si III]λ1892, and λ1400 feature. Fe III UV 34 (λλ 1895, 1914, 1926) also contributes more when Fe II is strong. Mkn 478 in our sample, and I Zw 1 (see Laor et al. 1997b), have especially soft X-ray spectra, especially strong Fe II (optical), as well as strong Fe III (I Zw 1 did not meet the Galactic obscuration criteria for inclusion in the sample, but is otherwise eligible). The strength of C IVλ1549 is inversely correlated with the strength of Fe II (optical) (Wang et al. 1996) and correlated with [O III] (Brotherton, this volume.) There are also very significant correlations among the UV parameters by themselves (§3.2). Correlations as strong as we have found should show up in a visual inspection of the spectra. They do (see Figure 1, being careful to account for the effects of line width on blended features).

Also shown in Table 1 and Fig. 3 are correlations between UV emission-line parameters and L_{1216}, log of the continuum luminosity at 1216Å. The Baldwin relationships are present. The significance depends largely on the highest luminosity QSO 3C 273 with the smallest EWs, and the lowest luminosity QSO PG 1202+281 with the largest EWs. A larger sample is needed to show this result clearly.

3.2. Principal Components Analysis

We perform a principal components analysis (PCA) to investigate which sets of observational variables correlate or anticorrelate together, and therefore whether we can define a smaller number of new variables that are linear combinations of the measured variables. This would simplify a description of our dataset. Moreover, it may suggest one or more physical processes giving rise to the spectrum-to-spectrum variations. An introduction to PCA is given in Francis and Wills of this volume, where our present dataset is used as an example.

We choose some of the same variables as as in §3.1, and perform the analysis on the ranks of the measurements for each observational variable. The results are shown in Table 2. Half of the sample variance (49.9%) is described by a linear combination of variables related to the optical–X-ray principal component PC1.

Figure 3. The Baldwin relationships for Lyα, C IVλ1549 and C III]λ1909 for ∼20 QSOs of the PG X-ray sample.

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2For the results of a PCA on the unranked data, see Table 3, of Francis and Wills in this volume).
Table 2. Principal Components Analysis

| Variable          | PC1   | PC2   | PC3   |
|-------------------|-------|-------|-------|
| \( L_{1216} \)    | +0.01 | +0.52 | −0.30 |
| \( \alpha_x \)    | +0.32 | −0.16 | +0.03 |
| FWHM H\( \beta \) | −0.35 | +0.03 | −0.32 |
| FeII/H\( \beta \) | +0.35 | −0.09 | +0.09 |
| EW [O III]        | −0.30 | +0.02 | +0.25 |
| FWHM C III       | −0.20 | −0.06 | −0.61 |
| EW Ly\( \alpha \) | −0.15 | −0.51 | +0.10 |
| EW C IV          | −0.33 | −0.24 | +0.05 |
| C IV/Ly\( \alpha \) | −0.34 | +0.18 | +0.03 |
| EW C III         | −0.25 | −0.47 | −0.08 |
| Si III/C III     | +0.35 | −0.06 | −0.02 |
| NV/Ly\( \alpha \) | +0.23 | −0.14 | −0.54 |
| \( \lambda 1400/Ly\alpha \) | +0.23 | −0.31 | −0.24 |

There were 18 QSOs used in this analysis. \( L_{1216} \) represents continuum luminosity at 1216Å.

found by Boroson & Green (1992) and Laor et al. (1994, 1997a). The weights of these measured parameters are given in the PC1 column.

The second most important principal component (PC2) is dominated by an inverse relationship between \( L_{1216} \) and EW. All EWs except EW H\( \beta \), EW [O III], and EW Fe II(optical) show likely inverse relationships between EW and luminosity, and the correlation appears particularly strong for O VI\( \lambda 1034 \) (not shown; see the results of Zheng et al. 1995, for a large heterogeneous sample.) These are the same trends as seen in the classical Baldwin relationships (Kinney et al. 1990). The most interesting result of the PCA is that PC1 appears not to depend on luminosity at all (correlation coefficient \( \sim 0.1 \)): The Baldwin relationships appear independent of the X-ray–UV–optical PC1 relationships. C IV\( \lambda 1549 \) is present in PC1 and PC2, probably accounting for its weaker Baldwin relationship in our sample (Fig. 3).

PC3 appears to represent an independent relationship between luminosity and line widths, but we defer consideration of this until a larger sample is available. Each of the remaining principal components account for less than 5% of the sample variance and are not significant.

4. Summary

We show that optical principal component 1, linking steeper soft X-ray spectra with increasing optical Fe II strength, decreasing [O III]\( \lambda 5007 \) emission, and nar-
Figure 4. An approximate description of the relationships among $\alpha_x$, UV PC1 variables, and optical PC1 variables. Variables on the same side of the center correlate positively with each other, and on opposite sides, negatively. The lengths of the bars indicate an approximate strength of the correlation.

Rower BLR H$\beta$ emission, extends to the UV emission lines: narrower C III] $\lambda$1909, weaker C IV$\lambda$1549 emission, stronger low ionization emission lines – UV Fe II, Si III] $\lambda$1892, and probably O I $\lambda$1305, C II $\lambda$1335, and Fe III, and also a larger ratio Si III] $\lambda$1892/C III] $\lambda$1909. But N V and the O IV–Si IV $\lambda$1400 blend also increase in strength with steeper soft X-ray spectrum, increasing Fe II(optical), decreasing H$\beta$ width and decreasing [O III] strength. Figure 4 presents an approximate summary of these correlations and anticorrelations, based on the results for many line ratios.

While Fe II(optical) vs. $\lambda$1400/C IV and C IV/Ly$\alpha$, and $\alpha$(UV–X-ray) vs. C IV/Ly$\alpha$ relationships have been noted before in large, heterogeneous samples (Wang et al. 1996, 1998; see also Dultzin-Hacyan 1997), the spectacular related correlations that we have found among many variables may be attributed to the homogeneous and complete nature of the sample. For further illustration and discussion of the Fe II – Si III]/C III] relationships, as well as Al III/C III]
and Fe III/C III], see Aoki & Yoshida (this volume), and for an independent presentation of the C IV – [O III] relationship, see Brotherton (this volume).

5. Discussion

In the Introduction, we showed that the X-ray–optical relationships provide plausible strong links between central engine parameters and ionized gas on sub-parsec to kpc scales. Clearly the UV–soft-Xray continuum photoionizes the surrounding gas and the emission lines can, in principle, provide information on the shape of the ionizing continuum. UV spectrophotometry provides further pieces for the puzzle by relating the central engine to the kinematics, geometry and density of fueling gas or outflows:

• Si III]λ 1892 probably arises from almost the same region as C III] and most optical and UV Fe II, but C III]λ 1909 is collisionally suppressed at high densities >10^{10} \text{ cm}^{-3}, thus increasing the ratio Si III]/C III] (e.g. Laor et al. 1997b). Our observed dependence of Si III]/C III] on Fe II strength is therefore consistent with the high densities and column densities required to produce strong Fe II(optical) (Ferland & Persson 1989, Wills, Netzer & Wills 1985).

• The C IV emission is strongly correlated with [O III]λ 5007. As suggested to explain the inverse Fe II–[O III] relation, does this mean that thick high density Fe II-emitting gas shields more distant C IV-emitting gas?

• The strength of the higher-ionization N Vλ 1240 also appears to be associated with this higher density gas, while C IV strength decreases with increasing PC1 (i.e., Fe II, etc.) This apparent anomaly is reminiscent of the behavior of the EW(N V) Baldwin relation in which the slope of the Baldwin relation for several other species is tightly correlated with ionization potential, but for N V the dependence on luminosity is much less than expected. Korista et al. (this volume, 1998) show that the EW (N V) – luminosity relationship can be understood if very N-rich gas (Hamann & Ferland 1993) is irradiated by a UV–soft-Xray continuum whose strength increases with luminosity. While this is a complex issue, perhaps our N V anomaly can be similarly explained by enhanced N abundances.

The ‘mystery physics’ underlying the PC1 relationships could be an increase in L/L_{Edd} associated with an increase in dense, Fe II emitting gas of high metallicity. It has been suggested that the extreme low ionization spectra with strong Fe II are somehow related to starbursts (Lipari et al. 1993). Could starburst activity cause high accretion rates, hence strong soft X-rays?

What do our new results mean for the Baldwin Effect? Our PCA suggests that the strong first principal component (PC1) relationships that we find are independent of luminosity. The second principal component, PC2, apparently represents the Baldwin effect – inverse relationships between EW and luminosity. Because we find strong links among line strengths and UV–X-ray continuum parameters, it is clear that these relationships must cause significant variation in equivalent widths from one QSO to another. Even if their cause is unknown, the relationships between line strengths and observables independent of L could be used to remove most of the scatter in Baldwin relationships. Could the cause of PC1 remove not only the scatter from the Baldwin relationships, but also remove the Baldwin effect itself? Not if PC1 is independent of luminosity; investigation of larger samples is needed. However, if the variance of emission-
line strengths could be attributed entirely to differences in the ionizing spectral energy distribution, the crucial question would then become: How and why does the ionizing spectral energy distribution depend on luminosity?, and this gets to the heart of the Central Engine.

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