The PG X-Ray QSO Sample: Links among X-ray, UV & Optical Spectra

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Abstract. A unique, essentially complete sample of 22 QSOs, with high quality soft X-ray spectra from ROSAT, as well as HST and optical spectrophotometry from below Lyα to above Hα, is being used to investigate the relationships among the ionizing continuum and the optical and UV continuum, emission and absorption lines. Here we present a first analysis showing that optical ‘Eigenvector 1’ linking steeper soft X-ray spectra with increasing optical Fe II strength, decreasing [O III] λ5007 emission, and narrower BLR Hβ emission, extends to the UV emission lines, and is manifested by weaker C IV λ1549 emission, stronger Si III] λ1892/C III] λ1909 ratio, and narrower C III] λ1909 emission. Steeper soft X-ray spectra have been linked to higher L/L_Edd ratios, thus apparently linking BLR densities, high and low ionization gas, and kinematics, to the accretion process.

1. Introduction

In principle, relationships between QSOs’ EUV continuum and the emission-line gas that it ionizes should give us clues to any relationship between accretion power and the physical conditions and kinematics of accreting or outflowing material within ~ 1 pc, hence clues to the mechanism of the central engine. Several studies have shown that the soft X-ray spectrum is related to the emission line spectrum: steeper X-ray spectra are associated with stronger optical Fe II (BLR) emission, narrower (BLR) Hβ, weaker [O III] λ5007 (NLR) emission (Boroson & Green 1992; Grupe 1996; Grupe et al. 1998; Forster 1995; Laor et al. 1994, 1997; Corbin 1993). One of the greatest sources of variation from one spectrum to another can be represented as a linear combination of these observables – the so-called “Eigenvector 1” of principal component analyses. Its underlying physical cause is unknown, but an understanding seems likely to hold a clue

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to accretion conditions, and to the energy budget problem – in particular the too-great strength of low-ionization emission lines such as Fe II (Netzer 1985).

Laor et al. (1997) have investigated the soft X-ray and Hβ–[OIII]λ5007 region for a complete sample of all 23 QSOs from the PG UV-excess survey (Schmidt & Green 1983) with $z < 0.4$, and low Galactic absorption ($N_{HI} < 1.9 \times 10^{20} \text{cm}^{-2}$), discovering strong Eigenvector 1 relationships in this sample. The low redshift ensures detection of the soft X-ray emission down to the lowest possible rest frame energy (typically 0.2 keV), which is redshifted into the unobservable soft X-ray region ($< 0.15\text{keV}$) in higher redshift quasars. The low Galactic absorbing column, and accurate 21 cm measurements of this column for all objects, ensure small, accurate corrections for ultraviolet and soft X-ray absorption.

This sample is ideal for extending this study into the ultraviolet, where the highest energy continuum and important UV diagnostic lines can be measured with minimal confusion from intergalactic absorption lines. Thus 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 present highlights of a first look at our own and archival HST spectra and the X-ray and optical measurements presented by Laor et al. (1997), and Boroson & Green (1992).

2. Spectral Measurements, and Correlations

We have measured strengths, ratios and widths (FWHM) for the following emission lines: Lyα with NV λ1240 removed, C IV λ1549 with NV λ1486, He II λ1640 and [O III] λ1663 removed, and we have deblended Si III] λ1892 and C III] λ1909. In most cases it was possible to define a ‘rest frame’ wavelength scale referred to [O III] λ5007 in our McDonald spectra. Generally Fe III does not contribute much to the λ1909 blend. Evidence for this is that the wavelength of the peak corresponds to within 0.5-1Å rms of the expected wavelength of C III] λ1909. An exception is Mkn 478, where Fe III is a clear contributor. 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. (1998).

Table 1 presents a few of the correlation results. Eigenvector 1 observables, given in the first column, are correlated with important emission line parameters of the ultraviolet spectrum, given across the top of the table. Eigenvector 1 variables are chosen so as to correlate positively with X-ray spectral index $\alpha_x$ ($F_\nu \propto \nu^{-\alpha_x}$). Correlation coefficients are generally Pearson coefficients using line ratios, and logarithms of equivalents widths and FWHMs. Spearman rank correlations give similar results. The two-tailed significance levels are given at the end of the table. We note that a large fraction of our observationally-independent parameters are correlated. This means that the significance of an individual correlation is not much affected by the fact that we attempted a large number of correlations. Figure 1 plots some of the correlations of Table 1, the four columns representing Eigenvector 1 observables: the steepness of the X-ray spectrum, the strength of Fe II (optical), the strength of NLR emission
([OIII] $\lambda$5007), and the width of the broad H$\beta$ line. In Figure 2 we show the intensity ratio SiIII]/CIII] plotted against FeII/H$\beta$ and Ly$\alpha$/CIV.

Table 1. ‘Eigenvector 1’ Correlations.

| Eigenvector 1 Parameters | Ly$\alpha$/CIV | O VI/C IV | C III]/C IV | EW(C IV) | SiIII]/CIII] | FWHM (C III) |
|--------------------------|---------------|-----------|--------------|----------|--------------|--------------|
| $\alpha_x$               | 0.78          | 0.42      | ...          | -0.67    | ...          | -0.59        |
| EW (FeII)                | 0.69          | 0.70      | 0.53         | -0.68    | 0.72         | -0.52        |
| [H$\beta$]               | 0.80          | 0.85      | 0.54         | -0.46    | 0.89         | -0.63        |
| [OIII]                   | 0.71          | 0.59      | 0.63         | -0.66    | 0.28         | -0.37        |
| H$\beta$                 | 0.58          | 0.40      | 0.56         | -0.59    | 0.56         | -0.47        |
| EW([OIII])               | 0.63          | 0.40      | 0.60         | -0.64    | 0.60         | ...          |
| FWHM(H$\beta$)           | 0.68          | 0.65      | 0.53         | -0.69    | 0.56         | -0.78        |

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 30, 0.6 to 1 chance in 300, and 0.7 to 1 chance in 2000 of arising from uncorrelated variables.

3. Results and Discussion

Table 1 shows that line ratios involving C IV strength, including the EW (C IV), correlate significantly with nearly all Eigenvector 1 observables in the sense that C IV strength anticorrelates with steep soft X-ray spectrum, and strong FeII, and correlates positively with [O III] strength and FWHM (H$\beta$). We note that correlations of Ly$\alpha$/C IV and EW (C IV) with $\alpha_x$ are in the same sense as found by Wang et al. (1998) for a large, heterogeneous sample. Our result suggests that Eigenvector 1 is correlated with strengths of lines from low ionization transitions (Fe II) and anti-correlated with higher ionization transitions ([O III], C IV, O VI $\lambda$1034). If investigation of species over a wider range of ionization confirms this, one possible explanation may be along the lines hinted at by Boroson & Green (1992), and investigated more quantitatively by Brotherton (1996, 1998): the [O III] may be produced by ionizing photons that reach the NLR after penetrating the BLR. Higher BLR optical depths will result in stronger emission from lower ionization lines (Mg II $\lambda$2798, Fe II (optical)), hence reducing the ionizing flux to the NLR beyond. A more highly ionized BLR may produce stronger O VI $\lambda$1034, C IV $\lambda$1549, and lower column densities of Mg$^+$ and Fe$^+$, allowing greater ionizing flux to reach the NLR. For example, in a BLR consisting of clouds with a distribution of optical depths, increasing ionizing flux could increase the ratio of optically thin to optically thick clouds.

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Figure 1. UV observables vs. $\alpha_x$ and optical eigenvector 1 observables.
Figure 2. Correlations with the possible density indicator, Si III] λ1892/C III] λ1909.

The ratio Si III] λ1892/C III] λ1909 is strongly correlated with Eigenvector 1 in the sense of a positive correlation with Fe II (optical), and anticorrelations with [O III] strength and FWHM (Hβ). It is also correlated with Lyα/C IV (Fig. 2). These correlations are stronger than the positive (negative) correlations of Si III] strength (C III]) alone with Fe II/Hβ and Lyα/C IV. The similar (but not identical) ionization potentials of Si++ and C++ and photoionization models suggest that these ions are largely cospatial in the BLR. This line ratio is sensitive to density, with \( n_{\text{crit}} \sim 10^{11} \text{ cm}^{-3} \) for the Si III] λ1892 upper level and \( n_{\text{crit}} \sim 10^9 \text{ cm}^{-3} \) for C III] λ1909. Thus Eigenvector 1 appears strongly related to density, in the sense that the BLR high density gas contributes most when Fe II (optical) is strongest.

As found in other samples, FWHM (C III]) correlates well with FWHM Hβ, suggesting that these are from the same kinematic region. Similarly, there is a good correlation between FWHM (Lyα) and FWHM (C IV), but spanning a smaller range of FWHMs. These correlations, together with weaker correlations of FWHM Lyα with FWHM (C III]) or FWHM Hβ, and weaker correlations of FWHM (C IV) with FWHM (C III]) or FWHM Hβ suggest different kinematic origins for low and high ionization gas.

Overall, we were somewhat amazed at the strong correlations present in our small sample, and conclude that small, but carefully-defined, homogeneous samples with high quality spectra can yield significant information on the underlying physics. We suggest that Eigenvector 1, in the sense of increasingly steep soft X-ray spectrum, increasing Fe II (optical) strength, decreasing NLR emission, and narrower (BLR) Hβ, represents increasing dominance of low-ionization gas, and high densities, as well as decreasing dominance of high-ionization gas. The interpretation of narrower Hβ lines in terms of higher Eddington ratios, and the
correlation with steeper soft X-ray spectra, links the accretion process to density and ionization state of the surrounding gas (Wandel, Laor, these Proceedings).

Further results, including measurements of other lines (e.g., NV $\lambda 1240$, $\lambda 1400$, Al III $\lambda 1860$), will be presented by Wills et al. (1988a, b).

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Discussion

Dr. Binette: Have you looked at other density indicators besides the ratio Si III $\lambda 1892$/C III $\lambda 1909$?

Dr. Wills: Not yet, but this will be possible (see Ferland 1998, Quasars as Standard Candles for Cosmology, ASP Conference Series).
Dr. Dultzin: We find the same results as you have, and reported them in Dultzin-Hacyan, D. 1997, ‘Emission Lines in Active Galaxies: New Methods & Techniques’, ASP Conference Series, 113, 262.

Dr. Wills: After the meeting I have checked this. While your reported anti-correlation between EW (C IV) and Fe II (optical) strength may be the same as what we find, I’m not sure. Your EW (C IV) apparently was measured in a way rather different from the conventional one (Marziani et al. 1996, ApJS, 104, 37) and the sample you used was very heterogenous, covering a wide range in luminosity. Our EW (C IV) measurements include the total line flux, but with N IV λ1486, He II λ1640, and O III] λ1663 removed.