INDICATORS OF BLACK HOLE MASS AND
EDDINGTON ACCRETION RATIO FROM QSO X-RAY
AND UV SPECTRA

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ABSTRACT

The evolution of luminous QSOs is linked to the evolution of massive galaxies. We know this because the relic black-holes found locally have masses dependent on the properties of the host galaxy’s bulge. An important way to explore this evolution would be to measure dependences of black hole masses and Eddington accretion ratios over a range of redshifts, i.e., with cosmological age. For low redshift QSOs (and their lower luminosity Seyfert galaxy counterparts) it has been possible to infer black hole masses from the luminosities and velocity dispersions of their host-galaxy bulges. These masses agree with those virial black hole masses calculated from the Doppler widths of the broad Hβ emission lines. The latter method can then be extended to more distant and luminous QSOs, up to redshifts of 0.6 with ground-based optical observations. We discuss ways to extend these explorations to higher redshifts – up to ~3 using the widths of QSOs’ broad UV emission lines, and in principle, and to redshifts near 4 from ground-based infrared observations of rest-frame Hβ at 2.5µm. We discuss the possibility of investigating the accretion history of the higher redshift QSOs using measures of Eddington accretion ratio – the soft X-ray spectral index and the eigenvectors of Principal Components Analyses of QSOs’ UV emission-line spectra.

INTRODUCTION

Black holes appear to be ubiquitous in the nuclei of nearby galaxies (Magorrian et al. 1998) with the black hole mass directly proportional to the bulge luminosity or to σ^4, where σ is the bulge velocity dispersion of the host galaxy (Kormendy and Gebhardt 2001, Tremaine et al. 2002). The space density of these local supermassive black holes is similar to that of QSOs at the heyday of their evolution at redshifts of 2 – 3. By the present epochs, these QSOs have faded, leaving behind the relic black holes found in local galaxies (Soltan 1982, Fabian and Iwasawa 1999). This inference, together with the black-hole mass – σ relationship, shows that the evolution of QSOs and galaxies is intimately related (e.g., Fabian 1999). Measurement of black hole mass and Eddington accretion ratio of QSOs over a wide redshift range, i.e., with cosmological epoch, would allow us to explore the accretion history of QSOs, hence the evolution of galaxies.

In nearby, less-luminous active galaxies and QSOs it is difficult, but possible, to measure the bulge mass via bulge luminosities and stellar velocity dispersions. This has allowed the calibration of a virial method of measuring black hole masses using the broad Hβ emission line of active galaxies and nearby QSOs (Laor 1998, Gebhardt et al. 2000). In this method the Hβ emission-line gas within ~1 parsec of the nucleus is assumed to move under the gravitational influence of the central black hole. Thus the Hβ full-width at half maximum intensity (FWHM), together with the distance of this gas inferred from reverberation mapping (r ∝ L^{0.5}, where L represents the continuum luminosity – e.g., Kaspi et al. 2000, Vestergaard 2002, Maoz 2002), leads to a black hole mass:

M_{BH} ∼ FWHM^2 L^{0.5}
From this can be inferred an Eddington accretion ratio $\propto L/M_{\text{BH}} \sim \text{FWHM}^{-2} L^{0.5}$. Thus this H$\beta$ FWHM method can be used for higher luminosity and more distant QSOs for which, in the presence of the QSO nucleus, the host galaxy appears too small and dim to measure bulge luminosity or velocity dispersion (see Figure 4 in the paper by McLure and Dunlop 2002).

How can we extend these measurements to higher redshifts?

**NEW WAYS TO MEASURE $M_{\text{BH}}$ AND $L/M_{\text{BH}}$.**

There are several possibilities that we will discuss below.

1. Near infrared observations of the rest-frame H$\beta$ emission line can extend $M_{\text{BH}}$ measurements to redshifts of 1.5 – 2.5 (Yuan and Wills 2002a, 2002b).

2. It’s been suggested that widths of emission lines of Mg II$\lambda$2798 (McLure and Jarvis 2002) and C IV$\lambda$1549 (Vestergaard 2002) could be used instead of H$\beta$, in principle extending the method to redshifts of 1.9 and 4.2. These authors show that the widths of these UV lines can be used to estimate black hole masses, with a calibration based on the H$\beta$ method (McLure and Jarvis’ 2002 Figure 4; Vestergaard’s 2002 Figure 4b). However, the scatter is large. Both UV lines, but especially Mg II$\lambda$2798, are seriously affected by Fe II blends. These Fe II blends both contaminate the broad emission lines and make continuum determination in the region of the lines extremely unreliable (e.g., Vestergaard and Wilkes 2000).

3. At low redshifts, we have shown that X-ray spectra and optical-UV emission line relationships are closely related to Eddington accretion ratio (Yuan and Wills 2002a, 2002b, Boroson 2002, Laor et al. 1997). Emission-line relationships are probably determined by the available fuel supply. Thus Eddington accretion ratio and $M_{\text{BH}}$ can be determined.

We illustrate how the relationships in 3. above can be employed to measure Eddington accretion ratios, using results from the 18-22 QSO sample discussed by Shang et al. (2002a, 2002b).

![Fig. 1](image.png)

**Fig. 1** The dependence of soft X-ray spectral index $\alpha_x$ on the logarithm of FWHM$^{-2} L^{0.5}$ (proportional to Eddington ratio).

**X-ray Spectral Index and Eddington Ratio**

Figure 1 shows soft X-ray spectral index $\alpha_x$ (from Laor et al. 1997) vs Eddington ratio, calculated from H$\beta$ widths as described above. Measurement uncertainties on $\alpha_x$ are typically $\pm 0.05$, and the observational uncertainties on log [FWHM$^{-2} L(3000)^{0.5}$] are approximately $\pm 0.15$. 3C 273 is a radio-loud core-dominant QSO, with a strong jet contribution that flattens the X-ray spectrum. Therefore it should not be included.
Without 3C 273, the two-tailed probability $P_{2t}$ of a chance correlation is $< 2 \times 10^{-5}$. In principle then, $L/L_{\text{Edd}}$ can be determined from $\alpha_x$. At higher redshifts the rest frame soft X-ray spectrum is unobservable, redshifted to photon energies where it is absorbed by the interstellar medium in our Galaxy. However there is a correlation between hard and soft X-ray spectral indices (compare Fig. 8 of Boller, Brandt, and Fink 1996, with Fig. 1 of Brandt, Mathur, and Elvis 1997). The use of this relationship needs further understanding of the complex X-ray spectra being revealed by Chandra and XMM.

**UV Emission Line Spectra and Eddington Ratio**

At redshifts $z \sim 1.9 - 3.3$, H$\beta$ is redshifted out of the optical atmospheric window, but UV rest wavelengths are observable. So another approach is to use the UV emission-line spectrum.

One way is via a Principal Components Analysis of directly measured parameters. The method finds independent principal components, which are linear combinations of these measured input parameters. The first principal component is the linear combination that accounts for most of the spectrum-to-spectrum variance, the second principal component, the one that accounts for the next most variance, etc. The method is explained and described by Francis and Wills (1999), and Wills et al. (1999), who apply the technique to the low redshift sample discussed here. Here we demonstrate, using our low redshift QSO sample, that the UV spectra (observed with the Faint Object Spectrograph on the Hubble Space Telescope) can predict the Eddington ratio determined from H$\beta$ FWHM.

With just the UV emission-line strengths, ratios and widths as input (the data are tabulated by Francis and Wills 1999), Principal Components Analysis reveals a first principal component, UV PC1, accounting for 48% of the spectrum-to-spectrum variance. This linear combination of the input variables depends on $L/L_{\text{Edd}}$ (Figure 2).

A related Principal Components Analysis that uses the whole spectrum was just described by Shang et al. (2002b). Each QSO spectrum is represented by the flux in small wavelength bins along the entire spectrum. Instead of measured line and continuum parameters, this spectral PCA uses these binned fluxes as input parameters. In an analysis of just the UV spectrum (rest wavelengths 1171Å– 2100Å), about half of the spectrum-to-spectrum variance is described by the first principal component, and this linear combination of variables is dependent on luminosity (the Baldwin effect), but independent of Eddington ratio. The second most important linear combination (the Second Principal Component, UV SPC2), accounting for 20% of the spectrum-to-spectrum variance, is dependent on Eddington ratio (Figure 3).

Thus these linear combinations of input variables – using either PCA or spectral PCA – can be used to predict the Eddington accretion ratio. Figure 4 shows, as expected, the good correlation between the two linear combinations from PCA (UV PC1) and from spectral PCA (UV SPC2). The UV emission line principal components also agree well with the X-ray predictor of Eddington accretion ratio (Figure 5).

**CONCLUSIONS**

At low redshift ($\lesssim 0.6$), QSO X-ray spectral index and UV emission line spectra can predict the Eddington ratio, with small scatter. Given an appropriate luminosity one can therefore also derive $M_{\text{BH}}$. Spectral indicators can be observed at higher redshift, thus, in principle, enabling the investigation of the evolution of Eddington accretion ratio and $M_{\text{BH}}$ at epochs important for the growth of black holes and galaxy spheroids. Further investigation is needed to apply these methods at higher redshift. These relationships are empirical, and may evolve with cosmic epoch. We need to understand more clearly the physical basis of these relationships. At higher redshifts, only harder X-rays are available. Chandra and XMM spectroscopy may help us understand why the broad band spectral index shows these dependences. The UV emission line indicators may be a function of how the gas is illuminated – the geometry, the ionizing continuum. They may also be indicators of the available fuel supply – and therefore only indirectly related to Eddington ratio. One promising indication that these emission line properties are meaningful at redshifts up to 2.5, is the demonstration that emission line properties in the redshifted H$\beta$ region depend on Eddington accretion ratio, as derived from H$\beta$ FWHM (Yuan and Wills 2002a, 2002b). The existence of clear correlations at low redshift between Eddington ratio, $M_{\text{BH}}$, optical-UV emission line properties, and soft Xray spectrum is, in any case, giving us important information about the powering of QSOs’ central engines. Whether these relationships are the same at high redshift (or luminosity), they still hold important information about the evolution of the accretion process.
Fig. 2. The dependence of Principal Component 1, derived from a PCA of direct emission line measurements, on the logarithm of FWHM$^{-2}$ L$^{0.5}$ (proportional to Eddington ratio). $P_{2t} < 2.10^{-5}$.

Fig. 3. The dependence of Spectral Principal Component 2, from an SPCA of the UV emission line spectra, on the logarithm of FWHM$^{-2}$ L$^{0.5}$ (proportional to Eddington ratio). $P_{2t} < 6.10^{-5}$.

Fig. 4. The dependence of principal component 1, derived from a PCA of direct measurements of UV emission lines, on Spectral Principal Component 2, derived from a spectral PCA of the UV emission line spectra. $P_{2t} < 2.10^{-6}$.

Fig. 5. The dependence of soft X-ray spectral index $\alpha_x$ on Spectral Principal Component 2, from a spectral PCA of the UV emission line spectra. $P_{2t} < 2.10^{-5}$.

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