Measuring the black hole masses of high redshift quasars

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ABSTRACT
A new technique is presented for determining the black-hole masses of high-redshift quasars from optical spectroscopy. The new method utilizes the full-width half maximum (FWHM) of the low-ionization Mg\textsc{ii} emission line and the correlation between broad-line region (BLR) radius and continuum luminosity at 3000\AA. Using archival UV spectra it is found that the correlation between BLR radius and 3000\AA luminosity is tighter than the established correlation with 5100\AA luminosity. Furthermore, it is shown that, when considered together, both correlations are most consistent with a relation of the form $R_{\text{BLR}} \propto \lambda L_{\lambda 5100}^{0.7}$, as expected for a constant ionization parameter. Using a sample of objects with broad-line radii determined from reverberation mapping it is shown that the FWHM of Mg\textsc{ii} and H\textbeta are consistent with following an exact one-to-one relation, as expected if both H\textbeta and Mg\textsc{ii} are emitted at the same radius from the central ionizing source. The resulting virial black-hole mass estimator based on rest-frame UV observables is shown to reproduce black-hole mass measurements based on reverberation mapping to within a factor of 2.5 (1\sigma). Finally, the new UV black-hole mass estimator is shown to produce identical results to the established optical (H\textbeta) estimator when applied to 128 intermediate-redshift (0.3 < $z$ < 0.9) quasars drawn from the Large Bright Quasar Survey and the radio-selected Molonglo quasar sample. We therefore conclude that the new UV virial black-hole mass estimator can be reliably used to estimate the black-hole masses of quasars from $z \sim 0.25$ through to the peak epoch of quasar activity at $z \sim 2.5$ via optical spectroscopy alone.

Key words: galaxies: fundamental parameters – galaxies: active – galaxies: nuclei – galaxies: high redshift – quasars: general – quasars: emission lines

1 INTRODUCTION
A reliable method for estimating the black-hole masses of high-redshift quasars would provide crucial new information for understanding the nature and cosmological evolution of quasars. In this paper we address this problem by deriving a virial black-hole mass estimator based on rest-frame UV observables which is capable of producing reliable quasar black-hole mass estimates from optical spectra out to redshifts of $z \sim 2.5$.

Currently, the most direct measurements of the central black-hole masses of powerful active galactic nuclei (AGN) come from the reverberation mapping studies of 17 Seyferts and 17 PG quasars by Wandel, Peterson & Malkan (1999) and Kaspi et al. (2000) respectively. By measuring the time-lag between the variations of the AGN continuum and the broad H\textbeta (4861 \AA) emission line, these long-term monitoring programmes have delivered direct measurements of the radius of the H\textbeta emission region from the central ionizing source ($R_{\text{BLR}} = c \tau$, where $\tau$ is the time lag between the continuum and H\textbeta variations). By combining these measurements with the assumption that the FWHM of the H\textbeta line reflects the virialized bulk motion of the line-emitting material, it is then possible to produce the so-called virial estimate of the central black hole mass (see Wandel, Peterson & Malkan 1999 for a full discussion). Although the virial mass estimate is potentially subject to many uncertainties (eg. Krolik 2001), comparison with the predictions of the completely independent relation between black-hole mass and host-galaxy stellar velocity dispersion have shown the two to be in excellent agreement (Ferrarese et al. 2001, Gebhardt et al. 2000).

Unfortunately, because of the many years of monitoring required, it is unrealistic to expect that reverberation mapping measurements can be obtained for large samples of quasars, even at low redshift. However, the existing reverberation mapping of low redshift AGN has revealed a correlation between $R_{\text{BLR}}$ and the monochromatic AGN continuum luminosity at 5100\AA (eg. $R_{\text{BLR}} \propto \lambda L_{\lambda 5100}^{0.7}$; Kaspi et al.
By exploiting this correlation to estimate $R_{\text{BLR}}$ it is possible to produce a virial black-hole mass estimate from a single spectrum covering the Hβ emission line.

This technique has recently been widely employed to investigate how the masses of quasar black holes relate to the properties of the surrounding host galaxies (e.g., McLure & Dunlop 2002; Laor 2001) and the radio luminosity of the central engine (Dunlop et al. 2002; Lacy et al. 2001). However, because of the atmospheric restrictions and relative observational expense of near-infrared spectroscopy, the vast majority of previous studies have relied on optical spectroscopy of the Hβ region. Unfortunately, this effectively enforces a redshift upper limit of $z \approx 0.8 - 0.9$, with the vast majority of studies concentrating on samples at $z \leq 0.3$.

An ideal solution to this problem would be to calibrate a rest-frame UV emission line and continuum measurement such that it becomes possible to produce a virial black-hole mass estimate for high-redshift quasars from relatively straightforward optical spectroscopy. It is the purpose of this paper to provide the required UV calibration. There are two strong, permitted, broad UV lines which are candidates to replace Hβ in the virial black-hole mass estimate: Cτ(1549Å) and Mg ii(2798Å). We note here that in a recent pre-print Vestergaard (2002) derive a UV viral black-hole mass estimator using the Cτ FWHM and the continuum luminosity at 1350Å. Although Cτ does have the advantage of being accessible with optical spectroscopy at the very highest redshifts ($3 < z < 5$), where Mg ii is redshifted into the near-infrared, there are a number of reasons to believe that Mg ii represents a better substitute for Hβ over the redshift range $0.8 < z < 2.5$.

The main reason for adopting Mg ii as the UV tracer of BLR velocity is that, like Hβ, Mg ii is a low-ionization line. Furthermore, due to the similarity of their ionization potentials, we can be confident that the Mg ii and Hβ emission lines are being produced by gas at virtually the same radius from the central ionizing source. This has two important consequences. Firstly, it allows us to directly adopt the reverberation mapping determinations of $R_{\text{BLR}}$ when calibrating the correlation between $R_{\text{BLR}}$ and $3000\text{Å}$ continuum luminosity. Secondly, because the line-widths of Mg ii and Hβ should trace the same BLR velocities, we are able to simply substitute the FWHM of Mg ii for that of Hβ in the virial mass estimator.

There is one further practical advantage which favours Mg ii over Cτ as the UV substitute for Hβ. Due to the fact that Mg ii becomes accessible to optical spectroscopy at $z \sim 0.3$, both Hβ and Mg ii can be observed in a single optical spectrum within the redshift interval $0.3 \leq z \leq 0.9$. Consequently, it is therefore possible to directly compare the results of the new UV viral mass estimator against those of the established optical viral mass estimator for objects at intermediate redshifts. This test is performed in Section 7 using data for the Large Bright Quasar Survey (Forster et al. 2001) and the radio-selected Molonglo quasar sample (Baker et al. 1999).

The structure of this paper can be summarized as follows. In Section 2 we briefly review the main aspects of the virial black-hole mass estimate, before proceeding in Section 3 to describe the properties of the sample of low-redshift AGN with reverberation mapping results. In Sections 4 and 5 this sample is used to calibrate the relation between broad-line radius and $3000\text{Å}$ continuum luminosity ($R_{\text{BLR}} - \lambda L_{\text{3000}}$) and too demonstrate the viability of adopting Mg ii as a direct substitute for Hβ in the virial black-hole mass estimator. Our final calibration of the UV black-hole mass estimator is presented in Section 6. In Section 7 the effectiveness of the new UV black-hole mass estimator is demonstrated by application to members of the Large Bright Quasar Survey (LBQS) and the Molonglo quasar sample (MQS) for which both Hβ and Mg ii FWHM measurements are available. Our conclusions are presented in Section 8. All cosmological calculations presented in this paper assume $\Omega_m = 0.3$, $\Lambda = 0.7$, $H_0 = 70 \text{ km s}^{-1}\text{Mpc}^{-1}$.

## 2 THE VIRIAL BLACK-HOLE MASS ESTIMATE

The underlying assumption behind the method of estimating AGN black-hole masses from the width of their broad emission lines is that the motion of the line-emitting material is virialized. Under this assumption the width of the broad lines can be used to trace the keplerian velocity of the broad-line gas, and thereby allow an estimate of the central black-hole mass via the formula:

$$M_{\text{bh}} = G^{-1} R_{\text{BLR}} V_{\text{BLR}}^2$$

where $R_{\text{BLR}}$ is the BLR radius and $V_{\text{BLR}}$ is the keplerian velocity of the BLR gas. Recent evidence to support the keplerian interpretation of AGN broad-line widths has been presented by Peterson & Wandel (2000) and Onken & Peterson (2002). These authors demonstrate, at least for several Seyfert galaxies which have been well studied for reverberation mapping purposes, that the FWHM of various emission lines follow the $V_{\text{BLR}} \propto R_{\text{BLR}}^{0.5}$ relation expected for keplerian motion. It is important to note that it is not clear that the virial condition is satisfied for the Cτ emission line.

Substantial evidence exists in the literature that Cτ may be produced in some form of outflow, as is suggested by the systematic blue-shift of Cτ compared to Hβ (eg. Marziani et al. 1996).

### 2.1 Broad-line region geometry

In Eqn 1 the velocity of the BLR gas is taken as $V_{\text{BLR}} = f \times H\beta(\text{FWHM})$, where $f$ is a geometric factor which relates the $H\beta$ FWHM to the intrinsic keplerian velocity. Due to the fact that there is currently no consensus on the geometry of the BLR in radio-quiet quasars it is conventional to set $f = \sqrt{3}/2$. However, it is clear that if AGN broad lines are in general produced in a more disc-like configuration, evidence for which has been found in radio-loud quasars by numerous authors (eg. Wills & Browne 1986; Brotherton 1996; Vestergaard, Wilkes & Barthel 2000), then $f$ will be inclination dependent. Indeed, in McLure & Dunlop (2002) evidence was presented that the $H\beta$ FWHM is inclination dependent in radio-quiet quasars, and more consistent with the orbits of the $H\beta$ emitting material having a flattened disc-like geometry than being randomly orientated. However, even in the scenario where the FWHM of $H\beta$ and Mg ii are entirely orientation dependent, it will only have a significant effect on the virial black-hole mass estimate for those objects within $\sim 15^\circ$ of the line of sight. If
quasars are taken to be distributed randomly within \( \sim 45^\circ \) of the line of sight (Barthel 1989) then this will only affect some 10% of objects. Consequently, for the purposes of providing a generally applicable UV black-hole mass estimator we adopt \( f = 1 \) throughout this paper.

3 THE REVERBERATION MAPPED SAMPLE

As mentioned previously, the sample of 17 Seyferts and 17 PG quasars with reverberation mapping measurements (hereafter the RM sample) currently represents the best available set of black-hole mass estimates of powerful broad-line AGN. Therefore, it is the objects from this sample which we will use to calibrate the new UV virial black-hole mass estimator. Optical and UV data for the combined 34-object RM sample are listed in Table 1. The \( R_{BLR} \) data are taken from Kaspi et al. (2000), with the exception of NGC 4051 for which we take the updated figure of \( R_{BLR} = 5.9 \) light-days from Peterson et al. (2000).

3.1 Optical data

The 5100Å luminosities for the PG quasars have been calculated using the fluxes from the spectrophotometric study of Neugebauer et al. (1987). For the Seyfert galaxies the 5100Å luminosities are from Kaspi et al. (2000) after conversion to our cosmology. The H\( \beta \) FWHM values for the PG quasars are taken from Boroson & Green (1992). The H\( \beta \) FWHM values for the Seyfert galaxies are drawn from a number of literature sources which are listed in the caption to Table 1.

3.2 UV data

As with the optical continuum luminosities, the 3000Å luminosities listed in Table 1 for the PG quasars are derived from Neugebauer et al. (1987). In contrast, the 3000Å luminosities for the Seyfert galaxies, together with 17/22 of the Mg\( \text{ii} \) FWHM values, are new measurements based on our fitting of spectra from the International Ultraviolet Explorer (IUE) final data archive. A full discussion of our line-fitting method will be presented in a follow-up paper (McLure et al. 2002, in prep). In brief, we fit the region spanning the Mg\( \text{ii} \) emission line (2300Å\( \rightarrow \) 3100Å) with a combination of a power-law continuum, a Fe\( \text{ii} \) emission template based on I Zw 1 and two gaussians representing the broad and narrow components of the Mg\( \text{ii} \) emission line. The Mg\( \text{ii} \) FWHM figures for the remaining 5 objects are taken from Corbin & Boroson (1996).

4 ESTIMATING THE BLR RADIUS

In order to provide an estimate of \( R_{BLR} \) it is necessary, in the absence of reverberation mapping, to exploit the known correlation between \( R_{BLR} \) and AGN continuum luminosity. By combining the results of their reverberation mapping observations with those of Wandel, Peterson & Malkan (1999), Kaspi et al. (2000) investigated the correlation between \( R_{BLR} \) and 5100Å continuum luminosity and found a best-fit of the form \( R_{BLR} \propto \lambda L_{5100}^{0.70\pm 0.03} \). In their re-analysis of the same correlation, Peterson et al. (2000) found a best-fitting relation of the form \( R_{BLR} \propto \lambda L_{5100}^{0.62\pm 0.02} \). As well as being important within the context of the virial black-hole mass estimate, the slope of the \( R_{BLR} - \lambda L_{\lambda} \) relation is of intrinsic interest because it provides information about the AGN ionization parameter \( U \) (\( U = \frac{Q}{4\pi c r_c^3} \), where \( Q = \int \frac{\lambda d\lambda}{A(\lambda)} \)). For example, neither of the two fits mentioned above are consistent with the relation \( R_{BLR} \propto \lambda L_{\lambda}^{0.5} \) expected if the ionization parameter is approximately the same for all AGN, regardless of luminosity. In this section we investigate the correlation between \( R_{BLR} \) and continuum luminosity at both 5100Å and 3000Å, before proceeding to combine both continuum measurements to provide an improved estimate of the slope of the \( R_{BLR} - \lambda L_{\lambda} \) relation.

4.1 Regression analysis

Given the potential influence of the \( R_{BLR} - \lambda L_{\lambda} \) relation upon the accuracy of the virial black-hole mass estimator, we have chosen to employ three different regression techniques in our analysis to explore the possible variation in the best-fitting slope. The first technique is a straightforward weighted least-squares fit (WLS), in which the fit is weighted by the error in the reverberation mapping radius (Press et al. 1992). The second technique is a robust iterative chi-square fit (FITxy) in which the errors in both variables are taken into account (Press et al. 1992). However, although FITxy takes into account the errors on both variables, it does not account for the fact that there is likely to be intrinsic scatter in the \( R_{BLR} - \lambda L_{\lambda} \) relation. To account for this, the third technique we have employed is the BCES estimator of Akritas & Bershady (1996) which accounts for errors in both variables and intrinsic scatter.

4.2 The radius-luminosity relation at 5100Å and 3000Å

The results of the fitting process (in log – log space) of both the \( R_{BLR} - \lambda L_{5100} \) and \( R_{BLR} - \lambda L_{3000} \) relations are listed in Table 2, where it has been assumed for both the WLS and BCES fits that the BLR is a function of the continuum luminosity.

It can be seen from Table 2 that the results of all three regression methods are consistent with each other for both the \( R_{BLR} - \lambda L_{5100} \) and \( R_{BLR} - \lambda L_{3000} \) relations. Furthermore, it is clear from these results that, irrespective of the regression method, with the continuum luminosities adopted here the \( R_{BLR} - \lambda L_{\lambda} \) relation is not consistent with the \( \lambda L_{\lambda}^{0.7} \) relation found by Kaspi et al. (2000) at 5100Å or 3000Å. Indeed, it is clear from Table 2 that all of the regression fits are more consistent with a relation of the form \( R_{BLR} \propto \lambda L_{\lambda}^{0.5} \).

4.3 A combined fit

Due to the consistency between the fits at 5100Å and 3000Å it is possible to exploit both continuum measurements to further constrain the form of the \( R_{BLR} - \lambda L_{\lambda} \) relation. In this process we make the usual assumption that the \( R_{BLR} \) is physically related to the strength of the intrinsic AGN ionizing continuum. Furthermore, we make the assumption that the continuum luminosity measurements at 5100Å and
Table 1. Data for the reverberation mapped sample. Columns 1 and 2 detail the name and redshift of each object. Columns 3 and 4 list the monochromatic luminosities at 3000˚A and 5100˚A respectively. The 3000˚A and 5100˚A luminosities for the PG quasars are derived from the spectrophotometric study of Neugebauer et al. (1987). For the Seyfert galaxies the 3000˚A luminosities are derived from new fits to IUE archive spectra, while the 5100˚A luminosities are taken from Kaspi et al. (2000) after conversion to our cosmology. Column 5 lists the BLR radius measurements from Kaspi et al. (2000), except for NGC 4051 which is taken from Peterson et al. (2000). Columns 6 & 7 detail the FWHM of the Mg\textsc{ii} and H\textsc{\textbeta} emission lines respectively. The references for the FWHM measurements are as follows : 1. Boroson & Green (1992), 2. This work, 3. Peterson, Wandel & Malkan (1999), 4. Marziani et al. (1996), 5. Corbin & Boroson (1996) and 6. Zheng et al. (1995)

3000˚A are directly proportional to the intrinsic ionizing continuum, albeit with different proportionality constants. Under these two assumptions, the slope (in log – log space) of the $R_{BLR} - \lambda L_\lambda$ relation should be identical at 5100˚A and 3000˚A.

Consequently, we performed a simultaneous WLS fit to the $R_{BLR} - \lambda L_{5100}$ and $R_{BLR} - \lambda L_{3000}$ relations with the restriction that the slope of the relation was required to be the same at both wavelengths. Under this restriction the best combined fit is equivalent to $R_{BLR} \propto \lambda L_{\lambda}^{0.50 \pm 0.02}$, in agreement with the expected relation for a constant ionization parameter. The $R_{BLR} - \lambda L_\lambda$ relation for all 34 objects from the RM sample is shown in Fig 1 for both 5100˚A and 3000˚A. Also shown in Fig 1 are the two best-fitting relations with a slope of $0.5 \pm 0.02$ (solid lines), and the individual BCES fits to the two relations separately (dotted lines). It can be seen that the combined fit provides an excellent description of both relations and, as expected from the results shown in Table 2, is not significantly different to the individual fits at 5100˚A and 3000˚A. It is interesting to note that the scatter around the $R_{BLR} - \lambda L_{3000}$ relation is lower (0.3 dex) than that around the $R_{BLR} - \lambda L_{5100}$ relation (0.4 dex). It is possible that this is due to the 3000˚A luminosity representing a more direct indicator of the intrinsic ionizing continuum than the 5100˚A luminosity. The linear versions of the two best-fitting relations are as follows:

$$R_{BLR} = (26.1 \pm 3.6) \left[ \lambda L_{3000} / 10^{37} \text{W} \right]^{0.50 \pm 0.02}$$ (2)
to this work, Vestergaard chose to continue to adopt the
Table 2. Results of the regression analysis of the correlation be-
Figure 1. The correlation between broad-line radius and AGN continuum luminosity at 3000Å and 5100Å. The 17 PG quasars are
shown as filled squares and the 17 Seyfert galaxies are shown as filled circles. The best-fitting relations resulting from a simultaneous fit to both correlations are shown as a solid line in both panels and correspond to $R_{BLR} \propto \lambda L_{\lambda}^{0.5}$ (see text for a discussion). Also shown are the BCES bisector fits (dotted lines) to both correlations individually (see Table 2).

<table>
<thead>
<tr>
<th>Method</th>
<th>$\lambda$</th>
<th>$b$</th>
<th>$a$</th>
</tr>
</thead>
<tbody>
<tr>
<td>WLS</td>
<td>5100Å</td>
<td>0.53 ± 0.02</td>
<td>-18.05 ± 0.74</td>
</tr>
<tr>
<td>FITXY</td>
<td>5100Å</td>
<td>0.56 ± 0.02</td>
<td>-19.19 ± 0.86</td>
</tr>
<tr>
<td>BCES(Y/X)</td>
<td>5100Å</td>
<td>0.58 ± 0.09</td>
<td>-19.90 ± 3.39</td>
</tr>
<tr>
<td>WLS</td>
<td>3000Å</td>
<td>0.48 ± 0.02</td>
<td>-16.20 ± 0.66</td>
</tr>
<tr>
<td>FITXY</td>
<td>3000Å</td>
<td>0.50 ± 0.02</td>
<td>-17.05 ± 0.76</td>
</tr>
<tr>
<td>BCES(Y/X)</td>
<td>3000Å</td>
<td>0.45 ± 0.04</td>
<td>-15.30 ± 1.58</td>
</tr>
</tbody>
</table>

Table 2. Results of the regression analysis of the correlation between BLR radius and the AGN continuum luminosity at 5100Å and 3000Å. The fits were performed in log–log space and are of the form: $\log R_{BLR} = b \log(\lambda L_{\lambda}) + a$. The three different regression methods are discussed in the text.

$$R_{BLR} = (35.5 \pm 4.9) \left[ \lambda L_{5100}/10^{47} \right]^{(0.50 \pm 0.02)}$$

where $R_{BLR}$ is in units of light-days. These fits are adopted as our best estimates of the $R_{BLR} - \lambda L_{\lambda}$ relation throughout the remainder of this paper. We note here that Vestergaard (2002) also find the slope of the optical $R_{BLR} - \lambda L_{5100}$ relation to be consistent with 0.5. However, in contrast to this work, Vestergaard chose to continue to adopt the $R_{BLR} \propto \lambda L_{\lambda}^{0.7}$ form of Kaspi et al. (2000).

5 ESTIMATING THE BROAD-LINE VELOCITY

After successfully calibrating the $R_{BLR} - \lambda L_{3000}$ relation, the second required element of the UV black-hole mass estimator is to calibrate the Mg II FWHM as a substitute for Hβ. As discussed in Section 1, the principle reason for adopting Mg II as the UV Hβ proxy is that it is a strong, fully-permitted, low-ionization line, and as such should provide the best UV analog of Hβ. Moreover, because the ionization potentials of Hβ and Mg II are very similar, the two lines should both be emitted at approximately the same radius from the central ionizing source. Fortunately, this assumption can be tested directly using the 22 objects from the RM sample for which we have Mg II FWHM measurements. If Mg II and Hβ are being produced at the same broad-line radius then, if the BLR is virialized, we should see a 1:1 relation between Mg II FWHM and Hβ FWHM. Fig 2 shows Mg II FWHM versus Hβ FWHM for the 22 objects from the RM sample with Mg II FWHM measurements. The solid line in Fig 2 shows an exact 1:1 relation between Mg II and Hβ FWHM. It can be seen that, with the exception of NGC 4051, the objects in the RM sample are perfectly consistent with Mg II and Hβ tracing the same BLR velocity. The clear outlier, NGC 4051, is a well studied example of a narrow-line Seyfert 1 (NLS1). The Hβ FWHM for this object has been determined by numerous authors and is consistently found to be around 1000 kms$^{-1}$ (eg. Wandel, Peterson & Malkan (1999) find Hβ FWHM=1170 kms$^{-1}$). However, from our line-fitting of IUE archive spectra we find a strong broad component to the Mg II emission line with FWHM=2790 kms$^{-1}$.

In fact, several previous studies have found that the UV emission lines of NLS1 possess strong broad components which are not seen in their Balmer lines (eg. Rodríguez-Pascual, Mas-Hesse & Santos-Lleó 1997, Zheng et al. 1995). This suggests that Mg II may actually provide a better estimate of the BLR velocity of low-ionization gas in NLS1, where the Balmer lines could be biased, at least in part, by inclination effects. Irrespective of the reason why NGC 4051 is an outlier in Fig 2, we can safely exclude it from a regression fit to the Mg II - Hβ FWHM relation. The reason for this is that we are principally interested in providing a UV black-hole mass estimator for high redshift quasars, the vast majority of which have Hβ FWHM > 2000 kms$^{-1}$. The dotted line in Fig 2 shows the BCES bisector fit which is equivalent to a relation of the form:

$$H\beta(\text{FWHM}) \propto Mg II(\text{FWHM})^{1.02 \pm 0.14}$$
6.1 Accuracy of the UV estimator

Having arrived at the final calibration of the UV black-hole mass estimator it is of obvious interest to access the accuracy with which it can reproduce the full reverberation mass estimate. Excluding Mrk 335, the mean difference between the reverberation mass and the UV estimator is:

\[
< \log(M_{bh}(RM)) - \log(M_{bh}(UV)) > = 0.00 \pm 0.40
\]

where the quoted uncertainty is the standard deviation (σ) and not the standard error. Therefore, provided the RM sample is representative of broad-line AGN in general, we conclude that the UV black-hole estimator provided by Eqn 7 can reproduce the reverberation black-hole mass to within a factor of 2.5 (1σ). For the same sample the uncertainty on the optical estimator given in Eqn 8 is also a factor of 2.5.

7 APPLICATION TO QUASAR SURVEYS: THE LBQS AND MQS

Having derived the desired black-hole mass estimator in the previous section, we next access its performance when applied to the spectra of the LBQS and the radio-selected MQS. If the new UV black-hole mass estimator is to be used in the analysis of high-redshift quasars, it is clearly important to ensure that it does not produce results which are biased with respect to the usual optical (Hβ) estimator. Therefore, our intention in this section is to simply test how the new UV mass estimator (Eqn 7) compares to the usual optical mass estimator (Eqn 8) when applied to those objects from the LBQS and MQS for which both the appropriate UV (λL3000, MgII FWHM) and optical (λL5100, Hβ FWHM) data are available.

Due to the fact that the LBQS is optically selected, while the MQS is a complete radio-selected quasar sample, applying the UV black-hole mass estimator to both samples allows us to ensure that Eqn 7 is equally applicable to both radio-quiet and radio-loud quasars.
7.1 The Large Bright Quasar Survey

The LBQS consists of 1058 optically-selected quasars in the redshift range 0.2 < z < 3.3 (see Hewett, Foltz & Chaffee (1995) for a full description). A comprehensive study of the optical continuum and emission line properties of 992 quasars from the LBQS has recently been published by Forster et al. (2001). In this section we use data from Forster et al. for a 99-object sub-sample with reliable measurements of both MgII and Hβ FWHM and continuum fluxes at 3000Å and 5100Å. This sub-sample comprises 68% of the 145 LBQS objects in the redshift range 0.20 < z < 0.66 within which both MgII and Hβ fall on the LBQS spectra.

7.2 The Molonglo quasar sample

The Molonglo quasar sample is a complete, radio-selected, sample consisting of 111 quasars in the redshift range 0.1 < z < 2.9 with a 408 MHz flux density greater than 0.95 Jy (Kapahi et al. 1998). Optical spectra for 79 MQS quasars were published by Baker et al. (1999), together with a preliminary analysis of their emission line properties. We are currently engaged in an automated study of the optical and UV emission lines from the MQS optical spectra (kindly provided by J. Baker), from which it has been possible to reliably measure the MgII and Hβ FWHM for 29/38 objects where the MQS spectra include both emission lines. Unlike the LBQS, Baker (1997) has shown that many MQS objects display substantial reddening in their optical spectra. As a result, the continuum luminosities of the reddest MQS objects were de-reddened using the SMC extinction curve of Pei (1992), assuming an intrinsic continuum slope of $\alpha = 0.5$ ($f_{\nu} \propto \nu^{-\alpha}$) which was found by Baker (1997) to be typical of the least reddened MQS objects.

7.3 Optical versus UV black-hole mass estimators

In Fig 4 we show the optical black-hole mass estimator plotted against the new UV black-hole mass estimator for a combined sample of 150 objects, comprising 99 from the LBQS, 29 from the MQS and the 22 objects of the RM sample. The dotted line in Fig 4 is an exact 1:1 relation, which can be seen to be an excellent representation of the data. The solid line is the BCES bisector fit which has the form:

$$\log M_{bh}(H\beta) = 0.95(\pm 0.06) \log M_{bh}(MgII) + 0.37(\pm 0.47)$$  \hspace{1cm} (10)

which, as expected, is entirely consistent with a linear relation. In Fig 5 we show a histogram of log $M_{bh}(MgII) - \log M_{bh}(H\beta)$ for the 128 objects from the LBQS and MQS. The solid line shows the best-fitting gaussian which has $\sigma = 0.41$. These results, in combination with those of Section 6, lead us to conclude that compared to the traditional optical black-hole mass estimator, the new UV estimator provides results which are unbiased and of equal accuracy.

7.4 Black-hole mass and the radio-loudness dichotomy

Although a full analysis of the black-hole masses of the LBQS and MQS samples is beyond the scope of this paper, we will briefly comment here on one obvious feature of Fig 4. It is immediately apparent from Fig 4 that the black-hole masses of the MQS are exclusively $\geq 10^{8.5} M_{\odot}$, adopting either the UV or optical mass estimator. In contrast, only 16% of the 99 LBQS quasars have UV and optical black-hole masses estimates which are both $\geq 10^{8.5} M_{\odot}$. Naively this would appear to suggest that there is a clear division in black-hole mass between the radio-selected MQS and the largely radio-quiet LBQS. However, because the wavelength...
The origin of the additional factor of three difference in the black-hole mass distributions is a highly significant difference in the distributions of Hβ and Mγ FWHM. For example, the average Mγ FWHM of the MQS sub-sample is a factor of 1.56 ± 0.11 greater than the average Mγ FWHM of the LBQS sub-sample. The equivalent factor for Hβ FWHM is 1.68 ± 0.14. The application of a Kolmogorov-Smirnov test returns a probability of $p = 1.33 \times 10^{-6}$ that the two Hβ FWHM distributions are drawn from the same parent distribution ($p = 4.1 \times 10^{-9}$ for the Mγ FWHM distributions).

It is important to note that the differences in the FWHM distributions of the two samples do not appear to be related to the previously mentioned redshift/luminosity bias. An application of the partial spearman rank correlation test (Macklin 1982) reveals no significant correlations between Hβ FWHM, redshift and $\lambda L_{5100}$ or Mγ FWHM, redshift and $\lambda L_{3000}$. In fact, these results are in good agreement with previous studies of the black-hole masses of radio-quiet and radio-loud quasars which were not subject to a redshift/luminosity bias. In their study of a sample of radio-loud and radio-quiet quasars with a matched redshift-luminosity distribution at $z \lesssim 0.5$, McLure & Dunlop (2002) found the average black-hole mass of the radio-loud quasars to be a factor of $\sim 2$ larger than their radio-quiet counterparts, albeit with a large overlap. Likewise, Laor (2000) found a clean separation in black-hole mass within the PG quasar sample, with the radio-loud quasars being confined to $M_{bh} \gtrsim 10^8 M_\odot$. In contrast, from their study of the First Bright Quasar Survey (FBQS) Lacy et al. (2001) concluded that the apparent gap in the quasar black-hole mass – radio-power plane is in fact filled by previously undetected radio-intermediate quasars.

In either case, it is clear that genuinely powerful, low-frequency selected, radio-loud quasars harbour central black-hole masses drawn from the extreme end of the AGN black-hole mass function. At present it is not clear whether the low frequency of radio-quiet quasars with $M_{bh} > 10^9 M_\odot$ is real or, alternatively, is due to an inclination selection effect whereby the line-widths of optically selected quasars are biased to low values by a preference for selecting objects close to the line of sight. A more detailed analysis of the black-hole masses of high redshift radio-loud and radio-quiet quasars, the correlation between black-hole mass and radio power and the evidence for the role of inclination effects will be presented in a series of forthcoming papers (McLure et al. 2002, in prep).

Finally, we note that our finding that the FWHM of Hβ and Mγ in the powerful radio-selected MQS objects are exclusively restricted to $\gtrsim 4000$ kms$^{-1}$ is of interest in the context of recent work on the location of radio-loud and radio-quiet AGN in so-called eigenvector 1 space (Marziani et al. 2001). In their study Marziani et al. concluded that powerful radio-loud quasars appear to be restricted to Hβ FWHM $> 4000$ kms$^{-1}$, in excellent agreement with our analysis of the MQS spectra.

8 CONCLUSIONS

A new technique for estimating the central black-hole masses of high-redshift quasars using the Mγ FWHM and 3000Å quasar continuum luminosity has been presented. The new technique has been calibrated using a sample of 34 low redshift AGN with black-hole mass measurements based on long-term reverberation mapping experiments. The reliability of the new technique, with respect to the established optical virial black-hole mass estimator, has been tested using published data for the LBQS together with the results of a new analysis of the emission line properties of the MQS. The main conclusions of this study can be summarized as follows:

- The correlation between $R_{BLR}$ and monochromatic 3000Å continuum luminosity is found to display less scatter than that between $R_{BLR}$ and 5100Å monochromatic continuum luminosity.
The correlation between $R_{BLR}$ and both continuum luminosity measurements is consistent with a relation of the form $R_{BLR} \propto \lambda L_{\lambda}^{0.5}$, as expected for a constant ionization parameter in all AGN, irrespective of luminosity.

The FWHM of Mg$\text{\textsc{ii}}$ is found to be an effective substitute for the FWHM of H$\beta$. The relationship between the two FWHM is found to be perfectly consistent with an exact 1:1 scaling.

Combining the $R_{BLR} - \lambda L_{\lambda}^{0.5}$ relation with the FWHM of Mg$\text{\textsc{ii}}$ produces a virial black-hole mass estimator based on rest-frame UV observables which is capable of reproducing black-hole masses determined from reverberation mapping to within a factor of 2.5 ($1\sigma$).

An application to objects from the LBQS and MQS demonstrates that the new UV black-hole mass estimator produces results which are unbiased, and of equal accuracy to the established optical (H$\beta$) black-hole mass estimator.

We therefore conclude that the new UV black-hole mass estimator is ideal for determining quasar black-hole masses in the redshift range $0.25 < z < 2.5$ via optical spectroscopy alone.

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