THE EFFECT OF VARIABILITY ON THE ESTIMATION OF QUASAR BLACK HOLE MASSES

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ABSTRACT

We investigate the time-dependent variations of ultraviolet (UV) black hole mass estimates of quasars in the Sloan Digital Sky Survey (SDSS). From SDSS spectra of 615 high-redshift (1.69 < z < 4.75) quasars with spectra from two epochs, we estimate black hole masses using a single-epoch technique, which employs an additional, automated night-sky line removal and relies on UV continuum luminosity and C iv \( \lambda 1549 \) emission-line dispersion. Mass estimates show variations between epochs at about the 30% level for the sample as a whole. We determine that for our full sample, measurement error in the line dispersion likely plays a larger role than the inherent variability in terms of contributing to variations in mass estimates between epochs. However, we use the variations in quasars with r-band spectral signal-to-noise ratio greater than 15 to estimate that the contribution to these variations from inherent variability is roughly 20%. We conclude that these differences in black hole mass estimates between epochs indicate that variability does not make a large contribution to the current factor of 2 scatter between mass estimates derived from low- and high-ionization emission lines.

Subject headings: galaxies: active — quasars: general — techniques: spectroscopic

Online material: machine-readable table

1. INTRODUCTION

In active galactic nuclei (AGNs) and quasars, it is now generally accepted that low-ionization broad emission lines, such as H\( \beta \), the line width is mostly controlled by gravity and thus closely related to the mass of the quasar central black hole (Osterbrock & Shuder 1982; Peterson & Wandel 1999, 2000; Onken & Peterson 2002; Kollatschny 2003). However, there is some debate as to the physical processes responsible for producing the observed profile of higher ionization lines, such as C iv \( \lambda 1549 \). The C iv line has been observed to be both blueshifted (see, e.g., Wilkes 1984; Richards et al. 2002a) and asymmetric (Wilkes 1984; Vanden Berk et al. 2001), hinting that physical processes other than gravity may be at least partially responsible for the C iv profile. Recently, Baskin & Laor (2005) demonstrated that, due to these differences in line profile, black hole mass estimates involving C iv line width may be less accurate than previously believed or even biased, perhaps with systematic over- or underestimates of mass by a factor of a few.

If one does assume that the width of a given quasar broad emission line can be related to the velocity of gas in orbit around the central black hole, a black hole mass can be computed via the virial equation

\[
M_{\text{BH}} = f \frac{R_{\text{BH}} \Delta v^2}{G},
\]

where \( f \) is a scale factor of order unity that depends on the geometry of the broad-line region (BLR), \( R \) is the distance from the black hole to the specific portion of the BLR that contains the emitting gas in question (a distance that likely differs for each species), and \( \Delta v \) is the velocity width of the broad emission line itself. While line width is easily determined from a single-epoch spectrum, determining the BLR size is less straightforward. Reverberation mapping techniques have proven very successful in estimating BLR sizes and, by extension, in determining the masses of the black holes at the centers of a few dozen AGNs (e.g., Wandel et al. 1999; Peterson et al. 2004). These radii are found by measuring the response time of variations in emission-line flux to changes in continuum flux. Although simple in principle, measuring these response times requires constant spectral monitoring and is observationally taxing. However, Wandel et al. (1999), Kaspi et al. (2000), and later Kaspi et al. (2005) demonstrated that a simple scaling relationship exists between BLR size and continuum luminosity (\( R \propto L^0.7 \)). Kaspi et al. (2005) determined that the size of the H\( \beta \) BLR scales with both optical and UV continuum, allowing for the use of continuum luminosity in both of these wavelength ranges as a proxy for BLR size and paving the way for reliable, single-epoch black hole mass estimates.

Single-epoch estimates have been calibrated using the H\( \beta \) (Wandel et al. 1999) and Mg \( \text{II} \) \( \lambda 2798 \) (McLure & Jarvis 2002) emission lines. Vestergaard (2002) developed a method of estimating black hole masses derived from C iv FWHM and \( \Delta L_j \) (1350 Å) (abbreviated \( L_{1350} \)), calibrated by the corresponding reverberation-mapping masses, using the scaling relationship determined by Kaspi et al. (2000), namely, \( R_{\text{CIV}} \propto L_{1350}^{0.7} \).

More recently, Peterson et al. (2004) reanalyzed a large amount of reverberation-mapping data, removing lower quality data and reestablishing the scaling relationships used for the calibration of single-epoch mass estimates. Subsequently, Kaspi et al. (2005) used these revised relationships to update the BLR size—continuum luminosity relationships, and Bentz et al. (2006) made additional corrections after correcting for luminosity contributions from host galaxies’ starlight. These developments led to a recalibration of UV black hole masses in Vestergaard & Peterson (2006), who used an empirically determined radius-luminosity relationship more consistent with photoionization theory: \( R_{\text{CIV}} \propto L_{1350}^{0.53} \). Early results of a monitoring campaign to apply reverberation mapping to \( z \sim 3 \) quasars indicate that, over 7 orders of magnitude in luminosity, the C iv BLR size—UV luminosity relationship has a slope similar to that of the H\( \beta \) BLR size—UV luminosity relationship.
(Kaspi et al. 2007), confirming the assumptions made by Vestergaard & Peterson (2006).

In addition, Vestergaard & Peterson (2006) calibrated an estimate for black hole mass that relies on the dispersion of the C iv line ($\sigma_{\text{CIV}}$, the second moment about the mean) and the luminosity density at 1450 Å:

$$\log M_{\text{BH}}(\text{C IV}) = \log \left( \frac{\sigma_{\text{CIV}}}{1000 \text{ km s}^{-1}} \right)^2 \left( \frac{\lambda L_{\lambda}(1450 \, \text{Å})}{10^{44} \text{ ergs s}^{-1}} \right)^{0.53} + (6.73 \pm 0.01). \quad (2)$$

Based on comparisons with reverberation mapping masses, Vestergaard & Peterson (2006) state that these masses are likely good to within a factor of 3.

One potential problem in estimating black hole masses from single-epoch spectra is the inherent variability of quasars. This variability is key to reverberation-mapping techniques, but it necessarily injects uncertainties into single-epoch mass estimates. The optical and ultraviolet portions of quasar continua have long been known to vary in luminosity on the order of 10%–20% on timescales from weeks to years (e.g., Smith & Hoffleit 1963; Uomoto et al. 1976; Hook et al. 1994; Giveon et al. 1999; de Vries et al. 2003).

Vanden Berk et al. (2004), using a sample of $\sim 25,000$ quasars, confirmed known correlations and parameterized relationships between variability and rest-frame time lag, luminosity, rest-frame wavelength, and redshift. In addition, Wilhite et al. (2005, hereafter Paper I) completed the first study of the detailed dependence of variability on wavelength, demonstrating that the variability increased with decreasing wavelength, but only at wavelengths less than 2500 Å. Increased variability at shorter wavelengths, such as that seen in Paper I and earlier (e.g., Cutri et al. 1985; Collier et al. 2001; Vanden Berk et al. 2004), can impact black hole mass estimates that rely on rest-frame UV luminosity.

In addition, the fluxes and profiles of quasar emission lines are known to vary with time (e.g., Peterson 1993; Wanders & Peterson 1996; Wandel et al. 1999; Sergeev et al. 2001), mostly in response to fluctuations in continuum luminosity. C iv has been closely monitored in a relatively small number of low-redshift, low-luminosity objects such as NGC 5548 (Clavel et al. 1991; Korista et al. 1995) and NGC 4151 (Crenshaw et al. 1996), as well as in a few high-redshift quasars (Kaspi et al. 2007). Recently, Wilhite et al. (2006, hereafter Paper II) studied C iv variability in an ensemble of $\sim 100$ SDSS quasars with multiple-epoch spectroscopy, finding that the width of an individual C iv line increases with line flux and varies by as much as 30% on rest-frame timescales of weeks to months. Paper I focused on the variability of the quasar continuum, while Paper II centered on variability of the C iv line. Given the interest in black hole mass estimates, we feel there is a definite need to reexamine UV variability in the context of mass estimators and to attempt to quantify the effect (or lack thereof) of variability on determining black hole masses.

We briefly describe the quasar sample and the additional, necessary spectrophotometric calibrations in § 2. We describe the process used to estimate black hole masses, including the continuum- and line-fitting techniques used, in § 3. The epoch-to-epoch black hole mass estimate differences are examined in § 4. The results are discussed in § 5, and we conclude in § 6.

As we are interested in variations in spectrophotometric mass-estimation techniques, we focus here on those quasars that have multiple spectrophotometric observations. Through 2004 June, objects on 181 different plates had been observed at least twice, with time lags between observations ranging from days to years. Fifty-three of these plates (containing roughly 2200 quasars) have observations more than 50 days apart, indicating that spectra from these observations have not been co-added and are therefore appropriate for variability studies (see Paper I for a longer discussion of these data). Of these 53 plate pairs 52 are contained in the Fourth Data Release (DR4; Adelman-McCarthy et al. 2006).

2. THE QUASAR DATA SET

2.1. The Sloan Digital Sky Survey

The Sloan Digital Sky Survey (York et al. 2000), using a dedicated 2.5 m telescope (Gunn et al. 2006) at the Apache Point Observatory in the Sacramento Mountains of New Mexico, has, through summer 2005, acquired imaging and spectroscopic data for $\sim 8000$ deg$^2$, mostly centered on the northern Galactic cap. A 54-chip drift-scan camera (Gunn et al. 1998) acquires imaging data, which are reduced and calibrated by using the astrometric (Pier et al. 2003) and photometric (Lupton et al. 2001) software pipelines. The photometric system is normalized such that SDSS $u$, $g$, $r$, $i$, and $z$ magnitudes (Fukugita et al. 1996) are on the AB system (Smith et al. 2002). A 0.5 m telescope monitors site photometric quality and extinction (Hogg et al. 2001; Ivezić et al. 2004; Tucker et al. 2006).

After image processing, selected objects are targeted for spectroscopy (Strauss et al. 2002; Eisenstein et al. 2001; Richards et al. 2002b; Stoughton et al. 2002) and grouped in $3^\circ$ diameter tiles (Blanton et al. 2003). For each tile, an aluminum plate is drilled with 640 holes reserved for roughly 500 galaxies, 50 quasars and 50 stars (40 calibration spectra—32 sky fibers and 8 reddening standards—are also taken with each plate). Plates are placed in the imaging plane of the telescope and the holes plugged with optical fibers running from the telescope to twin spectrographs.

SDSS spectra are obtained in three or four consecutive 15 minute observations and cover the observer-frame optical and near infrared, from 3900 to 9100 Å. The Spectro1d pipelineFlat fields and flux-calibrates spectra, and Spectro1d identifies spectral features and classifies objects by spectral type (Stoughton et al. 2002). Extragalactic objects with broad emissions lines (FWHM $\geq 1000$ km s$^{-1}$) are defined to be quasars.

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2.2. Refinement of Spectrophotometric Calibration

It was demonstrated in both Vanden Berk et al. (2004) and Paper I that additional spectrophotometric calibration beyond the standard SDSS processing is required for variability studies. Paper I contains a complete discussion of those calibration methods; we briefly summarize the salient points here. The Spectro1d pipeline determines three signal-to-noise (S/N) ratios for each spectrum by calculating the median S/N per pixel in the sections of the spectrum corresponding to the SDSS $g_r$, $r_i$, and $i$-filter transmission curves. Hereafter, we use the phrase “high-S/N epoch” to refer to the observation with the higher median $r$-band signal-to-noise ratio and “low-S/N epoch” to refer to the observation with the lower median $r$-band signal-to-noise ratio. Although most objects follow the plate-wide trend, this does not address the relative S/N values for any given individual object,
nor does it correspond to an object’s relative line or continuum flux at a given epoch. The stars on a plate are used to resolve calibration differences between the high- and low-S/N epochs, under the assumption that the majority of stars are nonvariable (obviously variable stars are removed from this recalibration).

For each pair of observations, we create a recalibration spectrum, equal to the ratio of the median stellar high-S/N epoch flux at a given epoch. The stars on a plate are used to resolve calibration differences between the high- and low-S/N epochs, leaving 615 objects to comprise the main sample studied below. (As discussed in Fig. 5 of Paper I, leaving a smooth, relatively featureless curve as a function of wavelength. All low-S/N epoch spectra are rescaled by this “correction” spectrum.

In Papers I and II, we studied only those objects that had been shown to vary significantly between epochs. Here we measure C IV line width and estimate the central black hole mass for all objects in which the entire C IV line and the 1450 Å luminosity are observed. (As discussed in § 3.3, this corresponds to objects with 1.69 < z < 4.75.) Out of the main sample of 2210 quasars, 702 are at a redshift at which C IV measurements can be made in the SDSS spectra. Of these, 87 (13%) are noted in Lundgren et al. (2007) for showing evidence of broad absorption near the C IV emission line. Because of the difficulties broad absorption lines (BALs) can create in estimating the continuum flux and fitting the C IV emission line, these BAL quasars are removed, leaving 615 objects to comprise the main sample studied below.

Table 1 gives a summary of the observations used in this paper, including the names and redshifts of the quasars observed, as well as the Modified Julian Dates (MJDs) and signal-to-noise ratios of the individual observations.

The distributions of the r-band spectral signal-to-noise ratio at both epochs are shown as histograms in Figure 1. The mean (S/N), at the high-S/N epoch [(S/N)HSN] is 12.0, while the mean (S/N)LSN = 9.9.

Figure 2 shows (S/N)HSN versus (S/N)LSN. As mentioned above, “high-S/N” or “low-S/N” epoch is a plate-wide designation; thus a few individual objects actually have greater (S/N)LSN than (S/N)HSN. For the vast majority of objects, however, (S/N)HSN > (S/N)LSN. In addition, most objects have (S/N) < 12.0 at the two epochs such that they lie near the line (S/N)HSN = (S/N)LSN. Therefore, when examining the effects of spectral signal-to-noise ratio on variations in black hole mass estimates between epochs, we rely on (S/N)HSN.

2.3. Sample Spectra

Figure 3 shows observed-frame spectra at both epochs for three quasars from the sample to demonstrate how spectral r-band signal-to-noise ratio relates to overall spectral quality. These three

| Number | SDSS J          | HSN  | LSN  | MJD  | HSN  | LSN  | z   | S/Nr |
|--------|-----------------|------|------|------|------|------|-----|------|
| 1      | 100543.42-005559.9 | 51,910 | 51,581 | 1.712 ± 0.002 | 1.717 ± 0.002 | 8.4 | 7.0 |
| 2      | 100356.15-005940.4 | 51,910 | 51,581 | 2.108 ± 0.002 | 2.108 ± 0.001 | 16.9 | 15.3 |
| 3      | 100013.37-011203.2 | 51,910 | 51,581 | 1.801 ± 0.003 | 1.805 ± 0.001 | 12.3 | 11.4 |
| 4      | 100246.85+002104.0 | 51,910 | 51,581 | 2.172 ± 0.002 | 2.169 ± 0.002 | 19.4 | 17.5 |
| 5      | 100412.88+001257.5 | 51,910 | 51,581 | 2.240 ± 0.002 | 2.243 ± 0.002 | 11.1 | 9.5  |
| 6      | 100428.43+001325.6 | 51,910 | 51,581 | 3.045 ± 0.001 | 2.989 ± 0.004 | 16.3 | 11.2 |
| 7      | 100623.58+001825.6 | 51,910 | 51,581 | 1.919 ± 0.001 | 1.916 ± 0.001 | 9.3  | 7.6  |
| 8      | 100715.53+004258.3 | 51,910 | 51,581 | 3.045 ± 0.001 | 2.989 ± 0.004 | 16.3 | 11.2 |
| 9      | 111603.99-011412.1 | 51,984 | 51,608 | 1.960 ± 0.002 | 1.959 ± 0.002 | 12.9 | 9.5  |
| 10     | 111502.65-002344.0 | 51,984 | 51,608 | 1.960 ± 0.002 | 1.959 ± 0.002 | 12.9 | 9.5  |

**Notes.**—Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content. HSN and LSN indicate the high- and low-S/N ratio epochs, respectively.
quasars, SDSS J150104.94–010727.9 (quasar 149 in Table 1; (S/N)_{\text{HSN}} = 4.9), SDSS J101416.97+484816.1 (quasar 551; (S/N)_{\text{HSN}} = 12.1), and SDSS J030449.86–000813.4 (quasar 259; (S/N)_{\text{HSN}} = 30.8), were chosen to represent a range of (S/N)_{\text{HSN}} values. Only the region of the spectrum used in the estimation of black hole mass (corresponding to the rest-frame interval [1440, 1710 Å]; see §3) is shown.

3. CALCULATING BLACK HOLE MASS ESTIMATES

This paper uses the Vestergaard & Peterson (2006) UV black hole mass estimator, seen in equation (2), which requires measurements of these two quantities are described below.

3.1. Sky Subtraction

It was determined in Paper II that occasional errors in the SDSS night-sky removal pipeline could lead to errors in continuum and line fitting. In a small fraction (less than 5%) of objects, night-sky lines are significantly under- or oversubtracted. In Paper II, spectra were visually inspected for signs of poor night-sky subtraction. For this work, with more than 600 C iv emission lines to fit (and for future work with larger samples of SDSS quasars), night-sky subtraction has been automated. The night-sky lines for which the algorithm searches are O i \lambda 5577, Na i \lambda 5890, O i \lambda 6300, and the well-known atmospheric O 2 Fraunhofer A and B bands (covering the [7594, 7621 Å] and [6867, 6884 Å] intervals, respectively). If any of these known night-sky lines lie in the part of the spectrum corresponding to the rest-frame interval [1440, 1700 Å] (the interval used to measure continuum luminosity and line dispersion; see §§3.2–3.3), the algorithm tests to ensure that the pipeline night-sky subtraction was done properly. The average flux in a 10 Å region centered on the night-sky line position (37 and 27 Å regions are used for the wider A and B bands, respectively) is compared to the average flux of the 25 Å range on either side of the 10 Å region. If the night-sky region flux is more than 3 standard deviations larger or smaller than the average flux of the surrounding region, then the flux in the night-sky region is estimated using a linear interpolation based on the pixels in the surrounding continuum region. If the 25 Å range overlaps with the C iv emission line (corresponding to the rest-frame interval [1496, 1596 Å]), the region is truncated to include only known continuum flux. The flux density uncertainties in the individual pixels are not altered, however. This may lead to a slight overestimation of the errors in the given quantities, but it not likely to have a large effect.

3.2. 1450 Å Continuum Luminosity

After the night-sky subtraction errors have been corrected, the 1450 Å flux density, f_i(1450), is calculated by taking the mean of the flux density in the pixels corresponding to the rest-frame interval [1445, 1455 Å]. This value is translated to a luminosity density by calculating the luminosity distance analytically from the redshift, and then to luminosity by multiplying by wavelength: L_{1450} = 1450 Å \times L_i(1450). Figure 4 shows the distribution of 1450 Å luminosities, L_{1450} at both epochs. Values for L_{1450} range from 10 to roughly 500 \times 10^{44} ergs s^{-1}, with a median at the high-S/N epoch of 93.1 \times 10^{44} and 92.6 \times 10^{44} ergs s^{-1} at the low-S/N epoch.

The distribution of estimated uncertainties in L_{1450}, calculated through standard error propagation, with the standard deviation in flux in the [1445, 1455 Å] interval used as the uncertainty in
of interest by assigning a random number drawn from a Gaussian distribution with mean equal to the measured flux in that pixel and standard deviation equal to the measured error in that pixel. The continuum is fit and the line median and standard deviation calculated; this is done 1000 times per quasar. The standard deviation of the distribution of resulting values is assigned to be the error in that quantity. The uncertainties in the line width (as seen in Fig. 5) are for the most part less than 500 km s\(^{-1}\), with a median uncertainty of 159 km s\(^{-1}\) at the high-S/N epoch and 202 km s\(^{-1}\) at the low-S/N epoch—as with \(L_{1450}\), the uncertainties are roughly an order of magnitude lower than the values themselves.

### 3.4. Single-Epoch Mass Estimates

Once the continuum luminosity (\(L_{1450}\)) and emission-line dispersion (\(\sigma_{\text{C} v}\)) have been calculated, it is straightforward to estimate the quasar’s black hole mass from equation (2). This is done at both the high- and low-S/N epochs for all 615 objects in the main sample. The distributions of high- and low-S/N-epoch black hole masses are shown in Figure 6. The majority of objects are estimated to have high-S/N black hole masses, in the range from \(10^{8.5}\) to \(10^{9.5}\) \(M_\odot\). The median high- and low-S/N-epoch masses are \(10^{8.88}\) and \(10^{8.87}\) \(M_\odot\), respectively. The distributions

Fig. 4.—Left: 1450 Å luminosity (\(L_{1450}\)) at the high-S/N (dark histogram) and low-S/N (gray histogram) epochs. Right: Uncertainty in the 1450 Å luminosity at the high-S/N (dark histogram) and low-S/N (gray histogram) epochs.

Fig. 5.—Same as Fig. 4, but for \(C\) \(iv\) line dispersion (\(\sigma_{\text{C} v}\)).

Fig. 6.—Same as Fig. 4, but for the logarithm of the estimated black hole mass (\(M_{\text{BH}}\)). The logarithm of the uncertainty is calculated by propagating measurement errors in \(L_{1450}\) and \(\sigma_{\text{C} v}\).
of uncertainties in $M_{\text{BH}}$ (calculated by propagating measurement errors in $L_{1450}$ and $\sigma_{C\text{iv}}$) at each epoch are shown in Figure 6. The median uncertainty at the high-S/N epoch is $10^{7.37} \, M_\odot$; at the low-S/N epoch it is $10^{6.04} \, M_\odot$.

Figure 7 shows the fractional uncertainty in $L_{1450}$, $\sigma_{C\text{iv}}$, and $M_{\text{BH}}$ as a function of $(S/N)_r$ at the high-S/N epoch. (The low-S/N versions of these plots are very similar and therefore are not shown.) The uncertainty in the 1450 Å luminosity appears to dominate the $M_{\text{BH}}$ measurement error. It should also be noted that for virtually all quasars with a signal-to-noise ratio greater than 15, our estimate of the measurement uncertainty for $M_{\text{BH}}$ is less than 10%.

Table 2 contains the relevant quantities in the estimation of black hole mass at both epochs, including the masses themselves and the measured luminosities and line dispersions.

### 4. MEASURING THE CONSISTENCY OF ESTIMATES OF $M_{\text{BH}}$

#### 4.1. Variations in Luminosity and Line Dispersion

Figure 8 shows the high- versus low-S/N epoch values for $L_{1450}$, $\sigma_{C\text{iv}}$, and $M_{\text{BH}}$. The width of these distributions is due to a combination of the intrinsic variability of the quasars and the uncertainty in the measurement of those quantities.

### TABLE 2

| Number | $L_{1450}$ ($10^{44}$ ergs s$^{-1}$) | $\sigma_{C\text{iv}}$ (km s$^{-1}$) | $\log (M_{\text{BH}}/M_\odot)$ |
|--------|-----------------------------------|-----------------------------------|--------------------------------|
| 1................. | 48 ± 8 | 57 ± 11 | 3834 ± 97 | 3740 ± 159 | 8.79 ± 0.05 | 8.81 ± 0.06 |
| 2................. | 197 ± 17 | 212 ± 22 | 4197 ± 125 | 4408 ± 122 | 9.19 ± 0.03 | 9.25 ± 0.03 |
| 3................. | 105 ± 10 | 193 ± 18 | 3456 ± 141 | 3440 ± 261 | 8.88 ± 0.04 | 9.01 ± 0.07 |
| 4................. | 396 ± 23 | 315 ± 22 | 3371 ± 118 | 3320 ± 119 | 9.16 ± 0.03 | 9.10 ± 0.04 |
| 5................. | 208 ± 21 | 164 ± 20 | 3942 ± 144 | 3970 ± 159 | 9.15 ± 0.04 | 9.10 ± 0.05 |
| 6................. | 379 ± 45 | 268 ± 49 | 2919 ± 114 | 2708 ± 174 | 9.03 ± 0.04 | 8.88 ± 0.07 |
| 7................. | 86 ± 11 | 73 ± 10 | 3294 ± 181 | 2229 ± 475 | 8.79 ± 0.06 | 8.41 ± 0.19 |
| 8................. | 58 ± 8 | 45 ± 6 | 3786 ± 189 | 3904 ± 155 | 8.82 ± 0.06 | 8.81 ± 0.05 |
| 9................. | 224 ± 20 | 235 ± 24 | 3786 ± 184 | 3732 ± 218 | 9.13 ± 0.05 | 9.13 ± 0.06 |
| 10................. | 127 ± 12 | 117 ± 13 | 3735 ± 164 | 3627 ± 174 | 8.99 ± 0.04 | 8.95 ± 0.05 |

**Note.**—Table 2 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.
To measure the relative change in a quantity, we use the fractional change with respect to the average over the two epochs observed. The fractional change in 1450 Å luminosity is given by equation (4):

$$\Delta L_{1450} = 2(L_{1450, HSN} - L_{1450, LSN}) / (L_{1450, HSN} + L_{1450, LSN}).$$

The two panels of Figure 9 show the distribution of values of $\Delta L_{1450}$ and $\Delta C_{IV}$. The sample standard deviation for the $\Delta L_{1450}$ distribution is 0.161, corresponding to a change in continuum luminosity of roughly 16% between epochs.

The sample standard deviation of the $\Delta C_{IV}$ distribution is 0.108, which corresponds to a change in line width of $\sim 11\%$ between epochs. It should come as no surprise that the continuum luminosity exhibits larger variations between epochs than the line dispersion. Much of this variation is due to the intrinsic variability of the quasars themselves, and it is well known that quasars' continua are more variable than their emission lines (see, e.g., Paper I, Fig. 13).

Figure 10 shows the fractional changes in $L_{1450}$ and $C_{IV}$ as a function of high-S/N epoch signal-to-noise ratio. The average variations are clearly, and unsurprisingly, larger for quasars with low spectral signal-to-noise ratios ($[S/N]_{r, HSN} \lesssim 15$) than for quasars with high values ($[S/N]_{r, HSN} \gtrsim 15$). However, the variations are nonzero for quasars with the highest spectral signal-to-noise ratios, an indication that intrinsic variability does play a role in these variations.

The fractional changes in continuum luminosity and $C_{IV}$ line dispersion are shown in Figure 11 as a function of rest-frame time lag between epochs ($\Delta t$). To test the role of variability in these changes, we divide the quasars into two bins in $\Delta t$, as suggested by the distribution of observations in Figure 11: one bin for quasars with $\Delta t < 50$ days and another for quasars with $\Delta t > 50$ days. In intrinsically time-variable populations, one would expect the variations in these quantities to show a time dependence, as seen in structure functions (di Clemente et al. 1996; de Vries et al. 2005). $\Delta L_{1450}$ shows such a dependence. The mean $\Delta L_{1450}$ in the low-$\Delta t$ bin is 0.11; in the high-$\Delta t$ bin, it is 0.18. However, there is no such dependence for $\Delta C_{IV}$. The mean values of $\Delta C_{IV}$ are 0.099 and 0.092 for the low- and high-$\Delta t$ bins, respectively.
This indicates that the intrinsic variability of the quasars themselves plays a larger role in the variations seen in $L_{1450}$ than in those seen in $C_{iv}$. The fact that there appears to be little difference in the size of the $C_{iv}$ variations between the low- and high-$\Delta \tau$ bins indicates that these variations are likely dominated by measurement uncertainty, not by intrinsic variability in the width of these lines. This finding also suggests that the measurement errors quoted in $\sigma_{C_{iv}}$ and Table 2 may be underestimated.

4.2. Variations in Estimated Black Hole Mass

In Figure 12 the estimate for black hole masses at the high-$S/N$ epoch is plotted against the mass estimate from the low-$S/N$ epoch. Most quasars do lie near the $M_{BH,HSN} = M_{BH,LSN}$ line, indicating good general agreement in estimated mass measurements between the two epochs.

Figure 13 shows the distribution in fractional change in the estimate of black hole mass between epochs, $\Delta M_{BH}$. The standard deviation is 0.301, corresponding to a roughly 30% change in the estimate between epochs.

This scatter represents total interepoch variation in the mass estimate, due to variations in either $L_{1450}$, $\sigma_{C_{iv}}$, or both.

Some of this change is simply due to random error in the measurements. The rest of this scatter is due to the intrinsic variability of the quasars’ luminosities and line dispersions between epochs.

Figure 14 shows the fractional change in estimated black hole mass as a function of the fractional change in $1450$ Å luminosity. $\sigma_{C_{iv}}$ is the fractional change in estimated black hole mass as a function of the fractional change in the $C_{iv}$ line dispersion.

In fact, given that the time delays between observations for our sample are only of the order of weeks or months in the quasars’ rest frames, one would expect the continuum luminosity variations to play a larger role in samples with longer time baselines, as structure function studies (di Clemente et al. 1996; de Vries et al. 2005) demonstrate that longer time baselines lead to larger average variations between observations.

For now we adopt $\sim 30\%$ as the contribution of interepoch variations to the uncertainty in the estimation of black hole masses from SDSS spectra, using the $\sigma_{C_{iv}}$ line and nearby continuum. Given the apparent dominance of measurement uncertainty in the interepoch variations in the measured line dispersion and the line dispersion’s dominance of the variations in black hole mass estimate, it is not clear whether we are able to set a lower limit on the effect of the variability that lies below 30%.

Figure 15 shows the fractional change in $M_{BH}$ as a function of the $r$-band spectral signal-to-noise ratio. As was the case with $\Delta L_{1450}$ and $\Delta \sigma_{C_{iv}}$, the width of the $\Delta M_{BH}$ distribution decreases with increasing $(S/N)_{r,HSN}$. However, although the distribution narrows, it does not appear to be approaching zero width.

Though some of the scatter is a result of measurement uncertainties, the width of the $\Delta M_{BH}$ distribution for high signal-to-noise ratio objects [(S/N)$_{r,HSN} > 15$] does give some sense for the magnitude of the variations due to inherent quasar variability. Thus, although it is only a rough estimate, we adopt the
standard deviation of the $\Delta M_{BH}$ distribution as a rough estimate for the size of the interepoch variations in estimated back hole mass. For the 148 quasars with $(S/N)_{r, HSN} > 15$, the standard deviation is 0.219, corresponding to a roughly 20% change. This is decidedly larger than the $M_{BH}$ measurement uncertainty of less than 10% for virtually all quasars, as seen in Figure 7 and discussed in § 3.4.

5. DISCUSSION

Mass estimates of objects in the main sample are consistent between epochs at the 30% level. Given that the mass estimate is a function of the line width squared, but only the square root of the luminosity, it should not come as a surprise that the variations in mass estimates are more strongly dependent on $\Delta C_{lin}$ than on $\Delta L_{1450}$.

Even with the recalibrated UV black hole masses, Vestergaard & Peterson (2006) find a scatter of a factor of about 2 between the UV and optical mass estimates. Variability of the quasar continuum luminosity and line width was thought to be a possible source for this scatter. However, this scatter is much larger than the differences in mass estimates seen between epochs in either our full sample or the quasars with signal-to-noise ratio greater than 15. This suggests that variability is not a likely cause for the majority of this scatter.

That said, if improvements in UV techniques are possible, variability will set an ultimate limit on the precision of these techniques; it is unlikely that any estimate that relies solely on the C iv emission line could do better than the 20% uncertainty in $M_{BH}$ that comes solely from the inherent variability of the continuum luminosity and C iv line dispersion, as suggested by those quasars with $(S/N)_{r, HSN} > 15$.

6. CONCLUSIONS

We have explored the effect of continuum and C iv emission-line variability on single-epoch estimators of quasar black hole mass. Our findings are as follows:

1. Quasar black hole mass estimates determined from SDSS spectra of the rest-frame ultraviolet show interepoch variations at the 30% level, due to the combination of the intrinsic variability of quasars and uncertainty in the measurement of continuum luminosity and C iv emission-line width.

2. For our full sample, measurement error and inherent quasar variability contribute roughly equally to the inconsistencies between epochs in the estimation of $M_{BH}$.

3. The ~20% uncertainty in $M_{BH}$ due to inherent variability, as suggested by the quasars with $(S/N)_{r, HSN} > 15$, sets a lower limit on the reproducibility of future UV black hole mass estimates.

4. Current UV black hole mass estimates for high-redshift quasars are believed to only be accurate to a factor of 2, based on correlations seen with low ionization line mass estimates, but the smaller scatter seen here between epochs (30% for the full sample) seems to indicate that much of this scatter is yet to be understood.

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