The Quasar Mass-Luminosity Plane III: Smaller Errors on Virial Mass Estimates

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ABSTRACT
We use 62,185 quasars from the Sloan Digital Sky Survey DR5 sample to explore the quasar mass-luminosity plane view of virial mass estimation. Previous work shows deviations of \( \sim 0.4 \) dex between virial and reverberation masses. The decline in quasar number density for the highest-Eddington ratio quasars at each redshift provides an upper bound of between 0.13 and 0.29 dex for virial mass estimates. Across different redshift bins, the maximum possible MgII mass uncertainties average 0.15 dex, while H\( \beta \) uncertainties average 0.21 dex and CIV uncertainties average 0.27 dex. Any physical spread near the high-Eddington-ratio boundary will produce a more restrictive bound. A comparison of the sub-Eddington boundary slope using H\( \beta \) and MgII masses finds better agreement with uncorrected MgII masses than with recently proposed corrections. The best agreement for these bright objects is produced by a multiplicative correction by a factor of 1.19, smaller than the factor of 1.8 previously reported as producing the best agreement for the entire SDSS sample.

Key words: black hole physics — galaxies: evolution — galaxies: nuclei — quasars: general — accretion, accretion discs

1 INTRODUCTION

Strong correlations between the mass of supermassive black holes (SMBH) and the stellar velocity dispersion (Ferrarese & Merritt 2000; Gebhardt et al. 2000) and luminosity (Ferrarese & Ford 2005) of their host galaxies argue that our understanding of galactic formation is incomplete without an understanding of the SMBH found at their centres. Our modern arsenal for learning about SMBH growth is predicated on four basic tools: (1) Large samples containing \( \sim 10^5 \) quasars provided by modern surveys (Schneider et al. 2007; Skrutskie et al. 2006; Croom et al. 2004); (2) Bolometric luminosity estimation comparing a piece of the spectrum (Richards et al. 2006) to templates made from composite quasar spectra (Elvis et al. 1994); (3) The Soltan argument (Soltan 1982; Salucci et al. 1999; Yu & Tremaine 2002) that the integrated luminosity density of active galactic nuclei is consistent with the mass density in the local SMBH population; and (4) A series of SMBH mass estimation techniques comprising the "BH Mass Ladder" (Peterson et al. 2004).

Until recently, the first three of these tools might have been thought sufficient. The highest-redshift rung of the black hole "ladder", virial masses, is the only option at redshift \( z \gtrsim 0.2 \), and comparison with reverberation mapping yields a \( \sim 0.4 \) dex statistical uncertainty (Vestergaard & Peterson 2006). Further, early constructions of the quasar mass-luminosity distribution showed a population of quasars all within \( \sim 1 \) dex of their Eddington luminosity (Kollmeier et al. 2006).

If quasars are all within \( \sim 1 \) dex of their Eddington luminosity (Kollmeier et al. 2006), then quasar luminosity would be a good proxy for supermassive black hole (SMBH) mass. Quasars could then be modelled as "light-bulbs" of a characteristic wattage, either operating near their Eddington luminosity or lying dormant (although Hopkins & Hernquist 2008 argue this is an oversimplification). If the relationship between quasar mass and luminosity were truly this simple, virial mass estimation would have little to add to the information already contained in quasar luminosity functions predicated on higher-precision bolometric luminosity estimates.

In Papers I and II (Steinhardt & Elvis 2009; Steinhardt & Elvis 2009), we discovered that the quasar mass-luminosity plane is quite complex. We demonstrated the existence of several surprising new boundaries in the mass-luminosity plane. So, quasar mass and luminosity functions are not enough; these projections of the quasar mass-luminosity plane hide information. In Paper II, we showed that the ratio of emission lines from the broad line region may be evolving as quasars approach turnoff. High-precision black hole mass estimation would allow the identification of specific quasars very close to these boundaries as part of a search for a signature of their
underlying physical causes. However, SMBH masses cannot simply be well-estimated from the quasar luminosity, and so the investigation of SMBH evolution indeed requires all four tools.

Our initial work relied upon Hβ- and CIV-based virial mass estimates from Vestergaard & Peterson (2006) and MgII-based estimators from McLure & Dunlop (2004). There have been several attempts to improve these virial mass scaling relationships (Onken & Kollmeier 2008; Risaliti, Young, & Elvis 2009; Marconi et al. 2009). In this paper, we reconsider virial mass scaling relations in light of these new boundaries in the quasar M − L plane.

Every boundary in the SDSS quasar locus in the mass-luminosity plane is a combination of a real, underlying physical boundary, SDSS selection, statistical uncertainty, and systematic uncertainty. The Eddington luminosity and sub-Eddington boundary (SEB) characterise the quasars with the highest Eddington ratios at each mass, or equivalently, quasars with the highest Eddington ratio at fixed luminosity. While we have termed this boundary “sub-Eddington” because of its behaviour at high mass, the SEB is flatter than the Eddington limit and for the lowest-mass objects at most redshift, the Eddington luminosity is the more restrictive bound. As discussed in Paper I, the SDSS selection function is not a factor in the location of the SEB. Therefore, the decline in number density is a combination of statistical uncertainty, systematic uncertainty, and an underlying physical cutoff, and as such, its sharpness can be used to derive an upper bound on the maximum statistical uncertainty in virial mass estimation. The statistical uncertainty has been estimated as 0.4 dex via comparison of virial and reverberation masses (Vestergaard & Peterson 2006).

In §2 we use the sharpness of boundaries in mass to place a tighter upper bound on the statistical uncertainty of virial mass estimates. In §3 we show that proposed corrections to MgII-based virial mass estimation are inconsistent for the brightest quasars at 0.6 < z < 0.8. We discuss the implications of these results in §4.

2 A NEW BOUND ON STATISTICAL UNCERTAINTIES IN SMBH MASSES

We use black hole masses for 62,185 of the 77,429 SDSS DR5 quasars (Schneider et al. 2007) as determined by Shen et al. (2008) using Hβ- and CIV-based virial mass estimators from Vestergaard & Peterson (2006) and MgII-based estimators from McLure & Dunlop (2004). We divide the SDSS quasar population into 14 redshift bins, of width 0.2 below z = 2 and wider at higher redshift. In each bin, we consider the mass distribution of quasars in a luminosity bin of width 0.2 dex centred at the average bolometric luminosity for the catalogue at that redshift. Choosing this fixed luminosity gives us a large number of objects in our attempt to fit the decay rate at low mass. The decay at low mass is more rapid than at high mass. In each bin, we fit the decline in number density as both a Gaussian and an exponential decay (Figure 1), reporting the dispersion or e-folding in Table 1.

What form should we expect from the decay in quasar number density? Let the true quasar mass distribution be \( \rho_p(M) \) and let \( \phi(x) \) be the probability distribution that a virial mass is incorrect by \( x \). Then, the observed quasar mass distribution \( \rho(M) \) is the convolution

\[
\rho(M) = (\rho_p * \phi)(M) = \int_{-\infty}^{\infty} \rho_p(M - \mu) \phi(\mu) \, d\mu. \tag{1}
\]

For example, if \( \rho_p(M) \) were a step (Heaviside) function, i.e., a constant number density at low mass and zero above the SEB, and the uncertainty \( \phi(x) \) were Gaussian, we would see

| z | N | (log L) | σ (dex) | \( \chi^2 \) | e-folding (dex) | \( \chi^2_d \) |
|---|---|---|---|---|---|---|
| Hβ | 0.2-0.4 | 2690 | 45.25 | 0.23 | 2.93 | 0.19 | 0.77 |
| 0.4-0.6 | 4250 | 45.54 | 0.18 | 2.73 | 0.20 | 0.75 |
| 0.6-0.8 | 3665 | 45.89 | 0.24 | 1.40 | 0.24 | 0.90 |
| MgII | 0.4-0.6 | 4203 | 45.56 | 0.16 | 0.71 | 0.17 | 0.58 |
| 0.6-0.8 | 4727 | 45.80 | 0.19 | 2.80 | 0.16 | 1.00 |
| 0.8-1.0 | 5197 | 46.02 | 0.13 | 3.58 | 0.15 | 1.24 |
| 1.0-1.2 | 6054 | 46.21 | 0.22 | 1.55 | 0.13 | 1.05 |
| 1.2-1.4 | 7005 | 46.32 | 0.14 | 3.18 | 0.14 | 1.50 |
| 1.4-1.6 | 7513 | 46.43 | 0.18 | 2.22 | 0.13 | 1.10 |
| 1.6-1.8 | 6639 | 46.57 | 0.23 | 2.29 | 0.18 | 0.53 |
| 1.8-2.0 | 4900 | 46.71 | 0.27 | 1.32 | 0.19 | 0.96 |
| CIV | 1.8-2.0 | 4627 | 46.60 | 0.25 | 2.68 | 0.26 | 0.71 |
| 2.0-3.0 | 7079 | 46.79 | 0.27 | 4.34 | 0.27 | 0.94 |
| 3.0-4.1 | 2859 | 46.98 | 0.29 | 3.64 | 0.29 | 1.38 |

Figure 1. Top: The quasar M − L plane for MgII masses at 0.4 < z < 0.6. We take the quasar number density as a function of mass around the average luminosity (between the red, dashed lines). Quasar luminosity variability of 0.3 dex might lead to a change in estimated virial mass of 0.15 dex (blue). Bottom: The low-mass decay in quasar number density as a function of mass at 45.46 < log L_{bol} < 45.66 is best-fitting by an exponential decay with an e-folding of 0.15 dex (red). For comparison, the best-fitting decays using the average e-foldings for Hβ (cyan, 0.21 dex) and CIV (magenta, 0.27 dex) are also indicated.
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3 THE MgII VIEW OF THE SUB-EDDINGTON BOUNDARY

MgII has the sharpest boundary in the $M - L$ plane, and so appears to be the most precise mass indicator. Currently, though, Hβ-based masses are considered to be the most reliable, because they have been calibrated directly against reverberation masses at low redshift. Certainly, several potential problems with CIV virial masses have been suggested [Shen et al. 2008, Marconi et al. 2009].

Corrections have also been suggested to the MgII masses derived by McLure & Dunlop (2004) (MD04). Onken & Kollmeier (2008) examine SMBH for which both Hβ and MgII masses are available and find that the MgII-based $M_{BH}$ may be overestimated at high Eddington ratio and underestimated at low Eddington ratio. Risaliti, Young, & Elvis (2009) (RYE09) quantify this correction empirically as

$$\log[M_{BH}(H\beta)] = 1.8 \times \log[M_{BH}(MgII)] - 6.8 \quad (3)$$

In addition to correcting the central values of MgII virial (2)masses, the RYE09 correction also increases the e-folding decay by the same factor of 1.8, to an average of 0.27 dex, which would make MgII masses less precise than Hβ and comparable to CIV.

This multiplicative correction is surprising, because it requires that the gas emitting either Hβ or MgII lines has a non-virial component. If Hβ is virial, as expected from calibration between Hβ and reverberation masses (Vestergaard & Peterson 2006), then the mass-velocity relation for MgII would need to be $M \propto v^{1.6}$. RYE09 propose that this mismatch might instead be due to uncertainties in measurement of the MgII line, mainly because of potential FeII contamination.

To test the multiplicative correction we examine the SEB more closely. The slope of the SEB is sensitive to the multiplicative correction to MgII-based virial masses but not to any additive correction. As the SEB is composed of the brightest quasars in each redshift bin they typically have the best-measured spectra at each mass, minimising MgII measurement errors. Both MgII and Hβ masses are available at the 0.4 < z < 0.8. Using the techniques detailed in Paper I we subdivided this bin into four redshift bins of width $\Delta z = 0.1$. We then calculated the slope of the best-fitting SEB in each bin using both the MD04 scaling relation and the RYE09 correction. In Figure 2 we show the four Hβ SEB slopes (green) compared to slopes using MD04 (blue) and RYE09 (magenta).

In each redshift bin, the deviations between MD04 and Hβ slopes are between 0.3 $\sigma$ and 1.6 $\sigma$ (MD04 averages 0.8$\sigma$ higher). Deviations between RYE09 and Hβ are between 0.9 and 2.7 $\sigma$ (average 1.9 $\sigma$), with the RYE09 slope always lower. If MgII masses with the RYE08 correction produced identical SEB slope estimates to Hβ, the probability that all four measurements would be this far below the Hβ slope is 0.2% (comparing to a Monte Carlo of normally-distributed measurements). A best-fitting correction between Hβ and MgII slopes (Figure 2) reduces the factor of 1.8 to one of 1.19. The $M - L$ plane view of MgII virial masses for the brightest quasars at each redshift is that corrections might not be necessary, and if necessary, are likely substantially smaller than previously proposed. Most of the RYE09 correction may indeed be a result of measurement difficulties for MgII, which become unimportant for the brightest quasars with the best-measured spectra.

2.1 Effects of quasar variability on virial mass estimation

Virial mass estimates take the form

$$\log(M/M_\odot) = A + \log\left(\frac{\text{FWHM}(\text{BLR line})}{1000 \text{ km/s}}\right)^2 \left(\frac{\lambda L_\lambda(B \text{ Å})}{10^{44} \text{ erg/s}}\right)^C$$

for emission lines in the broad line region (BLR) and a nearby continuum flux. For the virial mass estimates used in the Shen et al. (2008) catalogue, $C$ is between 0.50 and 0.53 (McLure & Jarvis 2002, McLure & Dunlop 2004, Vestergaard & Peterson 2006). One possible explanation for this discrepancy, then, is that the analysis above only considers quasars at fixed bolometric luminosity, while the adjacent continuum is one component of virial mass estimation. Perhaps the statistical uncertainty in virial mass estimation is mostly caused by quasar variability, in which the bolometric luminosity (and adjacent continuum) change on a timescale of years while the black hole mass remains very nearly constant.

Variability moves objects along a $L = M^2$ line (Figure 1), blurring each thin luminosity slice along the mass axis by 0.18 dex for typical long-term, 0.3 dex optical variations (de Vries et al. 2003). This blurring is larger than most of the MgII decays, notably smaller than the CIV decays, but is consistent with the Hβ decays. The additional CIV scatter must have some other cause. Variability is wavelength dependent in quasars, being stronger toward the UV, but the difference between 2800 Å and 1500 Å is too small to explain the different MgII and CIV decays.

Similarly, the adjacent luminosity used to estimate the black hole mass is based on the continuum local to each line, while the bolometric luminosity is based on the five SDSS photometry points. Thus, systematic offsets between these two luminosities could cause a scatter. The correction would have to have a peculiar shape as the longest and shortest Hβ and CIV measurements both have larger scatter than the intermediate wavelength MgII value.

decay taking the form of the error function, $1 + \text{Erf}(x) = \int_{-\infty}^{x} e^{-t^2} dt$. In practice, the exact form of the tail is highly sensitive to $\rho_\beta$, and the exponential decay described in Table 1 is a better fit to the low-mass tail of $\rho_\beta$ than a Gaussian (Table 1), polynomial, or $\text{Erf}(x)$. The exact form of $\rho_\beta$ appears to be more complicated than a step function at masses above the SEB (Figure 1). However, the convolution acts to spread out the signal, and therefore the dispersion of features in $\rho_\beta$ will be at least as large as those in $\phi(x)$. So, the e-foldings of best-fitting exponential decays in Table 1 are inconsistent with an 0.4 dex statistical uncertainty for virial mass estimation.
Figure 2. A comparison of best-fitting slopes to the sub-Eddington boundary in four redshift ranges using different virial mass scaling relations. The Hβ-based estimates (green) are a better fit for the original McLure & Dunlop (2004) MgII masses (blue) than the Risaliti, Young, & Elvis (2009) correction (magenta). The best match between slopes is produced by a smaller MgII correction (red). The black dashed line is drawn at the slope of the Eddington luminosity.

4 DISCUSSION

The rapid falloff in quasar number density at fixed luminosity near the sub-Eddington boundary (SEB), places a strong upper bound on the statistical uncertainty of virial mass estimation, of, on average, 0.21 dex for Hβ-based virial masses, 0.15 dex for MgII, and 0.27 dex for CIV. We considered the possibility that the narrow spreads were induced by quasar variability. We find that variability can explain only ~0.15 dex of spread.

The small scatter in MgII-based virial masses at the SEB implies, surprisingly, that the MgII masses are more reliable than the Hβ-based masses. We also find that, at least for the most luminous objects in each redshift bin, any MgII to Hβ mass corrections are likely smaller than previously thought.

We note that the ordering of the decay sizes is inverse to the ordering of the emission lines by distance from the ionising continuum, as derived from reverberation mapping (Peterson et al. 2003). This ordering suggests a physical explanation in which the non-virial motions in the broad-line region behave differently and are weaker with increasing distance from the continuum. An obvious candidate is a reduced role of radiation pressure at larger distances (Marconi et al. 2000), which would affect CIV most strongly and MgII the least.

The measured decays provide a fixed error budget to be distributed between non-viral motion and quasar luminosity variability. If fluctuations in the adjacent continuum scale linearly with the quasar bolometric luminosity, the ~0.15 dex bound on MgII masses limits quasar variability to ~0.33 dex. If the decay rate is due primarily to non-viral motion in the broad line region, then the contribution from quasar luminosity variability is smaller.

However, if the statistical uncertainty is truly smaller in virial masses than previously believed, then we must explain the origin of the ~0.4 dex scatter between virial and reverberation masses, which would have to be dominated by uncertainties in reverberation masses. This situation is not easy to understand. It would be remarkable if the continuum fit at one wavelength from a single-epoch spectrum (virial masses) provides a more precise radius indicator than a time-series of high-resolution spectra (reverberation masses). Both virial mass estimation and reverberation mapping are based on assumptions about quasar geometry, so some of these assumptions would need to be wrong. The basic difference between reverberation and virial masses lies in how each method determines the radius to broad emission lines, so the larger statistical uncertainty may lie in using time delays to estimate the radius.

Reverberation data is also used to calibrate the relation that allows the use of adjacent continuum as a proxy for radius in virial masses. A restriction to the best reverberation data includes scatter corresponding to typical uncertainties of 0.09 dex for broad line region radii from reverberation mapping, with an 0.11 dex uncertainty for the Hβ line (Peterson, B. M., private communication). If the scatter in the R − L relation is uncorrelated with other errors, this would restrict the remaining uncertainty to just ~0.1 dex for MgII. Further, these uncertainty measurements use an improved R − L relation (Bentz et al. 2009), while the Shen et al. (2008) catalogue does not include these improvements.

The two methods also differ in that virial estimates use the entire emission line, while the best reverberation methods use the rms line profile, i.e., the minority fraction of the emission line that responds to continuum changes. Korista et al. (2001) show that only the gas that is optimally emitting the ionising line, while the best reverberation and virial masses lie in how each method determines the radius to broad emission lines, so the larger uncertainty may lie in using time delays to estimate the radius. In some manner, virial masses appear to be giving better values than reverberation masses. We cannot satisfactorily explain this surprising result.

5 CONCLUSIONS

We used the sub-Eddington boundary (SEB) in the quasar mass-luminosity plane to compare different virial mass estimators for quasar black hole masses. In particular, the MgII estimator developed by McLure & Dunlop (2004) has been considered less reliable than the Hβ-based estimator of Vestergaard & Peterson (2006), with several proposals for corrections (Onken & Kollmeier 2008; Risaliti, Young, & Elvis 2009; Marconi et al. 2009). The quasar M − L plane indicates, surprisingly, that MgII may be the most reliable virial mass estimator. A decline in the relative importance of non-virial motions at large radii may account for the differences in precision when using different emission lines.

Surprisingly, using the adjacent continuum as a proxy for radius seems to be more precise than using time delays. If the statistical uncertainties of virial mass estimates are really smaller than previously believed, this would be a substantial improvement. It means that we produce better black
hole mass determinations using one lower-resolution optical spectrum than from a time-series of high-resolution spectra.

Moreover, many of the conclusions drawn from quasar mass functions, in Papers I and II, and in other work rely on the ability to segregate quasars into mass bins. With an uncertainty of 0.4 dex, cross-contamination is a concern. An uncertainty of 0.15 dex allows us to divide a quasar sample into 2-3 times as many independent bins. Given the large systematic uncertainties in fitting bolometric luminosities to templates, it is possible that quasar mass functions will be more reliable than luminosity functions.

The quasars that define the SEB are necessarily the closest to the Eddington limit of their cohort. It could be that this gives them a greater uniformity of properties, including more accurately virial motion in the broad-line region, than quasars at lower Eddington rates. Lower Eddington rate quasars, such as those used in reverberation mapping, might then have a wider dispersion in these same properties, leading to the difference in observed spread. However, since the location SEB moves with redshift, something more complex than just the Eddington ratio would need to be responsible for this possible greater uniformity in quasar properties near the SEB.

We also compared the SEB slopes using MgII masses and Hβ. Proposed corrections to MgII masses comparing the two methods for the entire SDSS catalogue are quite severe, but these corrections might be due to uncertainties in the measurement of MgII lines parameters. For the brightest objects at 0.4 < z < 0.8, the SEB produced by the Risaliti, Young, & Elvis (2009) correction is a significantly worse match for the SEB produced by Hβ than using uncorrected MgII-based virial masses.

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