AN IMPROVED METHOD FOR USING Mg \textsc{ii} TO ESTIMATE BLACK HOLE MASSES IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

We present a method for obtaining accurate black hole (BH) mass estimates from the Mg \textsc{ii} emission line in active galactic nuclei (AGNs). Employing the large database of AGN measurements from the Sloan Digital Sky Survey (SDSS) presented by Shen et al., we find that AGNs in the redshift range 0.3–0.9, for which a given object can have both H\textbeta and Mg \textsc{ii} line widths measured, display a modest but correctable discrepancy in Mg \textsc{ii}-based masses that correlates with the Eddington ratio. We use the SDSS database to estimate the probability distribution of the true (i.e., H\textbeta-based) mass given a measured Mg \textsc{ii} line width. These probability distributions are then applied to the SDSS measurements from Shen et al. across the entire Mg \textsc{ii}-accessible redshift range (0.3–2.2). We find that accounting for this residual correlation generally increases the dispersion of Eddington ratios by a small factor (∼0.09 dex for the redshift and luminosity bins we consider). We continue to find that the intrinsic distribution of Eddington ratios for luminous AGNs is extremely narrow, 0.3–0.4 dex, as demonstrated by Kollmeier et al. Using the method we describe, Mg \textsc{ii} emission lines can be used with confidence to obtain BH mass estimates.

Subject headings: black hole physics — galaxies: active — quasars: emission lines — surveys

1. INTRODUCTION

The \( M_{\text{BH}}-\sigma \) correlation between supermassive black hole (BH) mass and the velocity dispersion of the surrounding stellar system indicates a significant connection between galaxy and BH assembly (Ferrarese & Merritt 2000; Gebhardt et al. 2000). Thus, it is essential to establish the most basic BH parameters: their intrinsic distribution of masses and growth rates.

It is extraordinarily difficult to measure BH masses directly, even in the nearby universe, because of the small spatial scales that must be resolved to probe the gravitational influence of the BH. In active galactic nuclei (AGNs), the technique of reverberation mapping (Blandford & McKee 1982; Peterson 1993) employs high resolution in the time domain to probe gas dynamics on spatial scales close to the BH. However, the long-duration spectroscopic monitoring campaigns required for reverberation studies currently preclude the method from being applied to large numbers of objects. Therefore, one must rely on even more indirect techniques of BH mass estimation to build up statistically significant samples.

The “virial” method has been empirically calibrated from reverberation mapping experiments (Wandel et al. 1999; Vestergaard 2002; McLure & Jarvis 2002) and allows a BH mass estimate from a one-time measurement of the width of a broad emission line and the AGN luminosity (see § 2). To facilitate application of the virial technique to large optical AGN surveys, versions have been developed for H\textbeta at low redshift, for the Mg \textsc{ii} doublet near 2800 Å at intermediate redshift, and for the C \textsc{iv} doublet near 1550 Å at high redshift (for recent prescriptions, see Vestergaard & Peterson 2006; McGill et al. 2008).

In this paper, we present evidence of a systematic discrepancy in Mg \textsc{ii}-based BH mass estimates as a function of Eddington ratio (the ratio of the bolometric luminosity, \( L_{\text{bol}} \), to the luminosity required for radiation pressure to balance the gravity of the BH), as well as a method to correct this trend.

2. METHOD OF ANALYSIS

The standard equation for estimating BH masses in AGNs from single-epoch spectroscopy is:

\[
\log M_{\text{BH}} = a + b \log L_\star + 2 \log V,
\]

where \( V \) is the width of the broad emission line, \( L_\star \) is the continuum luminosity near the line, and \( a \) and \( b \) are constants (which vary from line to line). The dependence on \( L_\star \) arises because the distance of the broad emission line gas from the BH has been observed to correlate tightly with the AGN luminosity over 4 orders of magnitude in \( L_\star \) (Bentz et al. 2007). Thus, the mass equation reverts to the simple, virial combination of radius and velocity. The calibration of these relations rests on the bedrock of reverberation mapping measurements of local AGNs. By far, the best reverberation mapping data set exists for H\textbeta (Peterson et al. 2004). The \( a \) and \( b \) coefficients for both C \textsc{iv} and Mg \textsc{ii} principally rely on empirical correlations with H\textbeta-reverberation masses. However, whereas C \textsc{iv} reverberation studies of a handful of objects are consistent with expectations from H\textbeta (Peterson et al. 2005), a clear indication of reverberation has not yet been found for Mg \textsc{ii}. Although the line has been seen to vary in both flux and width (e.g., Clavel et al. 1991; Dietrich & Kollatschny 1995; Metzroth et al. 2006; Woo 2008), only weak Mg \textsc{ii} reverberation signals have been seen (Reichert et al. 1994). Thus, the mass relation for Mg \textsc{ii} relies on the correlation of single-epoch estimates with H\textbeta masses and the argument that Mg \textsc{ii} and H\textbeta have similar ionization potentials (McLure & Dunlop 2004).

With the wide wavelength coverage of Sloan Digital Sky Survey (SDSS) spectra, certain redshift windows allow for two of these three emission lines to be measured simultaneously: H\textbeta and Mg \textsc{ii} are both accessible for \( z \sim 0.3–0.9 \), while Mg \textsc{ii} and C \textsc{iv} can both be measured for \( z \sim 1.7–2.2 \). By comparing the BH mass estimates from the two lines, we are thus able to study systematic trends. Such a comparison has been done previously for the mean relation, but the large sample size of
the SDSS permits an analysis of higher order correlations, which prove to be quite important.

Shen et al. (2008) have provided line width (FWHM) measurements and BH mass estimates—using the relations of McLure & Dunlop (2004) and Vestergaard & Peterson (2006)—for roughly 60,000 AGNs from the SDSS, including ~8000 with both Hβ and Mg II, and ~15,000 with both Mg II and C IV. They provide a detailed analysis of the relationship between Mg II and C IV, but simply describe the ratio of Hβ to Mg II FWHM as following a lognormal distribution with a mean of 0.0062 dex and a dispersion of 0.11 dex. Shen et al. noted that the relation of the two FWHMs deviates slightly from a perfect correlation, but did not explore the issue further.

Under the premise that Hβ, being the most extensively reverberation-mapped emission line, provides the best indicator of the BH mass, we examine AGNs having both Hβ and Mg II mass measurements. Due to uncertainties in the line width measurements, we exclude the small number of AGNs that were flagged by Shen et al. as broad absorption line objects. However, the inclusion of these objects has a negligible effect on our results. In Figure 1, we plot the difference in the (log of the) BH mass as a function of Eddington ratio. The strong correlation implies that if Mg II is calibrated simply from the mean of the Hβ-Mg II relation, then it will underestimate the BH mass at low Eddington ratio and overestimate the mass at high Eddington ratio. This would lead one to infer a narrower mass measurements. Due to uncertainties in the line width measurements, we exclude the small number of AGNs that were flagged by Shen et al. as broad absorption line objects. However, the inclusion of these objects has a negligible effect on our results. In Figure 1, we plot the difference in the (log of the) BH mass as a function of Eddington ratio. The strong correlation implies that if Mg II is calibrated simply from the mean of the Hβ-Mg II relation, then it will underestimate the BH mass at low Eddington ratio and overestimate the mass at high Eddington ratio. This would lead one to infer a narrower

4 The Eddington ratio is computed with the Hβ-based BH mass.

5 We note that the same trend from Fig. 1 is seen when replacing FWHM with the interpercentile value measurements of Fine et al. (2008).

### Table 1

| Mg II FWHM | Probability |
|------------|-------------|
| 3.05       | 0.0000  |
| 3.15       | 0.0000  |
| 3.25       | 0.0000  |
| 3.35       | 0.0000  |
| 3.45       | 0.0000  |
| 3.55       | 0.0000  |
| 3.65       | 0.0000  |
| 3.75       | 0.0000  |
| 3.85       | 0.0000  |
| 3.95       | 0.0000  |
| 4.05       | 0.0000  |
| 4.15       | 0.0000  |
| 4.25       | 0.0000  |
| 4.35       | 0.0000  |
| 4.45       | 0.0000  |

Notes.—The values listed are the probabilities of the Hβ FWHM falling within a particular bin, given an input Mg II FWHM. All velocities are in km s⁻¹, and all bins are ±0.05 dex.
distribution of Eddington ratios than actually exists. One way to quantify this effect is to measure the slope of the correlation

\[ \beta = \tan \left( \frac{1}{2} \arctan \frac{2c_{12}}{c_{11} - c_{22}} \right), \]  

where \( c_{ij} \) is the covariance matrix of the distribution shown in Figure 1. A slope \( \beta = 0 \) would imply that Mg \( \text{II} \) provided completely independent information on the BH mass, while \( \beta = 1 \) would imply that no information is conveyed by the Mg \( \text{II} \) measurement. The actual value is \( \beta = 0.76 \), which means that Mg \( \text{II} \) is indicative of the BH mass, but must be treated with care.

Simply modifying the luminosity dependence of the Mg \( \text{II} \) mass formula (i.e., changing \( b \) in eq. [1]) cannot remove the trend. Therefore, to make a statistical correction to the Mg \( \text{II} \)-based masses, we adopt the following method. For the SDSS objects with both H\( \beta \) and Mg \( \text{II} \) FWHMs, we look at AGNs with Mg \( \text{II} \) lines in a given 0.1 dex bin of FWHM and tabulate the distribution of H\( \beta \) FWHMs for those objects. We take those H\( \beta \) distributions (normalized appropriately) as

\[ \begin{array}{cccccc}
\log L_{\text{bol}} & c_{11} & c_{12} & c_{22} \\
0.3<z<1.2 & 0.02 3.51 & 0.47 3.17 & 0.48 4.27 \\
1.2<z<2.2 & 0.06 3.52 & 0.47 3.17 & 0.48 4.27 \\
0.3<z<0.6 & 0.02 3.51 & 0.47 3.17 & 0.48 4.27 \\
1.2<z<2.2 & 0.06 3.52 & 0.47 3.17 & 0.48 4.27 \\
0.6<z<1.0 & 0.02 3.51 & 0.47 3.17 & 0.48 4.27 \\
1.2<z<2.2 & 0.06 3.52 & 0.47 3.17 & 0.48 4.27 \\
\end{array} \]

the probability distributions for the true FWHM underlying the observed Mg \( \text{II} \) value (Fig. 2 and Table 1).

For any object with an accessible Mg \( \text{II} \) line, each bin in true FWHM is combined with the observed continuum luminosity to calculate a BH mass (via eq. [1]), and the mass is then used with the object’s bolometric luminosity to derive an Eddington ratio. The probability for each bin of FWHM is added to the corresponding Eddington ratio bin (which is 0.2 dex wide, allowing a one-to-one match between FWHM and Eddington ratio bins). Thus, each Mg \( \text{II} \) FWHM becomes a weighted distribution of Eddington ratios, while H\( \beta \)- and C \( \text{IV} \)-based Eddington ratios contribute directly at their observed values.

We now apply this technique to the Shen et al. measurements of the uniformly selected subsample of SDSS AGNs (Richards et al. 2006).

If the observed Mg \( \text{II} \) FWHM falls in a bin in which there were no H\( \beta \)+Mg \( \text{II} \) measurements, it is given a probability of 1 within the bin corresponding to the Mg \( \text{II} \) FWHM. In the sample we consider, this applies to a single AGN.

### Table 2

| \( z_{\text{min}} \) | \( \log L_{\text{bol}} \) | \( N \) | \( \mu \) | \( \sigma \) | \( S_k \) | \( A_i \) | \( \mu \) | \( \sigma \) | \( S_k \) | \( A_i \) |
|----------------|----------------|------|-------|-------|------|-------|-------|-------|------|-------|
| 0.3–1.2 ...... | < 46          | 6187 | 0.97  | 0.33  | -0.48 | 4.27  | -0.98 | 0.39  | -0.33 | 3.30  |
| 1.2–2.2 ...... | < 46          | 15   | -1.03 | 0.40  | 0.55  | 2.07  | -0.92 | 0.44  | 0.05  | 2.17  |
| 0.3–1.2 ...... | 46–46.5       | 5233 | -0.77 | 0.25  | -0.24 | 3.39  | -0.79 | 0.36  | -0.04 | 2.95  |
| 1.2–2.2 ...... | > 46.5        | 5360 | -0.76 | 0.24  | -0.02 | 3.51  | -0.72 | 0.35  | 0.05  | 2.82  |
| 0.3–1.2 ...... | > 46.5        | 789  | -0.61 | 0.22  | 0.47  | 3.17  | 0.61  | 0.34  | -0.06 | 2.92  |
| 1.2–2.2 ...... | > 46.5        | 9860 | -0.65 | 0.25  | 0.06  | 3.73  | -0.65 | 0.34  | 0.24  | 3.27  |

Note.—For each bin in redshift \( z_{\text{min}} \) and luminosity \( L_{\text{bol}} \), the table lists: \( N \), the number of AGNs; \( \mu \), the mean logarithm of the Eddington ratio; \( \sigma \), the dispersion in \( \log (L_{\text{bol}}/L_{\text{bol}}) \); \( S_k \), the skewness; and \( A_i \), the kurtosis.
3. RESULTS AND DISCUSSION

We construct distributions of Eddington ratios for SDSS in ranges of \((L_{\text{bol}}, z)\) in Figure 3, showing the results both with (solid histogram) and without (dotted histogram) the Mg Ⅱ substitution presented above. The statistics of the distributions are given in Table 2. After correcting the Mg Ⅱ measurements in the uniformly selected SDSS sample, we find that the average width of the Eddington ratio distribution increased by 0.09 dex for objects in the redshift range 0.3−2.2. We therefore find that the distribution of Eddington ratios remains very narrow at ∼0.4 dex, as was found by Kollmeier et al. (2006) for the AGES-I survey.

To test our procedure, we apply it to multiple subsamples for which we have both H Ⅱ and Mg Ⅱ data. Figure 4 shows the distribution of Eddington ratios for each subsample calculated in two ways, first using the true H Ⅱ mass (solid histogram) and second using our procedure applied to the Mg Ⅱ mass (dashed histogram). The similarity of these distributions (and the differences from the raw Mg Ⅱ-based values, shown as the dotted histograms) demonstrates that our procedure works well, recovering the true Eddington ratio distribution from the Mg Ⅱ derived masses.

The general trend we observe could be explained physically if the location where lines are formed in the broad-line region depends on accretion rate. In this case, the radius-luminosity relation would also depend on the Eddington ratio, and that would introduce an additional term in the virial mass relation.

It would then be possible, in principle, to remove this dependence entirely analytically by fitting the observed correlation. We investigate this further in an upcoming work.

The virial method for BH mass estimation has opened a new window in the study of supermassive BH demographics. While each indicator has systematics that must be addressed (i.e., asymmetric line profiles, contamination from disk winds and metal lines, etc.), it is important to understand and attempt to correct for these systematics so that this technique can be applied with confidence. In this contribution, we have identified a limitation in estimating BH masses from the Mg Ⅱ line and presented a way to remove it by exploiting the overlap of Mg Ⅱ and H Ⅱ measurements presented by Shen et al. (2008). This method puts Mg Ⅱ masses more securely on the same scale as H Ⅱ, which should be the most reliable in these studies. As the bias in the Mg Ⅱ masses is also seen in our analysis of the 2dF Quasar Redshift Survey (2QZ) and the AGN and Galaxy Evolution Survey (AGES), in forthcoming work, we will apply our correction technique to those data sets (including the expanded sample of AGES-II).

Understanding the transition between high-luminosity, high-redshift AGNs having a narrow Eddington ratio distribution (<0.4 dex) and low-luminosity, low-redshift AGNs with a broad Eddington ratio distribution (>1 dex; Ho 2002; Woo & Urry 2002) can provide important constraints on the physics of BH accretion. To determine these distributions, it is critical to continue to improve BH mass estimates that can be used through the bulk of the cosmic AGN activity.

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