On the Systematic Bias in the Estimation of Black Hole Masses in Active Galactic Nuclei

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In this report, we find the $M_{BH}$ estimated from the formalism of Wang et al. (2009)[1] are more consistent with those from the $M_{BH}$-$\sigma^*$ relation than those from previous single-epoch mass estimators, using a large sample of AGNs. Furthermore, we examine the differences between the line widths of H$\beta$ and Mg II in detail by comparing their line profiles. The flux around the line core and that in the wing of both H$\beta$ and Mg II show an opposite variation tendency, which indicates the BLR is multi-componential. The contribution of the wing makes the FWHM deviate from $\sigma_{line}$, and thus bias the $M_{BH}$ estimated from previous single-epoch mass estimators. Thus the correction on the formalism suggested by Wang et al. (2009)[1] is crucial to $M_{BH}$ estimation.

Quasars, Galactic nuclei, Masses, Statistical and correlative studies of properties

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1 Introduction

Accretion onto super-massive black holes (SMBHs) is generally considered as the energy engine of active galactic nuclei (AGNs). The determination of the mass of SMBH ($M_{BH}$) is crucial to the understanding of most physical processes associated with SMBH and the cosmological evolution of black holes. The $M_{BH}$ of type I AGNs are usually measured using the virial theorem, $M_{BH} = f R_{BLR} V^2 / G$, if the size of broad line region ($R_{BLR}$) and the virial velocity ($V$) of clouds in the BLR are known, where $f$ is a factor of order unity depending on the geometry and kinematics of the BLR. $R_{BLR}$ can be estimated using the reverberation mapping (RM) method[2], which monitors the variability of continuum and emission lines. $V$ can be estimated from the widths of emission lines. Conversely, $M_{BH}$ can also be estimated using the tight correlation between $M_{BH}$ and the stellar velocity dispersion of the galactic bulge ($M_{BH}$-$\sigma_*$ relation)[3,4,5]. However, both of these methods cannot be used for large samples of AGNs, because the RM method is time-consuming and the measurements of $\sigma_*$ are limited by the spectral and spaital resolution of telescopes.

For large samples of AGNs, $M_{BH}$ can be estimated by combining $R_{BLR}$, which is estimated using the important relationship between $R_{BLR}$ and the monochromatic continuum luminosity (R-L relation)[6,7,8], and the FWHM of emission lines. The single-epoch mass estimators have been studied for various broad lines, such as H$\beta$ [1,9], H$\alpha$ [10], Mg II $\lambda$2800 [1,11,12] and C IV $\lambda$1549[13]. If both H$\beta$ and Mg II FWHMs are good tracers of the virial velocity and can be used to estimated the $M_{BH}$, they should give the same $M_{BH}$ values. Some researchers found they are consistent with each other [11,14,15,16], while others came to an opposite conclusion [1,17,18]. Wang et al. (2009) found that Mg II FWHM is systematically smaller than H$\beta$ FWHM, and that the relationships between H$\beta$ and Mg II FWHM and $\sigma_{line}$, which is the best virial velocity tracer measured on the variable part of the spectrum[19], deviate from the 1:1 relationship. The dependance of $M_{BH}$ on FWHM should be $M_{BH}\propto$FWHM$^\gamma$, where $\gamma$ is smaller than 2 for both H$\beta$ and

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Mg II. If this is the case, most previous single-epoch mass estimators ($M_{\text{BH}} \propto \text{FWHM}^2$) would introduce systematic biases in $M_{\text{BH}}$ estimations [1, 20, 21, 22, 23] and result in many artificial conclusions, as discussed by Rafiee and Hall (2011) [21] and Croom (2011) [22]. Thus, further testing the validity of the formalism of Wang et al. (2009) [1] is critical for eliminating such biases in $M_{\text{BH}}$ estimations and many other related relationships in AGNs. The $M_{\text{BH}}$ estimated from the Hβ and Mg II formalisms of Wang et al. (2009) are more consistent with those from RM measurements than those from previous single-epoch mass estimators and are consistent with each other for a large sample culled from Sloan Digital Sky Survey (SDSS) Data Release 5 (DR5). However, one remaining issue is whether the new $M_{\text{BH}}$ estimates are consistent with those derived from the $M_{\text{BH}}$–$\sigma$ relation, which should be tested using a large sample.

Moreover, the reasons for the systematic deviations between Hβ and Mg II FWHM and $\sigma_{\text{line}}$ are unclear now. The profile of an emission line is determined by the structure and kinematics of the BLR, which are complex. It is possible that the broad lines in most AGNs are generated in multi-regions, including the gravitationally-bound BLR, outflows [24] and the surface of accretion disk (Wang et al. 2005 [25]; Wu et al. 2008 [26]). Different measurements of line width, such as $\sigma_{\text{line}}$ and FWHM, would represent different information about the structure and/or kinematics of the BLR. Special attention must be noted when using in the estimation of $M_{\text{BH}}$. The study of the structure and kinematics of the BLR would be helpful to understand why FWHM deviates from $\sigma_{\text{line}}$ and important for the $M_{\text{BH}}$ estimation of AGNs. In this report, we examine whether there are systematic biases between the $M_{\text{BH}}$ estimated from the single-epoch mass estimators and those from the $M_{\text{BH}}$–$\sigma$ relation. We also compare the profiles of Hβ and Mg II in order to understand their differences and why their FWHM deviates from $\sigma_{\text{line}}$.

2 The Bias in the $M_{\text{BH}}$ Estimates

We first verify the consistency between the $M_{\text{BH}}$ estimated from the single-epoch mass estimators and those from the $M_{\text{BH}}$–$\sigma$ relation (Gültekin et al. 2009) [27]. We select 8470 AGNs with $z < 0.35$ from SDSS DR4. The spectrum is corrected for the Galactic extinction using the extinction map of Schlegel et al. (1998) [28] and the reddening curve of Fitzpatrick (1999) [29]. The fitting method is described in Dong et al. (2008) [30] and described below. In the wavelength range 4030-7500 Å, we fit simultaneously the featureless continuum and the Fe II multiplets and other emission lines. Each of the [O III] $\lambda\lambda$ 4959,5007 doublets is modeled with two Gaussians, one for the line core and the other for the possible blue wing. The narrow components of Hα and Hβ are fitted with similar profile to the line core of [O III] $\lambda$5007 and the broad components of them are fitted with 1-4 gaussians. $M_{\text{BH}}$ can be estimated using the width of the line core of [O III] $\lambda$5007 as substitute for $\sigma$, [31]. Because Hβ is weak for many objects, we estimate Hβ FWHM from Hα FWHM [10] and then estimate the $M_{\text{BH}}$ using the single-epoch mass estimators. We find that the differences between the $M_{\text{BH}}$ estimated from the single-epoch mass estimators and those from the $M_{\text{BH}}$–$\sigma$ relation are correlated with Hα FWHM (Figure 1), if the formalisms from Greene and Ho (2005; hereafter GH05) [10] or Vestergaard and Peterson (2006; hereafter VP06) [9] are used. The correlation would decrease largely, if the formalism of Wang et al. (2009) [1] is adopted. The relationship between the $M_{\text{BH}}$ differences and FWHM(Hα) is somewhat linear in log-log space and can be expressed as $\log \frac{M_{\text{BH}}}{M_{\odot}} = k \log \frac{\text{FWHM}(\text{H}\alpha)}{\text{km s}^{-1}} + b$. The $(k, b)$ for the formalisms of GH05, VP06 and Wang et al. (2009) given by the regression method of Kelly (2007) [32] are $(2.05 \pm 0.04, -7.51 \pm 0.13)$, $(1.93 \pm 0.03, -6.73 \pm 0.09)$ and $(0.86 \pm 0.03, -2.99 \pm 0.11)$, respectively. All the intrinsic scatters of these relations are around 0.02 dex. This indicates that the $M_{\text{BH}}$ estimated from the formalism of Wang et al. (2009) [1] are less biased than those from previous single-epoch mass estimators ($M_{\text{BH}}$–FWHM$^2$). We attempt to estimate the $M_{\text{BH}}$ using the $M_{\text{BH}}$–$\sigma$ relation from other authors (Xiao et al. 2011 [33]) and find the $M_{\text{BH}}$ estimated from the formalism of Wang et al. (2009) are still less biased than those from previous single-epoch mass estimators.

![Figure 1](image-url)

**Figure 1** Correlations between FWHM(Hα) and the differences of $M_{\text{BH}}$ estimate from single-epoch mass estimators and those from $M_{\text{BH}}$–$\sigma$ relation [27] for the sample from SDSS DR4. The crosses are the median values and standard deviations of the $M_{\text{BH}}$ differences and FWHM in each bin of FWHM. The solid lines show the best-fit relations.

3 Profiles of Hβ and Mg II

The comparison above shows that the method of Wang et al. (2009) [1] is capable of correcting the systematic biases in the
$M_{BH}$ estimations over a large redshift interval. This indicates indirectly that Hβ and Mg II FWHMs are deviating from $\sigma_{line}$ systematically. The systematic deviation may be caused by the complex structure and kinematics of the BLR. We compare the profiles of Hβ and Mg II using the sample from Wang et al. (2009)[1], which was selected from SDSS DR5. The sample includes 495 AGNs with high signal-to-noise ratio (S/N > 20) in both the Hβ (4600-5100 Å) and the Mg II (2700-2900 Å) regions, which makes it suitable for the comparison. The spectrum is corrected for the Galactic extinction using the extinction map of Schlegel et al. (1998)[28] and the reddening curve of Fitzpatrick (1999)[29]. The redshifts of these quasars are from Hewett and Wild (2010)[34], which were derived by cross-correlating observed spectra with a carefully constructed template. The dependence of emission line shift on luminosity and redshift are corrected and the systematic errors of redshifts are reduced to the level of 30 km/s, which are important to our investigation. We perform the continuum and emission-line fitting using an Interactive Data Language (IDL) code based on MPFIT [35], which performs $\chi^2$-minimization by the Levenberg-Marquardt technique.

The spectrum is fitted in two wavelength range: Hβ range (4200-5600Å) and Mg II range (2200-3500 Å). For the Hβ range, the fitting method is similar to that described above. For the Mg II range, the method is described in Wang et al. (2009)[1]. The featureless continuum and Fe II multiplets were modeled simultaneously. The broad component of each of the Mg II λλ 2796,2803 doublets is modeled with a Gaussian. Usually, the shift and asymmetry of lines are studied separately, while they may be caused by the same process[24]. The blueshift and asymmetry index (BAI), which is defined as the flux ratio of the blue part to the total profile, measures their combined effects[24]. For Hβ and Mg II, the blue part is the part at wavelength short than 4862.68 and 2800.26 Å, respectively. The distributions of BAI are showed in Figure 2. The median value of the BAI distribution of Mg II is around 0.5, while that of Hβ is smaller than 0.5. Because both Hβ and Mg II show no evidence of shift (see Figure 3), the BAI is primarily caused by the line asymmetry. This indicates that Mg II profile is quite symmetrical in that there are more flux in the red part of Hβ than that in the blue part, which are consistent with the conclusion if the shift and asymmetry of lines are measured separately.

![Figure 2](image-url)

**Figure 2** BAI distributions of Hβ (solid line) and Mg II (dotted line).

A direct comparison between the profiles of Hβ and Mg II is showed in Figure 3. The spectra are normalized at the emission-line-free window 3030 – 3090 Å and the continuum and Fe II multiplets were subtracted. The last panel shows the line ratios of Hβ and Mg II. Black: FWHM(Hβ) < 3000 km/s; Red: 3000 km/s < FWHM(Hβ) < 4000 km/s; Green: 4000 km/s < FWHM(Hβ) < 5500 km/s; Cyan: FWHM(Hβ) > 5500 km/s.

![Figure 3](image-url)

**Figure 3** Composite profiles of Hβ and Mg II of four sub-sample divided by their Hβ FWHM, as well as their difference in velocity space. First two panels are Hβ and Mg II profiles. All these flux are normalized at the emission-line-free window 3030 – 3090 Å and the continuum and Fe II multiplets were subtracted. The last panel shows the line ratios of Hβ and Mg II. Black: FWHM(Hβ) < 3000 km/s; Red: 3000 km/s < FWHM(Hβ) < 4000 km/s; Green: 4000 km/s < FWHM(Hβ) < 5500 km/s; Cyan: FWHM(Hβ) > 5500 km/s.

For the Mg II multiplets are subtracted. The sample is divided into four sub-samples according to Hβ FWHM. The composite Hβ and Mg II profiles of each sub-sample, as well as their line ratio, are showed in Figure 3. The peaks of both Hβ and Mg II do not show evident shift. The flux in the wings increases with the increase of FWHM, while the flux around the line core decreases with the increase of FWHM. The change of Hβ is more rapid than that of Mg II. This indicates that Hβ and Mg II are not cospatial in BLR and the BLR in AGNs is multi-componential. At least two emitting regions are needed: an intermediate line region (ILR) producing the line core and a very broad line region (VBLR) producing the
line wings[36]. The emission in ILR makes larger contribution to the Mg II lines, while the emission in the VBLR makes larger contribution to the Balmer lines[36].

4 Discussion

Different structures of the BLR have been proposed to explain the profiles of emission lines. These models include: a rotating accretion disk, binary black holes, bipolar outflow and anisotropically illuminated spherical BLR (see Eracleous and Halpern 2003 and reference therein)[37], as well as the gravitationally-bound BLR-outflow model of Wang et al. (2011)[24]. The gravitationally-bound BLR-outflow model has succeeded in explaining the profiles of the high ionization C IV line[24], but is not suitable to explain the profile of low ionization Hβ line. This is because Hβ shows a systematically small BAI (<0.5) opposed to the expectation of the model (BAI=0.5). Eracleous and Halpern (2003) found the accretion disk emission could explain the double-peak profile and other spectroscopic properties of AGNs presenting the double-peaked Balmer lines, while other structures are unsatisfactory[37]. They attempted to explain the profiles of Hβ and Mg II using the accretion disk emission, but the model predicts lower Mg II flux than the observed flux. One of the possible reasons is that the BLR is two-componential. The contribution of the ILR to Mg II is critical but is not included in their model.

As showed in Figure 3, the contribution of the VBLR to Hβ and Mg II flux becomes more important with the increase of Hβ FWHM. However, the contribution of the VBLR to σ_{line} may be small, because clouds in the VBLR might be optically thin to the ionization continuum[38]. The emission from the VBLR does not vary with the variability of continuum and contributes little to the variable part of the spectrum. This may be the reason of the systematic deviations between Hβ and Mg II FWHM and σ_{line}. Moreover, the fraction of the contribution of the VBLR to Mg II is much smaller than that to Hβ, which makes the Mg II FWHM systematically smaller than Hβ FWHM. The contribution of the VBLR makes FWHM deviate from σ_{line} systematically and bias the M_{BH} estimation from previous single-epoch mass estimators (M_{BH} ∝ FWHM^2). When estimating the M_{BH} using FWHM as the tracer of the virial velocity, it is crucial to correct the biases by using the fitted index of the M_{BH}∝ FWHM^2 relation, rather than the assumed γ = 2, as suggested by Wang et al. (2009).

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