AGN Broad Line Regions Scale with Bolometric Luminosity[†]

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Abstract: The masses of supermassive black holes in active galactic nuclei (AGN) can be derived spectroscopically via virial mass estimators based on selected broad optical/ultraviolet emission lines. These estimates commonly use the line width as a proxy for the gas speed and the monochromatic continuum luminosity, λL_λ, as a proxy for the radius of the broad line region. However, if the size of the broad line region scales with the *bolometric* AGN luminosity rather than λL_λ, mass estimates based on different emission lines will show a systematic discrepancy which is a function of the color of the AGN continuum. This has actually been observed in mass estimates based on Hα/Hβ and C IV lines, indicating that AGN broad line regions indeed scale with bolometric luminosity. Given that this effect seems to have been overlooked as yet, currently used single-epoch mass estimates are likely to be biased.

Key words: galaxies: active — quasars: emission lines — black hole physics

1. Introduction

Supermassive black holes, with masses ranging from millions to billions of solar masses, are components of probably all galaxies (e.g., Fletcher 2003; Ferrarese & Ford 2005). Accretion of gas onto such black holes gives rise to the phenomenon of active galactic nuclei (AGN) which in turn are able to influence the evolution of their host galaxies via "AGN feedback" (e.g., Fabian 2012). Accordingly, knowledge of the masses of supermassive black holes is of great astrophysical importance.

For nearby galaxies, black hole masses M can be derived from the dynamics of stars (e.g., Bender et al. 2005; Oh et al. 2009), of gas (e.g., Walsh et al. 2013), or of interstellar masers (e.g., Herrnstein et al. 2005). For distant AGN, black hole masses can be derived from spectroscopy of broad optical/ultraviolet emission lines. Such mass estimates make use of a virial relation of the form

$$M = f \frac{v^2 R}{G} \qquad (1)$$

where v is the root-mean-squared line-of-sight gas velocity, R is the (effective) radius of the broad line region, G is Newton's constant, and f is a geometry factor of order unity. The velocity v is derived from the widths of the emission lines. The radius R can be derived via reverberation mapping (Peterson 1993). As radii derived from reverberation mapping are available only for a rather small number of AGN, the monochromatic luminosity of the AGN continuum is commonly used as a proxy for the radius. The virial mass estimator then takes the form

$$M = \kappa \, v^2 \, (\lambda L_\lambda)^\alpha \qquad (2)$$

where L_λ is the specific continuum luminosity at wavelength λ, κ is a constant to be calibrated, and $\alpha \approx 0.5$

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[†]Rapid Communication

(Kaspi et al. 2007; Bentz et al. 2009). The monochromatic luminosities λL_λ are estimated from the continuum close to the emission line from which v is derived. Estimators of this type, for various lines, have been used successfully for deriving black hole masses for large samples of AGN (Greene & Ho 2005; Vestergaard & Peterson 2006; Kim et al. 2010; Park et al. 2013; Jun et al. 2015).

Currently used mass estimators are based on the expectation that the best proxy for the radius of the broad line region for a given line is $R \propto (\lambda L_\lambda)^\alpha$. A priori however, this is an ad-hoc assumption that requires justification, and alternative scalings might be possible. In the following, I thus explore the hypothesis that the sizes of broad line regions do not scale with λL_λ but rather with *bolometric* luminosity.

2. Color Effects

I begin with the assumption that the correct mass estimator based on an optical/ultraviolet emission line i is

$$M_i = \kappa_i \, v_i^2 \, L^\alpha \qquad (3)$$

where L is the *bolometric* luminosity of the optical/ultraviolet AGN continuum and $\alpha \approx 0.5$ for all lines. At least in some cases, we can analyze the same target using two lines a, b, resulting in two mass estimates M_a, M_b. Provided that both mass estimators have been calibrated correctly, the results for M_a and M_b should be identical (within errors) for any given target, meaning

$$\frac{M_a}{M_b} = \frac{\kappa_a}{\kappa_b} \left(\frac{v_a}{v_b} \right)^2 = 1 \, . \qquad (4)$$

If we replace the bolometric luminosity L by the monochromatic luminosity derived from a narrow band

centered on a wavelength λ located close to the emission line to be analyzed, λL_λ, we find a modified mass estimator

$$M_i' = \kappa_i\, v_i^2\, \xi_i\, L_i^\alpha \qquad (5)$$

with $L_i \equiv (\lambda L_\lambda)_i$ for convenience and ξ_i being another constant. When analyzing the same target using two different lines a, b, we find

$$\frac{M_a'}{M_b'} = \frac{\kappa_a}{\kappa_b} \left(\frac{v_a}{v_b}\right)^2 \frac{\xi_a}{\xi_b} \left(\frac{L_a}{L_b}\right)^\alpha . \qquad (6)$$

Applying Equation (4), we can reduce Equation (6) to

$$\frac{M_a'}{M_b'} = \frac{\xi_a}{\xi_b} \left(\frac{L_a}{L_b}\right)^\alpha = \xi_{ab} \left(\frac{L_a}{L_b}\right)^\alpha \qquad (7)$$

using here $\xi_{ab} \equiv (\xi_a/\xi_b)$ for convenience.

Assuming that (i) both mass estimators $M_{a,b}$ have been calibrated independently and using sufficiently representative AGN samples, and (ii) the ratio M_a'/M_b' can be derived for a sufficiently large and representative sample of AGN, the *ensemble average* of the mass ratio, $\langle M_a'/M_b' \rangle$, will be unity (within errors) by construction:

$$\left\langle \frac{M_a'}{M_b'} \right\rangle = \left\langle \xi_{ab} \left(\frac{L_a}{L_b}\right)^\alpha \right\rangle = \xi_{ab} \left\langle \left(\frac{L_a}{L_b}\right)^\alpha \right\rangle = 1 . \quad (8)$$

This relation implies $\xi_{ab} = \langle (L_a/L_b)^\alpha \rangle^{-1}$, at least if the values M_a'/M_b' are derived for a sufficiently large and representative sample. In case of small samples (as frequently the case), ξ_{ab} needs to be estimated separately from the typical optical/ultraviolet color of the AGN continuum.

3. Comparison to Observations

Arguably the most careful cross-analysis of different mass estimators is provided by Assef et al. (2011) who compare mass estimates based on the C IV $\lambda 1549$ line to those based on the hydrogen Balmer lines Hα $\lambda 6565$ and Hβ $\lambda 4863$ (with all wavelengths in Å). Assef et al. (2011) apply the mass estimators

$$\frac{M_{H\beta}'}{M_\odot} = 6.71{\times}10^6 f \left(\frac{v_{H\beta}}{10^6\,\mathrm{m\,s^{-1}}}\right)^2 \left(\frac{L_{5100}}{10^{37}\,\mathrm{W}}\right)^{0.52}$$

$$\frac{M_{H\alpha}'}{M_\odot} = 7.68{\times}10^6 f \left(\frac{v_{H\alpha}}{10^6\,\mathrm{m\,s^{-1}}}\right)^{2.06} \left(\frac{L_{5100}}{10^{37}\,\mathrm{W}}\right)^{0.52}$$

$$\frac{M_{C\,IV}'}{M_\odot} = 10^\epsilon \left(\frac{v_{C\,IV}}{10^6\,\mathrm{m\,s^{-1}}}\right)^2 \left(\frac{L_{1350}}{10^{37}\,\mathrm{W}}\right)^{0.53}, \qquad (9)$$

drawn from Greene & Ho (2005), Vestergaard & Peterson (2006), and Bentz et al. (2009), to a sample of 12 lensed high-redshift quasars. Here L_{1350} and L_{5100} denote the continuum luminosities λL_λ derived at 1350 Å and 5100 Å, respectively; the values of the constants f and ϵ depend on if v is derived from the dispersion or the FWHM of a line. The relation between $M_{H\alpha}'$ and $v_{H\alpha}$ is actually $M_{H\alpha}' \propto v_{H\alpha}^{2.06\pm0.06}$, i.e., consistent with

$M \propto v^2$. Likewise, the power law indices of L_{1350} and L_{5100} are consistent with 0.5 within errors.

From their analysis, Assef et al. (2011) find a systematic discrepancy between the masses derived from the Balmer lines on the one hand and from C IV on the other hand. This discrepancy follows the relation (their Equation 8)

$$\frac{M_H'}{M_{C\,IV}'} = 10^{-y} \left(\frac{L_{1350}}{L_{5100}}\right)^{-x} \qquad (10)$$

where the subscript H denotes either Hα or Hβ. Depending on which Balmer line and which velocity indicator (line dispersion or line FWHM) is used, best-fit values range from 0.51 ± 0.14 to 0.95 ± 0.22 for x and -0.11 ± 0.06 to -0.27 ± 0.08 for y.

If indeed the broad line region radius scales with bolometric luminosity rather than with λL_λ, i.e., if Equation (3) gives the true underlying relation, then Equations (7) and (10) are equivalent. This can be checked in a straightforward manner by identifying either Hα or Hβ with "line a" and C IV with "line b". Evidently, Equation (7) predicts $\alpha = x$. Indeed, the values observed by Assef et al. (2011) for x are in agreement with $\alpha \approx 0.5$ within errors.

The *ensemble averaged* optical/ultraviolet continuum of quasars is known to follow the relation $\lambda L_\lambda \propto \lambda^{-0.56}$ in the wavelength range 1300–5500 Å (Vanden Berk et al. 2001). Using $\alpha = 0.5$, this implies[1] $\xi_{ab} \approx [(5100\,\text{Å}/1350\,\text{Å})^{-0.56}]^{-0.5} \approx 1.45$. Comparison of Equations (7) and (10) leads to the prediction $\log \xi_{ab} \approx 0.16 = -y$. Within errors, this is in agreement with the values observed by Assef et al. (2011).

4. Discussion and Conclusions

From the analysis provided in Section 3, it is straightforward to see that the observed systematic discrepancy between mass estimates based on different emission lines is in agreement with AGN broad line regions scaling with bolometric rather than monochromatic luminosity. On the one hand, the fact that AGN broad line regions are shaped by both the optical/ultraviolet and the ionizing Lyman continuum was already noted by Peterson (1993) and Baldwin et al. (1995). On the other hand, little effort has been made so far to distinguish scalings with L from those with λL_λ observationally. It now seems that the data of Assef et al. (2011) provide the as yet most direct evidence for a scaling of the radii of AGN broad line regions with bolometric luminosity.

Comparisons of black hole masses derived from optical and ultraviolet lines usually focus on the line widths rather than the broad line region radii (cf., e.g., Ho et al. 2012 vs. Runnoe et al. 2013); this might explain why color effects have largely been overlooked so far. Even though, an independent hint might have been provided by the *Baldwin effect* (Baldwin 1977), a characteristic anticorrelation between the equivalent widths

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[1] I use here $\langle (L_a/L_b)^\alpha \rangle^{-1} \approx \langle L_a/L_b \rangle^{-\alpha}$. This is possible because the ratio L_a/L_b is of order unity always and $0.56\alpha < 1$.

of ultraviolet emission lines and continuum luminosity: whereas equivalent widths are usually discussed as function of λL_λ, the actual underlying correlation might be the one between equivalent width and bolometric luminosity (cf., Xu et al. 2008, and references therein).

When expressed as functions of bolometric AGN luminosity (to ease comparisons of different lines), characteristic broad line region radii can be assigned to individual emission lines; for the case of Hβ vs. C IV, the radii of the former are about three times larger than the radii of the latter in general (cf., Chapter 7.1.8 of Netzer 2013). Such a gas stratification is the natural consequence of the differences in ionization potential; lines requiring higher excitation or ionization energies have to be located closer to the central source of radiation. Indeed, studies of the radius–luminosity relationships of broad line regions assume (at least implicitly) that λL_λ is a sufficient proxy for the bolometric continuum luminosity (e.g., Kaspi et al. 2007; Bentz et al. 2009). Such studies derive radius–luminosity relationships, as well as black hole mass–luminosity relationships, by analyzing radius or mass as function of λL_λ and applying global scaling factors that implicitly include an *ensemble averaged* bolometric correction. However, if broad line regions scale with bolometric AGN luminosity, bolometric corrections need to be applied *source by source*. As demonstrated by Assef et al. (2011), neglecting colors and bolometric corrections leads to differences up to a factor of four between black hole masses estimated from the Balmer lines and C IV, respectively. This also suggests that *all* emission-line based mass estimators are biased to varying degrees.

Assuming a scaling of mass estimates with bolometric luminosity, the cross-comparison of non-simultaneous virial mass estimates based on different lines is affected by the variability of the AGN luminosity. Quasars are known to vary in luminosity by factors up to about three on time scales of years (e.g., Schramm et al. 1993); AGN variability in general obeys *red noise* statistics, meaning that stronger variations occur on longer time scales (Park & Trippe 2012, 2014; Kim & Trippe 2013). However, such variability cannot introduce systematic trends into samples of sources; rather, it increases the measurement error for individual sources. In general, variability effects are relatively moderate because only the square root of the luminosity enters the mass estimate. The individual mass estimates used by Assef et al. (2011) come with errors of around 0.3 dex; accordingly, variations in luminosity up to factors of about 5 would be within the measurement errors (because $\log(\sqrt{5}) = 0.35$).

The discussion provided in this paper, along with the one by Assef et al. (2011), illustrates once more the fact that any systematic scatter in a given relation, like the one between mass estimates based on Hα/Hβ and C IV, is indicative of hidden parameters. Only a careful analysis of the impact of AGN continuum color eventually leads to the insight that AGN broad line regions scale with bolometric luminosity rather than λL_λ. (Another recent example is provided by the relation be-

tween Bondi accretion rate and kinetic jet power in radio galaxies; Trippe 2014.) In turn, blind application of "standard" relations despite the presence of obvious systematic scatter comes with the risk of producing results that are seriously biased.

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