NEW ESTIMATORS OF BLACK HOLE MASS IN ACTIVE GALACTIC NUCLEI WITH HYDROGEN PASCHEN LINES

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ABSTRACT

More than 50% of active galactic nuclei (AGNs) are suspected to be red and affected by dust obscuration. Meanwhile, popular spectral diagnostics of AGNs are based on optical or ultraviolet light, making dust obscuration the primary concern for understanding the general nature of AGNs and the supermassive black holes residing in them. To provide a method for investigating properties of dusty AGNs, we derive new black hole (BH) mass estimators based on velocity widths and luminosities of near-infrared (NIR) hydrogen emission lines such as Pβ and Pγ, and also investigate the line ratios of these hydrogen lines. To derive the BH mass (MBH) estimators, we used a sample of 37 unobscured type 1 AGNs with an MBH range of 10⁶.8–10⁹.4 M☉, where MBH comes from either the reverberation mapping method or single-epoch measurement method using Balmer lines. Our work shows that MBH can be estimated from the Paschen line luminosities and velocity widths to an accuracy of 0.18–0.24 dex (rms scatter). We also show that the mean line ratios of the Paschen lines and the Balmer lines are Hβ/Hγ ≃ 9.00, Hα/β ≃ 2.70, which are consistent with case B recombination under a typical AGN broad-line region (BLR) environment. These ratios can be used as reference points when estimating the amount of dust extinction over the BLR for red AGNs. We expect the future application of the new BH mass estimators on red, dusty AGNs to provide a fresh view of obscured AGNs.

Key words: galaxies: active – galaxies: nuclei – infrared: galaxies – quasars: emission lines – quasars: general

Online-only material: color figures

1. INTRODUCTION

Supermassive black holes (SMBHs), found at centers of massive spheroids and active galaxies, are considered to play an important role in the formation and evolution of galaxies. It is suggested that SMBHs regulate the star formation activities of galaxies through their enormous energy output during their active phases, providing a feedback mechanism to reconcile the observed trend of galaxy evolution downsizing with hierarchical galaxy formation models (Juneau et al. 2005; Bundy et al. 2006; Schawinski et al. 2006). However, the co-evolution of SMBHs and their host galaxies stand as an unsolved astrophysical problem, as such a process needs to eventually lead to a rather unexpected tight correlation between host galaxy properties and SMBH mass today (Ferrarese & Merritt 2000; Gebhardt et al. 2000; Tremaine et al. 2002).

One of the great challenges in understanding the evolutionary sequence of active galactic nuclei (AGNs) and the co-evolution of SMBHs and their host galaxies comes from the so-called red or dusty AGNs which are believed to occupy more than 50% of the AGN population (Comastri et al. 2001; Tozzi et al. 2006; Polletta et al. 2008). Red, dusty AGNs are expected, if the initial phase of AGN activity starts in a dust-enshrouded environment such as within massive starburst regions of luminous infrared galaxies. In such a scenario, AGNs become more visible after sweeping away cold gas and dust that are necessary to sustain the massive star formation in their host galaxies (Hopkins & Hernquist 2006). On the other hand, dust obscuration can arise in a different way in the unified model of AGNs when accretion disks and broad-line regions (BLRs) around SMBHs are viewed through a dusty torus. In any case, red, dusty AGNs can shed light on the properties and the evolution of the AGN population in general.

The phenomenological definition of “red, dusty AGNs” is rather broad. It can include AGNs selected using a variety of ways such as those selected by very red colors in optical through NIR and the radio detection (e.g., R–K > 5 mag and J–K > 1.3 mag of the sample in Urrutia et al. 2009; also see Cutri et al. 2001), red MIR colors (Lacy et al. 2004; Lee et al. 2008), and hard X-ray detections (e.g., Polletta et al. 2007). These different kinds of AGNs have a common characteristic: their SEDs are red, due to the obscuration of their light by the foreground gas and dust. Hence, they are considered to be the intermediate population between the dust-enshrouded star-forming galaxies and the unobscured AGNs. The dust obscuration does not necessarily exclude type 1 AGNs (AGNs with broad emission lines; e.g., Alonso-Herrero et al. 2006), as red, dusty AGNs with broad emission lines are found quite often. Of 23 X-ray QSOs with IR power-law spectral energy distributions and spectroscopic redshift identifications, 14 are classified as broad-line AGNs (Szokoly et al. 2004; Alonso-Herrero et al. 2006). More than 50% of the red AGNs with the radio and red optical/NIR color selection are found to be type 1 AGNs which can have the reddening parameter of 2 or more (Urrutia et al. 2009; Glikman et al. 2007). The existence of broad-line AGNs among red, dusty AGNs opens a possibility of studying the properties of dust-obscured quasars in more detail using traditional type 1 AGN diagnostics.

However, even the measurement of the most basic AGN parameters such as MBH and the Eddington ratio (the accretion rate) is a difficult task for the red, dusty AGNs. In general, MBH are derived from the optical or the ultraviolet (UV) part of the AGN spectra for which spectral diagnostics are well established. In the case of dusty AGNs, the dust obscures or significantly reduces the UV or the optical light coming from the region around SMBHs, making the popular AGN optical/
UV spectroscopic diagnostics useless. For example, popular \( M_{\text{BH}} \) estimators are based upon a virial relation between two parameters—the velocity width of the broad H\( \alpha \) or H\( \beta \) lines, and the size of BLR estimated from the continuum luminosity at 5100 Å (Kaspi et al. 2000) or the luminosities of H\( \alpha \) or H\( \beta \) (Greene & Ho 2005). If the light from a red, dusty AGN is extincted by a color excess of \( E(B-V) = 2 \) mag (Glikman et al. 2007; Urrutia et al. 2009), its H\( \alpha \) and H\( \beta \) line fluxes would be suppressed by a factor of 100 and 1000, respectively. One can try to estimate the amount of the dust extinction from a continuum fitting of the optical–UV spectrum or through the Balmer decrement, but such estimates are often inconsistent with each other and accompanied by uncertainties of the order of \( \delta E(B-V) \sim 0.5 \) mag or more which are related to the dispersion in the intrinsic properties of AGNs. The dust obscuration can arise from the Galactic extinction for AGNs at low galactic latitude (e.g., Im et al. 2007; Lee et al. 2008).

The problem can be substantially alleviated if we can use NIR lines instead of optical or UV lines, since NIR hydrogen lines such as Pa\( \alpha \) and Pa\( \beta \) are much less affected by the dust extinction than the UV/optical light. For the red, dusty AGNs with the color excess of \( E(B-V) = 2 \) mag, the line fluxes of Pa\( \alpha \) and Pa\( \beta \) are suppressed by a factor of only 2.3 and 4.7, respectively. This is a significant improvement over the optical lines. Since \( M_{\text{BH}} \propto L^2 \), where \( L \) is a luminosity of the continuum or an emission line, the suppression in the Paschen line luminosities introduces uncertainties in \( M_{\text{BH}} \) estimates only at the level of a factor of 2 or less, even without correcting for the dust extinction with the Paschen decrement.

In this paper, we will derive the \( M_{\text{BH}} \) estimators based on the NIR hydrogen lines of type 1 AGNs and investigate the line ratios of the Paschen lines, keeping in mind future applications of such relations to studies of dusty, red AGNs with broad emission lines.

2. DATA

2.1. The Sample

In order to construct mass estimators based on the NIR hydrogen lines, we used two samples of low-redshift type 1 AGNs with NIR spectra at 0.8–4.1 \( \mu \)m. One is from Landt et al. (2008; hereafter L08) who studied 23 well-known type 1 AGNs in the local universe. Among these, we use 16 and 21 AGNs that have line flux and width measurements in Pa\( \alpha \) or Pa\( \beta \) lines, respectively. Note that we excluded four objects, Mrk 590, NGC 5548, Ark 564, and NGC 7469, in all or some of our analysis even though Pa\( \alpha \) and Pa\( \beta \) line fluxes and FWHM measurements were available. For Ark 564 and NGC 7469, the FWHM values of Pa\( \alpha \) and Pa\( \beta \) lines listed in L08 are too discrepant from each other, differing by more than a factor of 1.5. This suggests that one of the two measurements is erroneous. Therefore, these two objects are excluded from all of the analysis performed below. For Mrk 590 and NGC 5548, the H\( \alpha \) and the H\( \beta \) widths listed in L08 differ by more than a factor of 1.5, but the Paschen line widths are consistent with each other. These two objects are excluded in the analysis of the correlation between the Paschen and Balmer lines, but their reverberation-mapping-derived \( M_{\text{BH}} \) are retained for the derivation of the black hole (BH) estimators (of method 2 and method 3 in Section 3.2).

Another sample comes from Glikman et al. (2006; hereafter G06). The G06 sample is made of 26 type 1 AGNs that were selected from a cross-match between the SDSS-DR1 quasar catalog (Schneider et al. 2003) and the Two Micron All Sky Survey (2MASS; Skrutskie et al. 2006), with the criteria of \( K < 14.5 \) mag, redshift \( z < 0.5 \), and the absolute magnitude in the \( i \) band \( M_i < -23 \) mag. Here, the absolute magnitude limit is imposed to minimize the contamination of the quasar light due to the host galaxy. The G06 sample provides 11 AGNs with Pa\( \alpha \) lines and 14 AGNs with Pa\( \beta \) lines showing up in their NIR spectra.

In all, we use 27 and 35 type 1 AGNs for the Pa\( \alpha \) and the Pa\( \beta \) line analyses, respectively. Table 1 summarizes the properties of these AGNs.

2.2. Black Hole Mass and Analysis of Optical Spectra

For the \( M_{\text{BH}} \) of our sample AGNs, we use the following values.

First, we use the \( M_{\text{BH}} \) derived with the reverberation mapping method from the literature if available. This applies to 10 AGNs with Pa\( \alpha \) and 11 AGNs Pa\( \beta \) data in L08 for which the \( M_{\text{BH}} \) are taken from Vestergaard & Peterson (2006).

Second, if the \( M_{\text{BH}} \) from the reverberation mapping method are not available, we derived the \( M_{\text{BH}} \) from the optical spectral information using single epoch \( M_{\text{BH}} \) estimators. For the L08 sample without the reverberation-mapping-derived \( M_{\text{BH}} \), we used the H\( \beta \) luminosity and FWHM listed in Table 5 of L08 to derive their \( M_{\text{BH}} \). For this, we adopted an \( M_{\text{BH}} \) estimator in Greene & Ho (2005), after adjusting their relation to have the virial factor of 5.5 (Onken et al. 2004; Woo et al. 2010) by multiplying their relation by a factor of 1.8. We also made a small correction to the L08 FWHM and luminosity values, since the way Greene & Ho (2005) derived FWHMs and luminosities is different from what L08 did—Greene & Ho (2005) adopted a multiple Gaussian component fitting to the broad line, while L08 adopted a single component fitting of the broad line after removing narrow-line components. We find the correction factor to be \( \text{FWHM}_{\text{multi}}/\text{FWHM}_{\text{single}} = 0.9 \) and \( \text{FWHM}_{\text{multi}}/\text{FWHM}_{\text{single}} = 1.08 \) on average through fitting of the Sloan Digital Sky Survey (SDSS) spectra of the G06 sample with the two methods (see below).

For the G06 sample, none of the objects have \( M_{\text{BH}} \) derived from the reverberation mapping method. Some of the G06 samples have their H\( \beta \) line luminosities and FWHMs listed in Shen et al. (2008), but after checking FWHM values in Shen et al. (2008) and the optical spectra, we find cases where FWHMs appear to be overestimated. Therefore, we used our own spectral-fitting routine (Kim et al. 2006) to obtain the H\( \beta \) FWHMs and the H\( \beta \) luminosities from the SDSS spectra. The fitting model includes components for a power-law continuum, the host galaxy light, broad Fe \( \lambda \) multiplet emissions, a Balmer continuum, and multiple Gaussian profiles for broad and narrow emission lines. The FWHM and the line luminosities are derived from the best-fit model profiles of the broad-line component, which can consist of a sum of multiple Gaussian components.

From the derived luminosity and FWHM values, we estimated \( M_{\text{BH}} \) by using an updated version of the H\( \beta \)-based virial mass estimator (Greene & Ho 2005). We updated Equation (7) in Greene & Ho (2005), by adopting a newer \( R_{\text{BLR}}/L_{\text{1000}} \) relation, i.e., Equation (2) of Bentz et al. (2009). The updated relation is given below:

\[
\frac{M}{M_\odot} = 10^{6.88\pm0.57} \left( \frac{L_{\text{H}\beta}}{10^{42} \text{ erg s}^{-1}} \right)^{0.46\pm0.05} \left( \frac{\text{FWHM}_{\text{H}\beta}}{10^3 \text{ km s}^{-1}} \right)^2.
\]

(1)

Again, a proper adjustment was made for the virial factor in order to make the relation consistent with the virial factor in
Vestergaard & Peterson (2006). The derived BH masses are listed in Table 1.

### Table 1
Paschen Parameters and BH Masses

| AGNs Name | Redshift | BH Mass | Pβ | Ps |
|-----------|----------|---------|-----|----|
|           | z        | log(M/M☉) | FWHM | ∆FWHM |
|           |          |         | (km s⁻¹) | (km s⁻¹) |
|           |          |         | Flux | ∆Flux |
|           |          |         | (erg s⁻¹ cm⁻²) | (erg s⁻¹ cm⁻²) |
| 3C273a    | 0.158    | 8.94d   | 2608 | ... |
| Mkn 876a  | 0.129    | 8.44c   | 5433 | ... |
| PG0644+349a | 0.064 | 7.96c   | 2144 | ... |
| Mkn 110  | 0.035    | 7.40c   | 1689 | ... |
| Mkn 599a  | 0.034    | 8.15c   | 2755 | ... |
| Arko 104a | 0.033    | 8.17c   | 4610 | ... |
| Mkn 817a  | 0.031    | 7.69c   | 4998 | ... |
| Mkn 335a  | 0.026    | 7.15c   | 1633 | ... |
| Mkn 590a  | 0.026    | 7.67c   | 3565 | ... |
| NGC 5548a | 0.017    | 7.82c   | 5891 | ... |
| NGC 4151a | 0.003    | 7.12c   | 4204 | ... |
| H1821+643a | 0.297 | 9.44d   | 4717 | ... |
| PDS456a   | 0.184    | 8.70d   | 1828 | ... |
| Mkn 290a  | 0.030    | 8.09d   | 3818 | ... |
| H2106−099a | 0.027 | 7.72d   | 2155 | ... |
| Mkn 79a   | 0.022    | 7.94d   | 3163 | ... |
| NGC 4593a | 0.009    | 7.83d   | 3407 | ... |
| NGC 3227a | 0.004    | 7.42d   | 2680 | ... |
| HE 1228+013b | 0.117 | 7.87d | 1731 | ... |
| H1934−063a | 0.011 | 6.80d | 1241 | ... |
| IRAS1750+508a | 0.300 | 8.33d | 1758 | ... |
| SDSS000943.1−000839.2b | 0.210 | 8.44c | 4817 | 818 |
| SDSS005812.8+160201.3b | 0.211 | 8.29c | 3158 | 409 |
| SDSS010226.3−003904.6b | 0.295 | 7.67c | 1565 | 184 |
| SDSS011110.0−101613.1b | 0.179 | 8.20c | 3695 | 496 |
| SDSS015530.0−085704.0b | 0.165 | 8.85c | 7355 | 1032 |
| SDSS015910.4+010514.5b | 0.217 | 7.98c | 2657 | 404 |
| SDSS015950.2+023430.8b | 0.163 | 8.09c | 2657 | 391 |
| SDSS021077.8−084743.4b | 0.292 | 7.84c | 1970 | 552 |
| SDSS024520.8−075914.2b | 0.378 | 8.00c | 1329 | 194 |
| SDSS031209.2−081013.8b | 0.265 | 8.29c | 3540 | 620 |
| SDSS032213.8+005513.4b | 0.185 | 8.03c | 2014 | 234 |
| SDSS150610.5+021649.9b | 0.135 | 8.11c | ... | ... |
| SDSS172711.8+632241.8b | 0.218 | 8.61c | ... | ... |
| SDSS211843.2−063618.0b | 0.328 | 8.42c | 2485 | 430 |
| SDSS234932.7−003645.4b | 0.279 | 8.19c | 2578 | 360 |
| SDSS235156.1−010913.3b | 0.174 | 8.89c | 6137 | 705 |

Notes.

* FWHM and Flux of these objects come from L08.
* FWHM and Flux of these objects are measured from spectra presented in G06.
* The Mfir values are determined from reverberation mapping techniques (Vestergaard & Peterson 2006).
* The Mfir values are based on Hβ widths and luminosities in L08.
* The Mfir values are based on Hβ widths and L,(5100) derived from our fit to SDSS spectra.

2.3. Analysis of NIR Spectra and Line Information

The G06 data were taken mostly with the SpeX instrument on the Infrared Telescope Facility (IRTF) with the spectral resolution of \( \frac{\lambda}{\Delta \lambda} \approx 1200 \) at 0.8–2.5 \( \mu \)m, and \( \frac{\lambda}{\Delta \lambda} \approx 1500 \) at 1.9–4.1 \( \mu \)m. G06 provide the flux-calibrated, reduced NIR spectra, and we used the following procedure to measure the Paschen line fluxes and FWHMs of the G06 sample. The G06 spectra were converted to the rest frame, and then the continuum around the Paschen lines was determined by fitting a linear function to the continuum at regions near the Paschen lines (Figure 1). We varied the wavelength centers and widths of the continuum-fitting regions, but typical values are chosen to be \(~2\) FWHM of the broad component of the Hβ line away from the Paschen line center and the width of 0.02 \( \mu \)m for the continuum-fitting region centers and widths, respectively. For the Ps line, this corresponds to the wavelength regions centered somewhere at 1.82 to 1.84 \( \mu \)m and 1.90 to 1.92 \( \mu \)m with the width of 0.02 \( \mu \)m, while for the Pβ line the wavelength centers are somewhere at 1.23 to 1.25 \( \mu \)m and 1.31 to 1.33 \( \mu \)m. When the continuum shows data points affected by imperfect sky subtraction, we adjusted the continuum-fitting regions. Also, the width of the continuum-fitting regions is varied from 0.01 to 0.03 \( \mu \)m, and the center wavelengths are shifted by 0.01–0.02 \( \mu \)m to provide robust measurements. Although the NIR spectra of type 1 AGNs are known to be dominated by black body radiation from warm dust, we find that the linear fitting of the continuum over the limited wavelength range provides a reasonable approximation of the continuum around the Paschen lines (see Figure 2; also see L08). After the
continuum subtraction, we used a single Gaussian function to fit an emission line. The fitted parameters are multiplied by correction factors to correct for systematic errors in the single component fitting (see the next paragraph). During the fitting, we set free the central wavelength of each Gaussian component. Therefore, the free parameters of the fit are FWHM, flux, and the central wavelength for the Gaussian component. The fit was performed with the MPFITEXPR procedure of the IDL. Figures 2 and 3 show the line-fitting results. The fits provide a formal error of 12% in flux and 9% in FWHM. We also estimated the error arising from uncertainties related to how the continuum is determined. This was done by varying the regions for the continuum fitting as described earlier. We find that the average uncertainty arising from the continuum determination is 4% (flux), 3% (FWHM), although we find cases where the FWHM values change by as much as 25%. Such cases occur when there is an extended feature at the wing of the emission line which may or may not be a true feature. The total errors in the flux and FWHM measurements are taken as the square root of the quadratic sum of the formal fitting error and the error from the continuum determination, which are found to be typically 12% and 9%.

Fitting a multiple component line with a single Gaussian function can produce systematic errors in the fitted parameters, and we tried to correct for such a bias by applying correction factors that are derived from Balmer lines. This is done by comparing the broad line widths and the line fluxes from multiple component fits of Balmer lines versus the fitted parameters from a single component fit of the same Balmer lines. In doing so, we correct potential systematics arising from not removing the narrow line components in the fitting process, too. The correction factors are computed for each object and they range over 0.74–1.01 with the mean of 0.91 for the FWHM ratios ($FWHMLmulti/FWHMLsingle$) and 0.98–1.17 for the line flux ratio with the mean of 1.06 ($Lmulti/Lsingle$). This procedure assumes that the line profile shapes of the Paschen lines follow those of the Balmer lines.

To confirm this assumption, we compared the Pβ line profiles with the model-fitted line profiles of Hα. Only the Pβ lines with S/N > 25 are shown in Figure 4. The Pβ lines are plotted as histograms with error bars, while the Hα lines are indicated with thick solid lines. The thin dotted lines and the thick dashed lines represent the broad and the narrow components of the Hα lines. The Pβ profiles are normalized to have the maximum value of 1, while the Hα are normalized to have the same total flux as the normalized Pβ profiles. Figure 4 demonstrates that the Pβ profile shapes are consistent with those of the Hα profiles, except for the width and the overall normalization, supporting our assumption that the Paschen line profiles are similar to those of the Balmer lines. We also tried fitting the Paschen line profiles with double Gaussian profiles for objects that seem to have narrow line components (SDSSJ010226.3−003904.6, SDSSJ015530.0−085704.0, SDSSJ015950.2+002340.8, SDSSJ031209.2−081013.8, SDSSJ015910.0+010514.5, SDSSJ235156.1−010913.3, SDSSJ000943.1−090839.2, and

Figure 1. Example of the continuum fitting of the G06 NIR spectra. On the top panel, we show the NIR spectrum of SDSSJ032213.8+005513.4, where the blue solid line indicates the continuum fit to the Pα wavelength region and the red solid line shows the continuum fit to the Pβ wavelength area. The wavelength ranges that were used for determining the continuum are indicated with the vertical dashed lines. In the bottom panels, we show the expanded views around Pβ and Pα lines together with the determined continuum.

(A color version of this figure is available in the online journal.)
For Hβ, we find that the double Gaussian fitting returns FWHM values greater than those from the single Gaussian fitting by a factor of 1.08 in average. However, the double Gaussian fitting (one for narrow line and another for broad line) tends to return FWHM values greater than the results from the multiple component fitting. Thus, another correction factor is needed to convert the double Gaussian fitting result to the multiple Gaussian fitting result, and the result from this double Gaussian fitting test should be taken seriously. We are presenting a result from this test in order to see if we find the same kind of dependence of fitted parameters on the fitting method which we find in the Balmer lines as a way to support our assumption that the Paschen line profiles are similar to the Balmer line profiles.

In most cases, the fitted values from the double component fit agree with those from the single component fit (without...
Figure 3. Gaussian fits of the Paschen lines of the G06 sample. AGNs with only Pa or Pb measurements are shown here. The meaning of the lines is identical to Figure 2.

the additional correction factor), where the FWHM and flux values from the double component fittings are in average 7% larger and 2% smaller than the single component fitting results, respectively. This agrees well with the trend we find from our analysis of the Balmer lines using single, double, and multiple component Gaussian fittings (see above). One exception is SDSSJ015950.2+002340.8 whose FWHM changed by about 50%. Distinguishing the narrow and the broad components is difficult for this object, therefore, the mean value between the parameters from the two different methods was adopted as the best-fit value, with half of the difference as its error. We note that the double component fit improved the reduced $\chi^2$ values significantly ($>1.3$) for only three objects, where the improvement came from the fitting of broad extended wings, which did not affect the derived fitting parameter values, rather than through the change of the FWHM values (except for SDSSJ015950.2+002340.8).

Finally, the measured FWHMs were corrected for the instrumental resolution and the fitting methodology (multiple component fit versus single component fit), and the fluxes were converted to the luminosity assuming a standard ΛCDM cosmology of $H_0 = 70$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.3$, and $\Omega_{\Lambda} = 0.7$ (e.g., Im et al. 1997). The measured line luminosities, fluxes, and FWHMs are presented in Table 1.

L08 present the results of their line analysis, based on the NIR spectra that were taken with the Spex spectrograph (Rayner et al. 2003) on IRTF at an average spectral resolution of 400 km s$^{-1}$. For the L08 sample, we use the line fluxes and FWHMs they derived and presented in their Table 2, after correcting FWHM values for the instrumental resolution. We also applied the correction factor of FWHM$_{\text{multi}}$/FWHM$_{\text{single broad}} = 0.9$ and $L_{\text{multi}}/L_{\text{single broad}} = 1.08$, which corrects for the difference in the line-fitting methods (L08 versus Greene & Ho 2005) to derive the line parameters which are similar to the correction factors we derived for the fitting process of the G06 spectra. As for the accuracy of the L08 measurements, L08 quote a typical error of 10% or less. Therefore, we adopt a conservative value of 10% for the measurement error of the fluxes and the FWHMs presented in L08.

We note that contamination from the host galaxy light to these measurements is negligible. The contamination of the line flux due to the host galaxy is possible, but the G06 data were taken with a narrow slit to minimize the host galaxy light to less than 8%. We expect that the same statement holds true for the L08 sample whose data were taken with a narrow slit for AGNs at $z<0.1$, which are located much closer to us than the G06 sample.

3. RESULTS

3.1. Empirical Relation Between Balmer and Paschen Lines

Before constructing mass estimators based on the Paschen lines, we show here how well the properties of the Paschen lines correlate with the Balmer lines. A tight correlation between the two lines would imply that the Paschen lines originate from the BLRs, similar to the Balmer lines, thus serving as a strong justification for the use of the Paschen lines as a mass estimator. Good correlations between the FWHM values of the broad Balmer lines and the broad Paschen lines were shown in L08. Here, we extend the analysis to the line flux ratios, and add quasars from the G06 sample to the L08 sample to strengthen the goodness of the FWHM correlation. Furthermore, we also derive equations that relate the properties of the Balmer and the Paschen lines. Figure 5 shows the correlation between the FWHM values of the Balmer and the Paschen broad lines, while Figure 6 shows a correlation of line luminosities of the broad lines. To derive the correlations between the two quantities, we
Figure 4. Comparison of the Pβ line profiles against the Hα line profiles. Only objects with Pβ line S/N > 25 are shown here (histogram with errors). The Hα lines are indicated with thick solid lines, and the thin dotted lines and the thick dashed lines represent the broad and the narrow components of the Hα lines. The Pβ profiles are normalized to have the maximum value of 1 while the Hα are normalized to have the same total flux as the normalized Pβ profiles. The figure shows that the Pβ line profile shapes are consistent with the Hα profile shapes.

(A color version of this figure is available in the online journal.)

performed a linear bisector fit using the equations below:

\[
\log \left( \frac{\text{FWHM}_Y}{1000 \text{ km s}^{-1}} \right) = A + B \log \left( \frac{\text{FWHM}_X}{1000 \text{ km s}^{-1}} \right) \tag{2}
\]

\[
\log \left( \frac{L_Y}{10^{42} \text{ erg s}^{-1}} \right) = C + D \log \left( \frac{L_X}{10^{42} \text{ erg s}^{-1}} \right). \tag{3}
\]

Here, X and Y are line identifiers, and A and B are the correlation coefficients in the fit for FWHM, and C and D are the coefficients for the line luminosity ratio fit. The results of the fitting are summarized in Table 2. The table also lists the rms scatter of the data points with respect to the best-fit lines.

These results show that the Paschen line luminosities and FWHMs correlate well with those of the Balmer lines. The rms
Figure 5. Comparison of the FWHM widths of the Paschen lines vs. the Balmer lines. The top panels compare the $\text{P}_\alpha$ FWHMs vs. the Balmer line FWHMs, while the bottom panels show the comparison of the $\text{P}_\beta$ FWHMs vs. the Balmer line FWHMs. The open circles are for AGNs from G06, while the red triangles are for the L08 sample. The solid line indicates a line where the Balmer and the Paschen quantities are identical. The dotted line indicates the best-fit line between the two quantities as described in the text.

(A color version of this figure is available in the online journal.)

Table 2

| No. | Y     | X     | FWHM   | Line Luminosity |
|-----|-------|-------|--------|-----------------|
|     |       |       | A      | B               | C        | D        | rms (dex) |
| 1   | $\text{H}\alpha$ | $\text{P}_\alpha$ | 0.074 ± 0.038 | 0.934 ± 0.084 | 0.916 ± 0.014 | 0.961 ± 0.025 | 0.141 |
| 2   | $\text{H}\beta$ | $\text{P}_\alpha$ | 0.105 ± 0.037 | 1.017 ± 0.080 | 0.444 ± 0.013 | 0.910 ± 0.018 | 0.188 |
| 3   | $\text{H}\alpha$ | $\text{P}_\beta$ | 0.076 ± 0.038 | 0.821 ± 0.075 | 0.985 ± 0.012 | 1.008 ± 0.015 | 0.117 |
| 4   | $\text{H}\beta$ | $\text{P}_\beta$ | 0.113 ± 0.033 | 0.895 ± 0.068 | 0.517 ± 0.011 | 0.943 ± 0.013 | 0.162 |
scatters in the line luminosity correlation are $\sim0.12$–0.14 dex against H$_\alpha$ and $\sim0.16$–0.19 dex against H$_\beta$. For the FWHM values, the rms scatters are 0.045–0.06 dex against H$_\alpha$ and 0.05–0.06 dex against H$_\beta$. The slightly larger scatters and a notable offset in FWHM values of H$_\beta$ against Paschen lines suggest the complexities in AGN spectra around the H$_\beta$ line noted in L08, an excess, broad component in the red part of the H$_\beta$ line caused by an unclear origin (e.g., Meyers & Peterson 1985; Véron et al. 2002). We also point out that the line widths of Balmer lines are systematically larger than those of the Paschen lines, and that the trend is stronger as the wavelength decreases.

This suggests that the Paschen broad lines and the Balmer broad lines originate from a similar BLR, but with Balmer lines originating from the inner region of the BLR than Paschen lines.

Similarly, we also examine correlations between ($L_{5100}$) and $L_{P\alpha,\beta}$. $R_{\text{BLR}}$ values are derived from $L(5100)$ using Equation (4) of Greene & Ho (2005). Figure 7 shows the correlation between $R_{\text{BLR}}$ and Paschen line luminosities, and Equations (4) and (5) are the best-fit results:

$$R_{BLR} = (50.5 \pm 1.0) \left(\frac{L_{P\alpha}}{10^{42} \text{ erg s}^{-1}}\right)^{(0.40 \pm 0.01)} \text{lt-days},$$

Figure 6. Comparison of the Paschen line luminosities against those of the Balmer lines. The top two panels compare the Pa fluxes against the Balmer lines fluxes, while the bottom two panels compare the P$\beta$ fluxes against the Balmer line fluxes. The symbols are the same as those in Figure 5. The meaning of the dotted line is identical to that in Figure 5.

(A color version of this figure is available in the online journal.)
and Hα that derive the M estimates are analogous to the M estimators (A1) of (Greene & Ho 2007) with those of the Paschen lines using the relation presented in Section 3.1. We used the Hα-based M estimators in three different ways as described below. We need to find three unknown parameters, a, b, and c, in the following equation:

\[
\log(M) = a + b \log(L) + c \log(FWHM). \tag{6}
\]

The expected values are c = 2 from the virial theorem and b = 0.5 if L \sim R_{BLR}^2 (Dibai 1977). Since there are several ways to derive M_BH estimators and the results may not be identical, we derive the M_BH estimators in three different ways as described below.

First, we derive the M_BH estimators by simply replacing the line luminosities and FWHMs of the hydrogen Balmer line mass estimators (A1) of (Greene & Ho 2007) with those of the Paschen lines using the relation presented in Section 3.1. We used the Hα-based M_BH estimator since the comparison of Hα and the Paschen line properties show smaller scatter values than Hβ. We replaced the Hα luminosity and FWHM in the base estimator with those of Hα or Pβ lines. A factor of 1.8 is multiplied to the Hα-based M_BH estimator of Greene & Ho (2005) so that the new relation is normalized to the virial factor of f = 5.5. The M_BH values for the left-hand side of Equation (6) are those listed in Table 1. The Paschen-line-based M_BH estimators derived this way are given below:

\[
\frac{M}{M_\odot} = 10^7 (0.29 \pm 0.10) \left( \frac{L_{P\beta}}{10^{42} \text{ erg s}^{-1}} \right)^{0.43 \pm 0.03} \left( \frac{FWHM_{P\beta}}{10^3 \text{ km s}^{-1}} \right)^{1.92 \pm 0.18}, \tag{7}
\]

\[
\frac{M}{M_\odot} = 10^7 (0.33 \pm 0.10) \left( \frac{L_{P\beta}}{10^{42} \text{ erg s}^{-1}} \right)^{0.45 \pm 0.03} \left( \frac{FWHM_{P\beta}}{10^3 \text{ km s}^{-1}} \right)^{1.69 \pm 0.16}. \tag{8}
\]

Figure 8 shows the M_BH from this estimator versus the input M_BH values. The estimators provide a reasonable fit with the rms scatter of 0.22, 0.23 dex for both M_BH(Pα) and M_BH(Pβ).

The second and the third methods utilize a direct fit of the M_BH values. In the second method, we fix the exponent of the velocity term c to 2 as expected in the virial relation, while setting the overall normalization, a, and the exponent of the luminosity term, b, as free parameters. For this, we performed a linear regression fit in the logarithmic scale as in Equation (6), using the REGRESS procedure in IDL.

For the second method, we obtain the following relation:

\[
\frac{M}{M_\odot} = 10^7 (1.04 \pm 0.00) \left( \frac{L_{P\beta}}{10^{42} \text{ erg s}^{-1}} \right)^{0.49 \pm 0.06} \left( \frac{FWHM_{P\beta}}{10^3 \text{ km s}^{-1}} \right)^2, \tag{9}
\]

\[
\frac{M}{M_\odot} = 10^7 (1.02 \pm 0.00) \left( \frac{L_{P\beta}}{10^{42} \text{ erg s}^{-1}} \right)^{0.48 \pm 0.03} \left( \frac{FWHM_{P\beta}}{10^3 \text{ km s}^{-1}} \right)^2. \tag{10}
\]
In Figure 9, we compare the input $M_{\text{BH}}$ versus the $M_{\text{BH}}$ from the Paschen estimators of the second method. We find that the estimators in Equations (9) and (10) reproduce the $M_{\text{BH}}$ with rms scatters of about 0.20–0.24 dex—not much different from method 1.

In the third method, we treat all the coefficients in Equation (6) as free parameters. To derive the coefficients in the relation, we use a multiple variable linear regression fit with the REGRESS fitting procedure in IDL.

For the third method, we obtain the following relation:

$$
\frac{M}{M_\odot} = 10^{7.31} \left( \frac{L_{\text{Pa} \alpha}}{10^{42} \text{ erg s}^{-1}} \right)^{0.48 \pm 0.03} \left( \frac{\text{FWHM}_{\text{Pa} \alpha}}{10^3 \text{ km s}^{-1}} \right)^{1.68 \pm 0.12}
$$

(A color version of this figure is available in the online journal.)
Figure 10. Similar to Figure 8, but with the Paschen-based $M_{\text{BH}}$ where $M_{\text{BH}}$ are derived with an estimator for which the power-law index of FWHM is set free during the fit. The meaning of the symbols and line are identical to Figure 8.

(A color version of this figure is available in the online journal.)

\[ M_{\odot} = 10^{7.40}\left(\frac{L_{\beta}}{10^{42}\text{ erg s}^{-1}}\right)^{0.46\pm0.02}\left(\frac{\text{FWHM}_{\beta}}{10^{3}\text{ km s}^{-1}}\right)^{1.41\pm0.09}. \]

Figure 10 shows the comparison of the input $M_{\text{BH}}$ versus the $M_{\text{BH}}$ from the estimators in Equations (11) and (12). The rms scatter in the derived $M_{\text{BH}}$ is reduced to 0.19, 0.21 dex while the exponents of the velocity term are found to be about 1.4–1.7 rather than the value of 2 expected in a virial relation. Compared to the second method, the third method improves the fitting accuracy by a small amount in terms of reducing the rms scatter by 0.03 dex.

Also, note that the scatter in the $M_{\text{BH}}$ estimator is intrinsic (e.g., the uncertainty in the input $M_{\text{BH}}$ values) rather than dominated by the measurement errors in the FWHM and line luminosity measurements. The estimated $1\sigma$ errors in FWHM and line luminosity measurements are 0.04 dex and 0.05 dex, respectively, and such errors can produce a scatter in the $M_{\text{BH}}$ estimators at the level of 0.09 dex only.

4. DISCUSSION

4.1. Consistency Between Three $M_{\text{BH}}$ Estimators

We derived the $M_{\text{BH}}$ estimators in three different ways. Ideally, each estimator should give an $M_{\text{BH}}$ value consistent with the others within the intrinsic rms scatter for a given set of realistic FWHM and line luminosity. To see if there is any noticeable deviation among the derived BH mass values from the three different estimators, we compare $M_{\text{BH}}$ values derived from the three estimators. For the input sets of FWHM and line luminosities, we convert the available H$\beta$ FWHM and $L(5100)$ of SDSS quasars from Shen et al. (2008) to the Paschen line quantities, which gives realistic sets of FWHM and line luminosity values in a large range of FWHM and luminosity parameter space occupied by quasars. To convert FWHM$_{\text{H}\beta}$ to FWHM$_{\text{P\beta}}$ or FWHM$_{\text{P\beta}}$ and $L(5100)$ to $L_{\text{P\beta}}$ and $L_{\text{P\beta}}$, we use the the empirical relations presented in Section 3.1 of this paper. The derived Paschen line FWHM and luminosities are fed into the new $M_{\text{BH}}$ estimators.

Figure 11 shows the comparison of $M_{\text{BH}}$ derived from three different estimators. The left panel of the figure shows the comparison between $M_{\text{BH}}$ values from method 1 against those from method 2. There is a small systematic offset of 0.1 dex and 0.15 dex in the derived $M_{\text{BH}}$ values at $M_{\text{BH}} \sim 10^{10} M_{\odot}$ and $M_{\text{BH}} \sim 10^{7.0} M_{\odot}$, with the overall rms scatter being 0.06 dex. Considering that the rms scatter in these two estimators is about 0.2 dex, these two estimators produce $M_{\text{BH}}$ values well within the rms scatter in their relation. The right panel of Figure 11 compares $M_{\text{BH}}$ from method 2 and method 3. There is a significant systematic offset of 0.2 dex at the high mass end of $10^{10} M_{\odot}$ and the low mass end of $10^{7} M_{\odot}$—both are comparable the rms scatter of the $M_{\text{BH}}$ estimators. The systematic offset results mainly from the difference in the exponent of the FWHM in the $M_{\text{BH}}$ estimators. The derived $M_{\text{BH}}$ is proportional to FWHM$^2$ in method 2, while $M_{\text{BH}}$ from method 3 is proportional to FWHM$^{1.5}$. Therefore, method 2 is bound to produce $M_{\text{BH}}$ values larger than method 3 at large $M_{\text{BH}}$ while the opposite trend appears at low $M_{\text{BH}}$.

It is difficult to determine which method gives the best estimate of $M_{\text{BH}}$. Method 3 gives the smallest scatter, but the FWHM exponent of 1.5 is less physical than the index of 2 in method 2. The estimator from method 3 may prove to be the best choice, if a good explanation can be provided why the exponent of FWHM is 1.5 and not 2. The $M_{\text{BH}}$ estimator from method 3 has a resemblance to the fundamental plane relation of early-type galaxies (Dressler et al. 1987; Djorgovski & Davis 1987) where it still remains controversial why the relation is slightly tilted off from the virial relation (e.g., see Jun & Im...
Figure 11. Left panel compares $M_{\text{BH}}$ from method 1 and method 2. In the right panel, we compare $M_{\text{BH}}$ from method 2 vs. method 3. The $M_{\text{BH}}$ values agree well with each other in this case. The data points come from SDSS DR5 quasars in Shen et al. (2008) where the Paschen FWHM and luminosities are estimated from the corresponding H$\beta$ quantities. The solid line indicates the case where the BH masses derived from different methods are identical.

Figure 12. Line ratio of type 1 AGNs compared with theoretical models from the CLOUDY code. Fluxes are normalized to that of P$\alpha$ . These models show that the typical type 1 AGN condition is $\alpha = -1.0$, $n = 10^9$ cm$^{-3}$, and $U = 10^{-1.5}$. The gray lines are theoretical models from various condition, within $\alpha = -1.5$ to $-1.0$, $n = 10^9$ to $10^{11}$ cm$^{-3}$, and $U = 10^{-1.5}$ to $10^{0.5}$.

(A color version of this figure is available in the online journal.)

2008), so a similar physical mechanism that produces the tilt in the fundamental plane might be at work for the $M_{\text{BH}}$ estimator. For now, we prefer method 2 simply because the formula can be justifiable easily on a physical basis.

4.2. Line Ratios

The line ratios of H$\beta$ through P$\alpha$ lines can give us clues on the physical conditions of the BLR region. The line ratios can
also serve as a basis for determining the extinctions at different wavelengths in BLR of dusty AGN. Therefore, we present the line ratios of the hydrogen lines of our sample.

Figure 12 shows the line ratios of H\beta, H\alpha, P\beta to P\alpha of our sample. Overplotted are theoretical line ratios based on the computation from the CLOUDY code (Ferland et al. 1998). Using the CLOUDY code, we calculate the expected line ratios by varying three parameters: the shape of the ionizing continuum ($\alpha = -1.0, -1.5$), the ionization parameter ($U = 10^{0.5}, 10^{-0.5}, 10^{-1.5}$), and the hydrogen density ($n = 10^9, 10^{10}, 10^{11}$ cm$^{-3}$). We find that the observed line ratios are reproduced most successfully with a set of parameters, $\alpha = -1.0, U = 10^{-1.5}$, and $n = 10^9$ cm$^{-3}$. Some line ratios that are below the theoretical expectation can be explained naturally if there is a small amount of extinction with a color excess of $E(B-V) < 0.4$ mag. The mean line ratios are found to be $H_\beta / P\beta = 2.70$, $H_\alpha / P\beta = 9.00$, and $P\beta / P\alpha = 0.91$. These values can be used as a basis for determining extinctions in the BLR of a dusty AGN. The perfect fit of the line ratios as a function of wavelengths is probably not possible with a simple model, considering that the broad emission lines at different wavelengths are not likely to originate from exactly the same BLR regions as we discussed in Section 3.1. Nevertheless, the observed line ratios are consistent with the expected ratios from a single set of ionization parameters.

5. CONCLUSION

We derived new $M_{BH}$ estimators using hydrogen P\alpha and P\beta lines of type 1 AGNs. The derived estimator allows the determination of $M_{BH}$ at the accuracy of $\sim 0.2$ dex, and they will be useful for estimating the $M_{BH}$ of red, dusty AGNs. Our analysis of the Paschen lines with respect to H\alpha and H\beta lines shows that the luminosities and FWHMs of the broad components of the Paschen lines correlate well with those of the Balmer lines. The hydrogen line ratios from H\beta through P\alpha are consistent with case B recombination with the parameters of $\alpha = -1.0$, $U = 10^{-1.5}$, and $n = 10^9$ cm$^{-3}$. The mean line ratios are $H_\beta / P\beta = 2.70$, $H_\alpha / P\beta = 9.00$, and $P\beta / P\alpha = 0.91$ which can be used to estimate the amount of dust extinction present in red AGNs in the future. Future applications of these results on red, dusty AGNs will enable us to better understand the nature of red, dusty AGNs whose properties are still hidden behind a wall of dusty gas.

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