Broad-line Balmer Decrement in Blue Active Galactic Nuclei

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ABSTRACT

We have investigated the broad-line Balmer decrements (H\textalpha/H\beta) for a large, homogeneous sample of Seyfert 1 galaxies and QSOs using spectroscopic data obtained in the Sloan Digital Sky Survey. The sample, drawn from the Fourth Data Release, comprises 446 low redshift (z \lesssim 0.35) active galactic nuclei (AGN) that have blue optical continua as indicated by the spectral slopes in order to minimize the effect of dust extinction. We find that (i) the distribution of the intrinsic broad-line H\alpha/H\beta ratio can be well described by log-Gaussian, with a peak at H\alpha/H\beta \approx 3.06 and a standard deviation of about 0.03 dex only; (ii) the Balmer decrement does not correlate with AGN properties such as luminosity, accretion rate, and continuum slope, etc.; (iii) on average, the Balmer decrements are found to be only slightly larger in radio-loud sources (3.37) and sources having double-peaked emission-line profiles (3.27) compared to the rest of the sample. We therefore suggest that the broad-line H\alpha/H\beta ratio can be used as a good indicator for dust extinction in the AGN broad-line region; this is especially true for radio-quiet AGN with regular emission-line profiles, which constitute the vast majority of the AGN population.

Key words: quasars: general — quasars: emission lines — line: formation — quasars: extinction

1 INTRODUCTION

Hydrogen Balmer decrements are often used to determine the amount of dust extinction attenuating the observed emission lines because the intrinsic decrements of Balmer recombination lines are quite insensitive to the gas temperature and density in low density, dilute radiation field conditions (Osterbrock 1989). Particularly, the H\alpha/H\beta ratio is most frequently used for the strength of the H\alpha and H\beta lines and their relatively large wavelength span, which render the derived amount of extinction less affected by measurement uncertainties. For HII region photoionized by a hot star, an intrinsic H\alpha/H\beta value of 2.87 is found, as predicted by Case B recombination (at a typical electron density of \lesssim 10^4 \text{ cm}^{-3} and temperature of 10^4 \text{ K}). A value of 3.1 is generally adopted for the narrow line region (NLR) of active galactic nuclei (AGN), where H\alpha emission is slightly enhanced by collisional excitation due to the presence of gas of higher densities and the presence of partly ionized transition region resulting from much harder ionizing continuum (Gaskell & Ferland 1984, Halpern & Steiner 1983). For the broad line region (BLR) of AGN, however, where the density is so high (typically n_e \gtrsim 10^6 \text{ cm}^{-3}) that collisional, optical-depth and radiative-transfer effects become important as predicted by BLR photoionization modeling (e.g., Netzer 1975, Kwan & Krolik 1981, Canfield & Puetter 1981, Collin-Souffrin et al. 1982, Rees et al. 1989, Dumont et al. 1998, Korista & Goad 2004, see Baldwin 1997 for a review), the broad-line H\alpha/H\beta ratio (H\betab/H\betab) varies widely in different BLR conditions. Observationally, the H\betab/H\betab ratios are larger (steeper) than the Case B recombination value in most Seyfert 1s and QSOs (e.g., Osterbrock 1977, Wu et al. 1980, Rafanelli 1985, and Fig. 3 of Dong et al. 2005); moreover, in broad-line radio galaxies and Seyfert 1.8/1.9 galaxies H\betab/H\betab can be as steep as 10 or higher (Osterbrock et al. 1976, Osterbrock 1981, Crenshaw et al. 1988). Thus, although it is unclear yet whether the observed steep H\betab/H\betab is due to the high-density effects mentioned...
above, or just to wavelength-dependent extinction by dust (e.g., Osterbrock 1984, Goodrich 1995), it has been generally believed that the $R_{b}^{H}/R_{b}^{H{\beta}}$ ratio cannot be used as an indicator of reddening in BLR, as is in AGN NLRs or HII regions.

However, we have noticed that the range of the $R_{b}^{H}/R_{b}^{H{\beta}}$ ratios of Seyfert 1/QSOs is fairly small, typically from 2.5 to 5 (see references above), probably suggestive regions.

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ally believed that the H (e.g., Osterbrock 1984, Goodrich 1995), it has been gener-

daus, for 94 Seyfert 1s and QSOs having $u' - g'$ $< 0.6$ culled from the Sloan Digital Sky Survey (SDSS; York et al. 2000) Early Data Release (EDR; stoughton et al. 2002), the standard deviation of Hα/Hβ is only 0.36 around a mean of 2.98 (Dong et al. 2005). This fact motivated us to explore system-

tically the intrinsic Balmer decrements in AGN, their distribution and potential dependence on other AGN properties (e.g. radio-loudness, luminosity, accretion rate, line-

profile parameters, continuum slope), by taking advantage of the unprecedented spectroscopic data from the SDSS. This study will be able to address the question as to whether the $R_{b}^{H}/R_{b}^{H{\beta}}$ ratio can be taken as an indicator of the BLR extinction, at least in a statistical manner and for specific sub-classes of AGN. To this end, we have compiled a larger sample of blue AGN, including both Seyfert 1s and QSOs, from the SDSS Fourth Data Release (Adelman-McCarthy et al. 2006) as to the shape of their continua. We assume a cos-

ology with $H_0$=70 km s$^{-1}$ Mpc$^{-1}$, $\Omega_M=0.3$ and $\Omega_\Lambda=0.7$.

## 2 SAMPLE CONSTRUCTION AND DATA ANALYSIS

### 2.1 Sample Definition

Our aim is to select blue AGN that are free of dust extin-

ction, it has been noted that even in quasars with rel-

tively blue colors, such as Palomar-Green (PG) quasars ($U - B < -0.44$, Schmidt & Green 1983), there is noticeable internal dust extinction inside the AGN (Rowan-Robinson 1995, Baskin & Laor 2004). A color criterion bluer than the average of QSOs is desirable. The average optical–near-

ultraviolet slope of QSO continuum is found to be $\alpha_\lambda \approx 1.5$ ($f_\lambda = \lambda^{-\alpha_\lambda}$; Vanden Berk et al. 2001 and references listed in their Table 5). We thus define blue AGN as those with a continuum slope $\alpha_\lambda \gtrsim 1.5$, where $\alpha_\lambda$ is fitted in the rest-

wavelength range of 4030–5600 Å. We consider thus selected AGN to be least affected by dust extinction. This point is to be further discussed in §4.1, as well as the representative-

ness of our sample. In practice, we limit redshifts $z \lesssim 0.35$ so that the Hα line lies within the SDSS spectral coverage. We select objects with the median spectral signal-to-noise ratio (S/N) $\geq 10$ per pixel only to ensure accurate measurement of the Balmer decrement.

### 2.2 Overview of Data Processing

Applying the above redshift and S/N cutoffs yielded a pool of $\sim$4100 objects classified as AGN in the SDSS DR4 spectral data set, from which our sample is to be culled. The spectra are first corrected for Galactic extinction using the extinction map of Schlegel et al. (1998) and the reddening curve of Fitzpatrick (1999). The spectra are transformed into the rest frame using the redshift as determined from the peak of the [O III]λ5007 emission line. In order to measure accurately broad Balmer lines, we have to subtract prop-

erly the continuum, the FeII emission multiplets, and other emission lines nearby. In common practice, the subtraction is performed step by step: first to fit and subtract the AGN continuum and then FeII multiplets (or the opposite) and finally to fit emission lines (e.g., Boroson & Green 1992, Marziani et al. 2003); or first to fit and subtract simultane-

ously the continuum and the FeII emission multiplets (so-called “pseudo-continuum”) and then to fit other emission lines (e.g., Dong et al. 2005, Greene & Ho 2005, Zhou et al. 2006). Unfortunately, for the optical spectra of most Seyfert 1s and QSOs, fitting the continuum and the FeII emission is highly complicated by several facts as follows. 1) There are essentially no emission-line–free regions where the contin-

uum can be determined (e.g., Vanden Berk et al. 2001). 2) The Fe II λ4344 – 4684 features, generally prominent, are often blended with broad lines of Hγ, He II λ4686 and Hβ. 3) Often the QSO continuum cannot be described by a single power-law from Hδ to Hα, which means that we have to de-

termine the local continuum for the Hβ and Hα regions separa-

ately. Limited by these complications, the common step-by-

step spectral subtraction procedure cannot achieve Balmer decrement measurement accurate enough for our purpose in this work, which is rather sensitive to the measurement uncertainties of the emission-line fluxes. Here we adopt an alternative method to fit simultaneously the continuum, the Fe II and the other emission lines, giving emphasis on proper determination of the local pseudo-continua. If there are still large residuals left in the Hβ and/or Hα regions, a refined fit of the emission-lines is performed to the pseudo-continuum subtracted spectra.

Having completed the spectral fitting procedure, we select blue AGN according to the above slope criterion. Several objects having many bad pixels in the Hβ or Hα regions are removed. For eleven objects having duplicated spectra, we retain the one tagged as ‘SciencePrimary’ only according to the SDSS Catalog Archive Server. Our final sample is composed of 446 Seyfert 1s and QSOs. Our spectral fitting method is described in detail in §2.3 and 2.4.

### 2.3 Simultaneous Fit of Continuum and Emission Lines

As discussed above, we need to fit simultaneously the re-

spective local continua in the Hβ and Hα regions and the Fe II emission spectrum. We follow the procedure described in below, which is implemented using IDL routines.

1. We fit each SDSS spectrum in the rest-wavelength range from 4030Å to 7500Å, assuming a broken power law with a break wavelength of 5600Å, i.e., $\alpha_1 \lambda^{-\alpha_1}$ for the Hβ–Hγ–Hβ region and $\alpha_2 \lambda^{-\alpha_2}$ for the Hα region. We limit the

\[ \text{http://cow.physics.wisc.edu/~craigm/idl/} \]

\[ \text{http://cas.sdss.org/} \]

\[ \text{http://cow.physics.wisc.edu/~craigm/idl/} \]
wavelength range redward of 4030 Å to avoid the broad-line He emission.

2. The optical Fe II emission is modeled as \( C(\lambda) = c_0C_b(\lambda) + c_1C_n(\lambda) \), where \( C_b(\lambda) \) represents the broad Fe II lines with the relative intensities fixed at those of IIZW 1 as given in Table A.1 of Véron-Cetty et al. (2004), and with the same line profile as the broad Hβ line. The redshift of the broad Fe II lines relative to Hβ is fitted as a free parameter. \( C_n(\lambda) \) denotes the narrow permitted and forbidden Fe II lines with their relative intensities fixed at those listed in Table A.2 of Véron-Cetty et al. (2004); which have the same redshifts and line profiles as the narrow H β line.

3. Emission lines other than Iron lines identified from the composite SDSS QSO spectrum (see Table 2 in Vanden Berk et al. 2001) from Hδ to [S II] λ6731 are modeled as follows. Broad Hydrogen Balmer lines are assumed to have the same redshifts and profiles, and each is modeled with 1–4 Gaussians. The broad He II λ4686 line is modeled with one Gaussian. [O III] λ4363 and the λλ4959, 5007 doublet are assumed to have the same redshifts and profiles, and each is modeled with 1–2 Gaussians. Other narrow lines are modeled with one Gaussian. Narrow Balmer lines, [N II] and [S II] doublets are assumed to have the same redshift and profile. The flux ratio of the [N II] doublet λ6583/λ6548 is fixed to the theoretical value of 2.96; the [O III] doublet is similarly constrained.

We note that in many cases the fit is not good in several wavelength regions, such as the small region around the minimum between Fe II 37,38 complex and Hβ, the joint part of Hβ and [O III] λλ4959. These are likely caused by the imperfection of the models, for instance, over-estimation of the continuum between the Fe II 37,38 complex and Hβ, over-fit of Hβ with a spurious very broad component, over-fit of [O III] with a spurious blue-shifted wing. These problems can be solved by assigning additionally larger weights to these critical regions in the fitting, following the weighting methods adopted by Tran et al. (1992) and Reichard et al. (2003). The exact weights are determined by trial-and-error as those which give the best fits—with the minimum \( \chi^2 \) calculated using the original weights (errors)—in the relevant regions.

We also note that the broad lines of He I λ4922 and 5016 may contribute to the “red shell” of Hβ (e.g., Véron et al. 2002). To investigate this possibility, we compare the H β profiles with the Hα profiles in our sample. Only 4 per cent of the sources are found to have apparent redward excess of Hβ, and the strength is typically less than 5 per cent of Hβ. We thus consider the contribution of the potential He I lines to be negligible.

The assumption that the broad Balmer lines have the same profiles is useful to well constrain these lines in the fitting since they are highly blended with other lines nearby. This assumption is found to have little effect on the determination of the local continua (see §2.2), although it is well known that broad Balmer lines have slightly different profiles (e.g., Osterbrock & Shuder 1982). A similar situation arises in the comparison of the [O III] λλ4363 and λ5007 line profiles, as the former being often broader.

We notice that in many objects the relative intensities of various Fe II multiplets, such as Fe II λλ49-50, are more or less different from those of IIZW 1, resulting apparent residuals left in some Fe II multiplet regions. For about two dozen such spectra we re-fit them with different scaling factors for the Fe II emission blueward and redward of Hβ. This yields better matched Fe II emission spectrum; the local continua and the Hβ and Hα fluxes remain unchanged, because the wavelength regions determining the continua and the “Hδ+Hγ+Hβ+Hα” lines have much larger total weights than that determining the abnormal Fe II multiplets. We thus adopt the fits that used the uniform factor for the whole Fe II spectrum, since we are not concerned with the properties of Fe II emission in this work. Example spectra as well as the fitting results are demonstrated in Fig. 1.

2.4 Refined Fitting of Emission-line Profile

We re-calculate the reduced \( \chi^2 \) of the fits around Hβ and the Hα regions (4750–5050 Å and 6400–6800 Å, respectively) using the original errors for the 446 spectra. Spectra having a fit with the reduced \( \chi^2 > 1.1 \) are picked up for further refined line-profile fitting using the code described in detail in Dong et al. (2005). Briefly, we fit each pseudo-continuum subtracted spectrum using various schemes and the one with the minimum reduced \( \chi^2 \) is adopted. Broad lines are fitted with multiple Gaussians, as many as 4 at most; the fits are accepted when the reduced \( \chi^2 \leq 1.1 \) or it cannot be improved significantly by adding in one more Gaussian (up to 4) with a chance probability less than 0.05 according to F-test. Narrow Balmer lines mostly have similar profiles to [N II], [S II] or the line core of [O III] λ5007. At this stage, the broad Balmer lines are not required to have the same profiles. Fig. 2 shows examples of refined line-profile fitting in the Hβ and Hα regions. The line fluxes of Hβ and Hα are listed in Table 1, and the broad-line profile parameters are listed in Table 2. The data and the fitted spectral parameters are available online for the decomposed spectral components (continuum, Fe II and other emission lines) for the 446 objects.

Our two-step procedure of pseudo-continuum and line-profile fitting has proved to be robust and self-consistent. As a reliability check, we perform the first-step fitting (as in §2.3) by setting the initial values of the free parameters of

4 Instead of the template spectrum of the broad Fe II emission of IIZW 1 readily provided by Véron-Cetty et al. (2004), we use two sets of Fe II emission templates in analytical forms constructed from their measurements, one for the broad line system L1 and the other for low-excitation narrow line system N3. In addition, we also add into our templates Ti II, Ni II, Cr II lines listed in their Table A.1 and A.2.
5 Several emission-line regions in the 4030–7500 Å range are simply masked out, because either they are too weak to constrain the fit or they have little effect on the results. These include He I λ4471, [N II] λλ5200, [Ca V] λ5430, [Cl III] λ5538, He I λ5876, He I λ7066, [Ar III] λλ7136 and [O II] λλ3720.
6 We have found through our experiment that these criteria based on \( \chi^2 \)-test and F-test work well, although, theoretically, these goodness-of-fit tests holds only for linear models (cf. Lupton 1993).
7 Available at http://staff.ustc.edu.cn/~xbdong/Data_Release/blueAGN_DRA/ together with an auxiliary code to explain the parameters and to demonstrate the fitting.
emission lines (except Iron lines) to those yielded from the refined line-profile fitting, and find that the best-fits of both the continuum and the Fe II emission are almost unchanged.

2.5 Estimation of Parameter Uncertainties

As we have argued above, estimation of the measurement errors of emission-line fluxes is important for deriving the intrinsic distribution of the Balmer decrements. The errors of line fluxes provided by MPFIT are unreasonably small: the median errors of broad Hδ, Hγ, Hβ and Hα are 13%, 12%, 6% and 4%, respectively. They do not account for the uncertainty introduced by the pseudo-continuum subtraction that severely complicates measurement of the broad Balmer lines (see Marziani et al. 2003 for a detailed discussion). To take this and other possible effects into account, we adopt a bootstrap approach to estimate the typical errors for the whole sample. We generate 500 spectra by randomly combining the strap approach to estimate the typical errors for the whole sample. We generate 500 spectra by randomly combining the

emission line model of object ‘A’ is scaled model emission lines of one object (denoted as ‘A’) to the emission-line subtracted spectrum of another object (denoted as ‘B’). The emission line model of object ‘A’ is scaled in such a way that it has the same broad Hβ flux as object ‘B’, in order to minimize changes in S/N within the emission-line spectral regions in the simulated spectra. Then we fit the simulated spectra following the same procedure as described in §2.3 and §2.4. For each parameter, we consider the error typical of our sample to be the standard deviation of the relative difference of the input (x_i) and the recovered (x_j), \( x_j - x_i \). These relative differences turn out to be normally distributed for every parameter. The thus estimated typical 1σ errors for the fluxes of broad Hδ, Hγ, Hβ and Hα are 19%, 19%, 8% and 5%, respectively. Hence the measurement error of the Hα/ Hβ ratio follows the log-normal distribution with 1σ = 0.046 dex. The uncertainties for the broad Hδ and Hγ line fluxes are large because they are relatively weak and/or are often severely contaminated by the FeII and [OIII]λ4363 emission. Considering the large uncertainties of their measurements, we do not discuss the Hδ/ Hβ and Hγ/ Hβ ratios in this study.

The errors provided by MPFIT are unusually small also for the power-law indices and normalizations, commonly being only 0.5 and 0.4 per cent, respectively. Using the above boot-strap approach, the typical errors are 8 per cent for \( \alpha_{\lambda,1} \) and \( \alpha_{\lambda,2} \), 5 and 3 per cent for \( \alpha_{1} \) and \( \alpha_{2} \), respectively. The mean errors of the fluxes of narrow Hβ and Hα are 6 and 5 per cent, respectively, which are almost unaffected by the pseudo-continuum subtraction.

3 RESULTS

3.1 Intrinsic broad line Hα/ Hβ Distribution

The measured Hα/ Hβ ratios range from 2.3 to 4.2, with a mean of 3.1 and skewed towards the large ratio end. Considering the log-normal distribution of their measurement errors, we plot the histogram in base-10 logarithm form by dividing the sample into 20 bins, as shown in Fig. 3. The profile of the distribution is very similar to Gaussian. We fit the distribution with a Gaussian function by minimizing \( \chi^2 \) assuming Poissonian errors for the counts in each bin. A good fit (see Fig. 3) is achieved with a minimum reduced \( \chi^2 = 0.89 \) (17 degrees of freedom), yielding a mean of 0.486 ± 0.002 and a standard deviation of 0.046 ± 0.002. This model distribution is identical to the histogram at the 96.5% significance level according to the Kolmogorov-Smirnov test. We re-fit the histogram by varying the number of bins from 10 through 30 and find that all the fits yield similar results at similar confidence levels. Therefore, the observed distribution of the Hα/ Hβ ratios is well described by log-normal, with a peak at Hα/ Hβ = 3.06. This fact, together with that the measurement errors have a log-normal distribution (see §2.5), indicate that the distribution of the intrinsic Hα/ Hβ ratios should be, at least very close to, log-normal. The intrinsic Hα/ Hβ distribution can be approximated by deconvolving the measurement uncertainty (1σ = 0.04 dex) from the observed distribution, yielding a standard deviation as small as about 0.03 dex. The deconvolved intrinsic distribution is also displayed in Fig. 3.

It should be noted that measurement of the broad Hα and Hβ line fluxes is insensitive to the deblending with the narrow Hα and Hβ components because of the weakness of the latter in blue AGN, which account for only ~3 and ~4 per cent of the total Hα and Hβ fluxes in the sample. The distribution of the total line flux ratios log(Hα/ Hβ) has a mean of 0.493 and a standard deviation of 0.046, nearly identical to those of the broad components log(Hα/ Hβ).

3.2 Dependence of Hα/ Hβ on AGN Properties

We conduct comprehensive statistical analysis using the present sample in an attempt to investigate whether there exist any systematic trends (biases) of the Hα/ Hβ dependence on AGN types and/or properties, such as radio-loud objects, objects with clumpy/double-peaked line profiles, objects in low states. This is important as any biases, if being significant, would affect the observed distribution of Hα/ Hβ. Correlation analysis is performed between Hα/ Hβ and various AGN properties, and the results are summarized in Table 3. We report the Spearman rank correlation coefficient (\( \rho \)) and the probability (\( P_{\text{rand}} \)) that a correlation is not present. When upper limits are present, we use the generalized Spearman rank correlation test as implemented in the ASURV package (Isobe et al. 1986). We also perform statistical tests to compare the Balmer decrements among various subsamples.

3.2.1 Luminosity and Eddington Ratio

We calculate monochromatic continuum luminosity \( L_{\lambda,100} \equiv \lambda L_\lambda \) at 5100Å from the power-law fit \( \lambda L_\lambda \). Due to the blue slope criterion the optical luminosities have little contribution from host galaxy starlight. Based on the empirical BLR radius–luminosity (R–L) relationship and the assumption that the BLR gas is virialized under the control of gravity of the central supermassive black hole, black hole mass \( M_{BH} \) can be estimated using the so-called linewidth–luminosity–mass scaling relation (e.g., Kaspi et al. 2000).

We calculate the black hole masses using the formalism presented in Vestergaard & Peterson (2006, their equation 5) with Hβ FWHM measured from the best-fit model of Hβ.
broad-line profiles. This formalism was calibrated with reverberation mapping-based masses and used the R–L relation by Bentz et al. (2006) corrected for host galaxy starlight contamination. The Eddington ratios \( \left(L_{\text{bol}}/L_{\text{Edd}}\right) \) are calculated assuming a bolometric luminosity correction \( L_{\text{bol}} \approx 9L_{5100} \) as for normal QSOs (Kaspi et al. 2000, Elvis et al. 1994). No correlation between the Balmer decrement and \( L_{5100} \), \( L_{\text{bol}}/L_{\text{Edd}} \) and \( M_{\text{BH}} \) are found to be significant at the \( \rho \) level (see Table 3). To check whether the results are dependent on the exact formalisms for black hole mass estimation, we re-calculate black hole masses using various formalisms, including Peterson et al. (2004) and Onken et al. (2004) and the R–L relation from Kaspi et al. (2005) and Bentz et al. (2006), respectively. For the line width, we also use the second moment of the line profile (\( \sigma_{\text{line}} \), often referred to as “line dispersion”) measured from the model line profile. To avoid possible contamination to the continuum luminosity from jet and host-galaxy starlight, we also try to use the H\( \beta \) luminosity to calculate the black hole masses. Yet no correlations are found, either. Also we consider the possibility that these correlations may be present but differ for different black hole masses, and as such the trend of the correlations could be reduced when the sample spans a large range of black hole masses. We divide the sample into several bins of \( M_{\text{BH}} \) with a bin size of 0.4 dex for each bin. We find that, in none of the bins, the correlations of H\( \alpha \) and H\( \beta \) with \( L_{5100} \) or \( L_{\text{bol}}/L_{\text{Edd}} \) are present. The correlations of H\( \alpha \) and H\( \beta \) with \( L_{5100} \) and \( L_{\text{bol}}/L_{\text{Edd}} \) are displayed in Fig. 4a and 4b, respectively, where the 122 objects in the \( M_{\text{BH}} \) bin of \( 10^{-8} \) and \( 10^{-8.5} \) \( M_\odot \) are denoted as solid black squares.

The luminosity \( L_{5100} \) ranges from \( 2 \times 10^{43} \) to \( 2 \times 10^{45} \) ergs s\(^{-1} \) with a median of \( 2 \times 10^{44} \) ergs s\(^{-1} \). We compile two subsamples with \( L_{5100} > 5 \times 10^{44} \) ergs s\(^{-1} \) (‘high-L’ sample, 45 objects) and \( L_{5100} < 1 \times 10^{44} \) ergs s\(^{-1} \) (‘low-L’ sample, 49 objects). The mean and standard deviation of \( \log(H\alpha/H\beta) \) in the ‘high-L’ subsample are 0.496 and 0.046, respectively; and 0.479 and 0.049 in the ‘low-L’ subsample. The mean values of the two samples are consistent with each other, with a chance probability of 9 per cent according to the Student’s \( t \)-test. The Eddington ratios range from 0.005 to 1.2 with a median of 0.2. We also compile two subsamples of objects with \( L_{\text{bol}}/L_{\text{Edd}} > 0.5 \) (‘high-state’, 57 objects) and \( L_{\text{bol}}/L_{\text{Edd}} < 0.03 \) (‘low-state’, 31 objects), respectively, which have the mean and standard deviation of \( \log(H\alpha/H\beta) \) of 0.488 and 0.043, and 0.499 and 0.058, respectively. Again, the two subsamples have mutually consistent mean values, at a chance probability of 35 per cent given by Student’s \( t \)-test.

### 3.2.2 Radio loudness

We cross-correlate the sample with the Faint Images of the Radio Sky at Twenty cm (FIRST; Becker et al. 1995) Survey following the procedure described in Lu et al. (2007). For unresolved FIRST sources a matching radius of 3\( '' \) is used; for resolved sources the FIRST images are visually inspected. In this way 68 matches are obtained. For these matches, we define and calculate the radio-to-optical flux ratio (radio-loudness) following Ivezic et al (2002), \( R_i \equiv \log(f_{20cm}/f_i) \), where \( f_i \) and \( f_{20cm} \) are the flux densities at \( i \)-band and 20 cm, respectively. For the rest 336 objects that were covered by FIRST, we calculate the upper limit of \( R_i \) by taking the FIRST detection limit of 1 mJy as the flux limits at 20 cm. Fig. 4c shows the H\( \alpha \)/H\( \beta \) ratio versus \( R_i \). The correlation is weak at most, as indicated by \( \rho = 0.205 \) incorporating both detections and upper limits of \( R_i \). We also calculate the k-corrected radio power at 20 cm as \( P_{20cm} = 4\pi D_L^2f_{\text{int}}/(1+z)^{1+\alpha_r} \), where the radio spectral index \( \alpha_r \) (\( F_v \propto v^{\alpha_r} \)) is assumed to be -0.5 for all the objects. Similarly, there seems at most a weak correlation, as indicated by \( \rho = 0.209 \).

It is well known that the radio-loudness distribution appears to be bimodal with \( \sim 90\% \) being radio-quiet (RQ) and \( \sim 10\% \) radio-loud (RL) (Kellermann et al. 1989, Ivezic et al. 2002 and references therein). Hence for the two populations the central engines or physical processes related to accretion/jet may be different (e.g., Blandford et al. 1990, Boroson 2002, Falcke et al. 1996). To further examine whether the Balmer decrements are systematically distinct for the two populations, we compile a RL and a RQ subsample following Ivezic et al (2002): 19 sources with \( R_i > 1 \) are regarded as RL, while the rest 385 sources covered by FIRST are RQ. The mean and standard deviation of \( \log(f_{20cm}/f_i) \) in the RL subsample are 0.528 and 0.057, respectively; and in the RQ subsample they are 0.483 and 0.046, respectively. The mean Balmer decrement appears to be slightly larger in the RL subsample by 0.05 dex than in the RQ one. This difference is significant according to Student’s \( t \)-test, with a chance probability \( \ll 0.01 \).

### 3.2.3 Line Profile

It has been known for a long time that the Balmer decrement is larger in the line core than in the line wings (e.g., Shuder 1982, Crenshaw 1986, Stirpe 1991, Korista & Goad 2004 and references therein). As a result the integrated Balmer decrement might depend on the line profile to some extent. To investigate this issue, we compute the skewness (the 3rd moment) and kurtosis (the 4th moment) based on the best-fit model of H\( \beta \) and H\( \beta \) broad-line profiles, as well as FWHM and \( \sigma_{\text{line}} \) obtained in §3.2.1. The correlation between the integrated Balmer decrement and skewness is at most weak, if exist at all, as indicated by \( \rho = -0.203 \). No correlations are found between the integrated Balmer decrement and kurtosis, FWIM and \( \sigma_{\text{line}} \), respectively. Considering that skewness and kurtosis are sensitive to the errors in the line wings caused by the subraction of the Fe II, [O III] and He II emission, we also compute some empirical yet robust profile parameters based on the model profile. We define three indices to characterize the asymmetry (e.g. skewness, \( A_I \)) shape (\( SI \)) and kurtosis (\( K_I \)) as, \( A_I = (C(2) - C(4))/\text{FWHM} \); \( SI = (\text{FW}(4) + \text{FW}(3))/(2 \times \text{FWHM}) \); and \( K_I = \text{FW}(4)/\text{FW}(3) \), following De Robertis (1985), Boroson & Green (1992) and Marzian et al. (1996), respectively. Where \( C(1), C(3), C(4) \) is the centroid at \( 1/3 \) maximum, and \( \text{FW}(3), \text{FW}(4) \), the full width at \( 1/3 \) maximum, respectively. These three dimensionless parameters thus de-

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\[^8\] However, the genuineness of this bimodality is still a matter of debate; see, e.g., Hooper et al. (1995), White et al. (2000) and Cirasuolo et al. (2003).
fined are not affected by the choice of the rest frame. Collin et al. (2006) characterize the broad-line profiles by the ratio of FWHM to $\sigma_{\text{line}}$, based on which the broad-line profiles of AGN are separated into two categories: the first, having $\frac{\text{FWHM}}{\sigma_{\text{line}}} < 2.35$, are narrower lines with relatively extended $\alpha$-wings; the second, having $\frac{\text{FWHM}}{\sigma_{\text{line}}} > 2.35$, are broader lines being relatively flat-topped. This linewidth ratio is similar to the above kurtosis index ($K1$), and is therefore also computed and denoted as $K12$. We perform correlation analysis of the integrated Balmer decrement with the above various parameters, and find no significant corrections (see Table 3). The relation between the integrated Balmer decrement and $K11$ is displayed in Fig. 4d.

Among our blue AGN sample, there are 23 objects having H$_\alpha$ or H$\beta$ lines of double or even multiple peaked profiles\[8\] (Shang et al., in preparation), with 5 being radio-loud. Such profiles are found in about 3 per cent of AGN (Strateva et al. 2003) and have a higher occurrence in LINERs (Eracleous 2004) and in RL sources (~20%, Eracleous & Halpern 2003). Using a sample selected from RL AGN, Eracleous & Halpern (1994) found that double-peaked emitters have the large integrated Balmer decrements, like their parent population of RL AGN; later they further found that their integrated Balmer decrements are even larger than that of the latter (on average 5.23 versus 4.26, Eracleous & Halpern 2003). We investigate this issue using the above 23 objects (DBP subsample). The mean and standard deviation of $\log\left(\frac{F_{H\alpha}}{F_{H\beta}}\right)$ in the DBP subsample are 0.515, 0.055, respectively, while these values are 0.484 and 0.046 in the rest of objects (non-DBP subsample). The mean integrated Balmer decrement appears to be slightly larger in the DBP subsample than in the non-DBP sample, which is significant with a chance probability of 0.002 (0.01) by Student’s $t$-test assuming the two distributions to have the same (different) variance. We cannot find any difference in integrated Balmer decrement between the DBP subsample and the RL subsample (with a $t$-test probability of 44%), possibly due to the small size of the two subsamples.

3.2.4 Other SED properties

The shape of the ultraviolet to X-ray ionizing continuum affects the extended partially ionized zone and thus the Balmer decrements (Kwan & Krolik 1981). Here we take the $\alpha_{\text{ox}}$ values (the slope of a hypothetical power law between 2500A and 2 keV) for 268 matched sources from Anderson et al. (2007). These values were derived from broadband X-ray (ROSAT) and $g$-band (SDSS) fluxes by assuming an X-ray energy index $\alpha_g = 1.5$ and an optical index $\alpha_{\lambda} = 1.5$. No correlation between the Balmer decrement and $\alpha_{\text{ox}}$ is found. We also perform correlation analysis between the Balmer decrement and the optical–near-ultraviolet continuum slope ($\alpha_{\lambda,1}$); and find no significant correlation (see Table 3). The relations of the $H_{\alpha}/H_\beta$ ratio with $\alpha_{\text{ox}}$ and $\alpha_{\lambda,1}$ are displayed in Fig. 4e and 4f, respectively.

9 Such profiles are defined as having the number of peak and “pseudo-peak” greater than 2; a “pseudo-peak” is defined as the point where the 2nd derivative is minimal and negative. See Shang et al. (in preparation) for details.

4 DISCUSSION

4.1 Representativeness of Unreddened AGN

Internal Dust extinction in objects of our blue AGN sample should be negligible. In the sample, $\alpha_{\lambda,1}$ varies in the range from 1.5 to 2.7 (see Table 1) with a standard deviation of 0.2. Such a scatter is consistent with previous results that there is a large intrinsic dispersion of the continuum slope (Elvis et al. 1994, Rowan-Robinson 1995, Natali et al. 1998, Kuhn et al. 2001). To check how much the sample suffers from extragalactic dust extinction, we cross-match these AGN with the Galaxy Evolution Explorer (GALEX; Morrissey et al. 2005) General Data Release 3 with a matching radius of 2′′6 in a way similar to Trammell et al. (2007). We obtain 253 objects with both reliable far-ultraviolet ($f$) and near-ultraviolet ($n$) magnitudes, while 185 of the rest have not been covered by GALEX yet. For the 253 objects we compute the relative $f-n$ colors defined as the $f-n$ colors minus the corresponding median color of quasars at the same redshift. The digital curve of median color versus redshift is kindly provided to us by G. Trammell, as presented in Fig. 13 of Trammell et al. (2007). We find the distribution of the relative $f-n$ colors can be well described by a Gaussian with a mean of zero and a standard deviation of 0.3, a dispersion caused by GALEX photometric uncertainties only (Trammell et al. 2007, see their Fig. 14). We also find that neither the $f-n$ color nor the relative $f-n$ color correlates with the Balmer decrement. Hence we believe that there is little dust extragalactic extinction in our sample.

We notice that there exists a potential bias against selecting AGN with intrinsic red slopes by our criterion. To test the representativeness of our sample, we perform Spearman correlation analysis of the continuum slope with all the various, above-mentioned parameters in the same way as in §3.2. The results are listed in Table 3. It turns out that no correlations of $\alpha_{\lambda,1}$ are present with the Eddington ratios, black hole mass, radio-loudness, radio power, linewidth and various other line-profile parameters. But there is a positive correlation between the continuum slope and the nuclear luminosity $L_{5100}$ as indicated by $\rho = 0.457$ and $P_{\text{null}} = 10^{-6}$ (see Table 3). Thus our sample is biased toward relatively high luminosity. This is consistent with the fact that the sample covers a high luminosity range as $L_{5100} \gtrsim 2 \times 10^{43}$ and H$\alpha$ luminosity $\gtrsim 5 \times 10^{41}$ ergs s$^{-1}$. To sum up, our sample...
ple is free from biases regarding the above-mentioned AGN properties except luminosity.

4.2 On the Intrinsic \text{H}\beta/\text{H}\alpha Distribution and Its Applications

As discussed in §1, historically the broad-line Balmer decrements in Seyfert 1s and QSOs have been generally thought to be considerably steeper than the Case B value and to have a large intrinsic dispersion. Such a belief may have originated from results of early studies with small samples, and was (mis-)reinforced by observations of Seyfert 1.8/1.9 and broad-line radio galaxies, and further assured by its consistency with photoionization modeling mainly of individual clouds in various conditions (see observational and theoretical references in §1). In a sample of 36 Seyfert 1s (including Seyfert 1.2 and 1.5) studied by Osterbrock (1977), the mean \text{H}\alpha/\text{H}\beta ratio is 3.6 with a range from 2.6 to 5.9 (uncorrected Galactic reddening). Similar results were found in a sample of 24 Seyfert 1/QSOs by Neugebauer et al. (1979), giving the mean \text{H}\alpha/\text{H}\beta ratio 3.6 with a range from 2.2 to 4.9 (uncorrected Galactic reddening; \text{H}\alpha measurements include \text{[N II]} flux). In addition to relatively large errors inherent in the early measurements and the neglect of Galactic reddening correction, we believe that internal reddening also plays a non-negligible role in causing the steeper Balmer decrements in previous results. Similar situation was found in PG quasars (Rowan-Robinson 1995, Baskin & Laor 2004). For instance, 1ZW I has an observed \text{H}\alpha/\text{H}\beta ratio of 4.86 as given in Table 1 of Osterbrock (1977), but actually its broad lines suffer internal reddening of \text{E}(B-V) \sim 0.1 (Rudy et al. 2000) as well as Galactic reddening of \text{E}(B-V) \sim 0.1 (Schlegel et al. 1998; Stark et al. 1992). Interestingly, for the 9 Seyfert 1s listed in Table 2 of Wu et al. (1983), the mean \text{H}\alpha/\text{H}\beta ratio is 3.1 after individual correction for Galactic reddening (Goodrich et al. 1990), which is almost the same as ours found here. Recently, in a sample of broad-line AGN with low starlight contamination, Greene & Ho (2005) found that the mean value of the total (narrow + broad) \text{H}\alpha/\text{H}\beta ratio is 3.5; the somewhat larger value compared to ours should also be due to internal reddening. In a large sample of about 2000 narrow-line Seyfert 1s (NLS1s), Zhou et al. (2006) found the mean \text{H}\alpha/\text{H}\beta ratio to be 3.0, close to the value derived here for blue AGN. In summary, results obtained from early small samples and from recent much large samples all point to that the mean \text{H}\alpha/\text{H}\beta ratio of Seyfert 1/QSOs is only slightly larger than the Case B value.

A surprising feature emerged from the present study is the actual dispersion of the intrinsic \text{H}\alpha/\text{H}\beta ratio being rather small (0.03 dex in a log-normal distribution)! This is contrary to the prevalent belief that there is a “considerable range of intrinsic (Balmer) line ratios” (Wu et al. 1980), which was based on early samples that were in fact too small to make a general conclusion. Our conclusion should hold for luminous Seyfert 1s and QSOs in general, since by selection our sample is only biased against AGN with intrinsic red continua, but the Balmer decrement does not correlate with the continuum slope as found in §3. We further suggest that our result is also likely to hold for AGN of low luminosity. Firstly, there is no correlation between the Balmer decrement and luminosity in our sample, and the ‘high-L’ and ‘low-L’ subsamples have the indistinguishable mean Balmer decrements. Secondly, in the large sample of about 2000 NLS1s that are generally at high accretion states, the Balmer decrements still cluster tightly around ~3 even when the nuclear \text{L}_{5100} goes down to 10^{41} ergs s^{-1} (Zhou et al. 2006). Moreover, as shown in §3, the Balmer decrement does not correlate with the Eddington ratio. Recently, contrary to our findings here, La Mura et al. (2007) found a weak correlation between the \text{H}\alpha/\text{H}\beta ratio and the \text{L}_{\text{bol}}/\text{L}_{\text{Edd}}. However, as suggested by those authors, this might result from the inclusion of reddened objects in their sample. They also found a weak correlation between the flux ratios of broad-line Balmer series (up to \text{H}\delta) and the line width; but, in the case of \text{H}\alpha/\text{H}\beta ratio, the correlation is not significant as indicated by \text{P}_{\text{null}} = 3.34 \times 10^{-2}.

It should be noted that in some variable objects an anti-correlation between the continuum flux (i.e., accretion state) and the \text{H}\alpha/\text{H}\beta ratio has been reported during flux variability over a time scale of months (e.g., the prototypical NGC 5548; Wamsteker et al. 1990, Dietrich et al. 1993, Shapovalova et al. 2004). Such a behavior has been well predicted and explained by theoretical models (e.g., Netzer 1975; Korista & Goad 2004). Thus the lack of such a correlation in the AGN ensemble seems to be somewhat unexpected. We guess that, instead of instantaneously responding to the continuum variation, the BLR clouds distribution (as a function of mass and/or luminosity) is perhaps determined/adjusted by the long-term average of the accretion state; for an AGN ensemble, this long-term adjustment may make the average \text{H}\alpha/\text{H}\beta ratio in a narrow range. In addition, according to Table 8 of Shapovalova et al. (2004) and Table 2 of Dumont et al. (1998), the Balmer decrement of NGC 5548 varies between 3.0 and 4.3, which is not extreme and is actually within the range for the blue AGN ensemble as reported here. Due to the small variability amplitude, any correlation, even if exists in individual objects, would be smeared out in the ensemble. In a few cases, such kind of variability can be explained by variation in extinction (Goodrich 1989, Tran et al. 1992, Goodrich 1995; see a discussion about the time scale of this kind of variability in Wang et al. 2007).

From theoretical perspective, however, a tight \text{H}\alpha/\text{H}\beta distribution around 3.1 seems to be quite surprising—all the BLR photoionization computations predict a rather large range in the Balmer decrement for individual clouds in plausible BLR conditions (see references in §1). It seems unlikely that such a discrepancy is mainly caused by the incapability of photoionization modeling of the BLR clouds, because all the model computations over the past 40 years gave the similar trend of large \text{H}\alpha/\text{H}\beta range (e.g., Netzer 1995, Dumont et al. 1998, Korista & Goad 2004), although such computations for a single cloud are still uncertain (see Netzer 1995 and references therein). Another possibility, in fact an old proposal, is that the BLR emitting gas of all AGN have been “fine-tuned” to a certain ionization parameter by some physical processes (e.g., the “hot-warm” model of Krolik et al. 1981). However, the existence of such a fine-tuning, among clouds in likely jumbled environments as in AGN BLRs, is questioned by others and deemed to be unnatural and unlikely (e.g., Mathews & Ferland 1987; Baldwin et al. 1995). Here, we suggest a plausible explanation to this seemingly discrepancy invoking the “locally optimally-emitting cloud” (LOC) model, as proposed by Baldwin et al. (1995).
essential idea of the LOC model is that each line arises predominantly from clouds only in a narrow range of density and distance from the continuum source, due to natural selection effects largely introduced by the atomic physics. In this scenario, the similar values of the Balmer decrements, just like other surprising similarities in emission-line spectra of Seyfert 1/QSOs (Davidson & Netzer 1979, Baldwin et al. 1995), appear to be a natural consequence. According to the recent calculation by Korista & Goad (2004, their Figure 5) using the spectral synthesis code CLOUDY (version 90.04), the \( \mathrm{H}\beta/\mathrm{H}\beta \) flux ratio varies from roughly 17 to approximately 1 across the parameter plane of gas density and ionizing flux characteristic of BLR clouds; the \( \mathrm{H}\alpha/\mathrm{H}\beta \) ratio, when integrated over the full BLR of their LOC model, varies from 3.7 (high state) through 4.9 (low state). Using CLOUDY version 07.02 (last described by Ferland et al. 1998) with improved collisional rates for excited states of hydrogen atoms, the \( \mathrm{H}\alpha/\mathrm{H}\beta \) ratio contours now have values that are typically \( \lesssim 0.1 \) dex smaller than those presented in Figure 5 of Korista & Goad (2004) (Korista, private communication). Thus there exists a large span of cloud parameters within the density-flux plane, over which most of the broad emission lines are emitted, for which the \( \mathrm{H}\alpha/\mathrm{H}\beta \) ratios lie between 2.5 and 4. In fact LOC integrations over the range of cloud parameters adopted by Korista & Goad (2004) now predicts an \( \mathrm{H}\beta/\mathrm{H}\beta \) ratio that is consistent with our measurements (Korista, private communication). We therefore suggest that the LOC model, together with improvement on the photoionization modeling, can give a natural explanation to the seemingly discrepancy between the theory and the measurements.

As is found here, radio-loud objects and objects having double-peaked emission-line profiles among the blue AGN ensemble have slightly larger Balmer decrements than the rest on average. In these kinds of AGN the physical conditions related to accretion/jet may be different (Blandford et al. 1990, Falcke et al. 1996, Eracleous & Halpern 2003), e.g., with additional X-ray ionizing radiation from the jet base. Thus collisional excitation, self-absorption, and other line-transfer effects may play roles to enlarge the Balmer decrements, as discussed by some authors (e.g., Osterbrock et al. 1976, Crenshaw et al. 1988, Netzer et al. 1995). Given the small fractions of these two classes (\( \sim 10 \) and 3 per cent, respectively) among the AGN population, the distribution of the \( \mathrm{H}\alpha/\mathrm{H}\beta \) ratios show little changes when the RL and double-peaked objects are excluded. In another word, for the bulk of the AGN population, such effects are insignificant.

Our finding out of this study may have an interesting implication: the precise distribution of the intrinsic \( \mathrm{H}\alpha/\mathrm{H}\beta \) ratio, that is insensitive to any nuclear properties known so far, renders it a useful tool with which the BLR extinction can be derived, at least in a statistical manner. Specifically, for a sample concerned, we can derive its internal \( E(B-V) \) distribution by de-convolving the observed \( \mathrm{H}\alpha/\mathrm{H}\beta \) distribution with the intrinsic \( \mathrm{H}\alpha/\mathrm{H}\beta \) distribution as found here. This approach has now been applied to a large sample of broad-line AGN culled from the SDSS DR4 to derive the internal \( E(B-V) \) distribution of the AGN BLR in the local universe, and hence to obtain the fraction of obscured AGN of various intrinsic luminosity and of various degree of extinction (Zhang et al., in preparation). At the zeroth-order approximation, Dong et al. (2005) have used the Balmer decrement to derive the BLR reddening for a sample of luminous Seyfert 1.8/1.9 galaxies culled from the SDSS EDR and derived the fraction of partially obscured quasars in the local universe. Follow-up XMM-Newton observations confirm that these sources have large absorption column densities in the X-ray (Zhou et al., in preparation).

5 SUMMARY

We have investigated the broad-line Balmer decrements for a large, homogeneous sample of 446 blue AGN, of Seyfert 1 galaxies and QSOs. They are selected from the Sloan Digital Sky Survey Fourth Data Release according to the criteria of redshift \( z \lesssim 0.35 \), the median spectral signal-to-noise per pixel \( \gtrsim 10 \), and the continuum slopes \( \alpha_{\lambda} \gtrsim 1.5 \) \( (f_{\lambda} = \lambda^{-\alpha_{\lambda}}) \) that are fitted in the rest-wavelength range of 4000–5600 Å. With the blue criterion of the continuum slope, dust extinction in the sample objects is expected to be negligible, which is also confirmed by their relative colors in the ultraviolet. The sample is fairly representative of normal Seyfert 1/QSOs (at least the luminous objects with \( \mathrm{H}\alpha \) luminosity greater than \( 10^{41} \) ergs s\(^{-1}\)), in light of the fact that the optical–near-ultraviolet continuum slope does not correlate with the Balmer decrement, nor with other AGN properties except nuclear luminosity. We find that (i) The distribution of the intrinsic broad-line \( \mathrm{H}\alpha/\mathrm{H}\beta \) ratios can be well described by log-normal, with a peak at \( \mathrm{H}\alpha/\mathrm{H}\beta = 3.06 \) and an dispersion of likely 0.03 dex only, (ii) there are no significant corrections between the Balmer decrement and the nuclear properties such as luminosity, accretion rate, continuum slope and \( \alpha_{\mathrm{OX}} \); (iii) on average, the Balmer decrements are slightly larger in radio-loud objects (3.37) and objects having double-peaked emission-line profiles (3.27). Therefore we suggest that the broad-line \( \mathrm{H}\alpha/\mathrm{H}\beta \) ratios can be used as a good indicator of dust extinction of the AGN broad-line regions, at least in a statistical manner. This result is especially true for radio-quiet AGN with regular emission-line profiles that constitute the vast majority of the AGN population. Such an application has significant implications for deriving the distribution of internal dust extinction in the BLR of AGN, and hence the obscuration fraction of AGN in the universe.

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Figure 1. Representative examples of the SDSS spectra and simultaneous fitting of the continuum, Fe II and other emission lines from 4030Å to 7500Å. In each panel, we plot the observed spectrum (black), the sum of the best-fit components (red), the continuum modeled as a broken power-law with a break at 5600Å (blue), and the Fe II emission (green). The radio-loudness ($R_i = \log(\frac{f_{20\text{ cm}}}{f_i})$), the continuum slopes blueward ($\alpha_{\lambda,1}$) and redward ($\alpha_{\lambda,2}$) of 5600Å are indicated. Note that the model Balmer broad-line profile in some objects differ more or less from the observed one due to that the Balmer lines are assumed to have the same profile in the fit; for such objects we refit the line profiles to obtain much accurate line parameters (see the text in §2.4 and Fig. 2).
Figure 2. Results of our line-profile fitting procedure applied to the Hβ region (left panels) and the Hα region (right panels) for the 3 objects demonstrated in Fig. 1. We plot the original data (black), the sum of all the best-fit components (red), the fitted narrow lines (green), the fitted broad Hβ and Hα (blue), and the residuals of the fit (bottom, offset downward for clarity). The broad-line Balmer decrements are indicated.
Figure 3. Histogram of $\log(H\alpha / H\beta)$ for the 446 blue AGN. Also displayed are the fit (solid line) with a Gaussian function yielding a mean of $0.486 \pm 0.002$ and a standard deviation of $0.046 \pm 0.002$. The intrinsic $\log(H\alpha / H\beta)$ distribution is over-plotted (dash line) with a standard deviation of $0.03$, that is estimated by de-convolving the observed distribution with the dispersion caused by measurement uncertainty.

Figure 4. Plots of $H\alpha / H\beta$ versus $\lambda L_\lambda(5100 \text{\AA})$, $L_{bol}/L_{Edd}$, radio loudness $R_i$, kurtosis index $K I_1$ as defined by Marziani et al. (1996), $\alpha_{ox}$, and the optical–near-ultraviolet continuum slope $\alpha_\lambda$. In panel (a) and (b), objects in the $M_{BH}$ bin of $10^{7.8} - 10^{8.2} M_\odot$ are denoted as solid black squares. In panel (c), the 404 objects covered by FIRST are plotted, among which 336 have only upper limits (grey circles with arrows). In panel (e), the 268 sources having ROSAT matches are plotted, where the $\alpha_{ox}$ values are taken from Anderson et al. (2007). Note that although the mean Balmer decrements are slightly larger in the radio-loud subsample and the subsample of objects with double-peaked line-profiles, there are no significant correlations of the Balmer decrement with $R_i$ or $K I_1$ in the blue AGN ensemble.
Table 1. Properties of Blue AGN

| Object               | z     | L_{5100} | F(Hβ)\(n\) | F(Hβ)\(b\) | F(Hα)\(n\) | F(Hα)\(b\) | \(\alpha_\lambda,1\) | \(\alpha_\lambda,2\) | f   | n   | \(E_Gal\) | \(J_{20cm}\) |
|----------------------|-------|----------|-------------|-------------|-------------|-------------|----------------|----------------|-----|-----|-----------|------------|
| 000710.01+005329.0   | 0.31  | 10621    | 4948.1      | 162        | 13694.1    | 18.24       | 17.69          | 0.032          | 1.44 |
| 000834.72+003156.1   | 0.26  | 10621    | 4948.1      | 162        | 13694.1    | 18.24       | 17.69          | 0.032          | 1.44 |
| 001224.02−102226.2   | 0.22  | 10621    | 4948.1      | 162        | 13694.1    | 18.24       | 17.69          | 0.032          | 1.44 |
| 001247.93−084700.4   | 0.32  | 10621    | 4948.1      | 162        | 13694.1    | 18.24       | 17.69          | 0.032          | 1.44 |

Note. — Col. 1, object name in J2000.0. Col. 2, redshift given by the SDSS spectroscopic pipeline. Col. 3, monochromatic luminosity \(L_\lambda\) at 5100 Å, in units of ergs s\(^{-1}\). Col. 4, Hβ narrow component flux; its typical error is 6%. Col. 5, Hβ broad component flux; its typical error is 8%. Col. 6, Hα narrow component flux; its typical error is 5%. Col. 7, Hα broad component flux; its typical error is 5%. Col. 8–9, continuum slopes blueward and redward of 5600 Å, respectively (\(f_\lambda = \lambda^{-\alpha}\)); their typical error is 8%. Col. 10–11, GALEX calibrated magnitude (AB) in the FUV (f) and NUV (n) bands, respectively, uncorrected for Galactic extinction; a “−999” is given for sources that are covered yet not detected by GALEX, and a blank is given for 185 sources that are not covered by GALEX. Col. 12, the SDSS i-band magnitude (AB), uncorrected for Galactic extinction. Col. 13, the Galactic color excess derived from Schlegel et al. (1998). Col. 14, the integrated flux density at 20 cm detected by FIRST, in units of mJy; the detection limit of 1 mJy is adopted as the upper limit for 336 objects that are covered yet not detected by FIRST, and a blank is given for 42 objects that are not covered by FIRST. Table 1 is now available in its entirety at [http://staff.ustc.edu.cn/~xbdong/Data_Release/blueAGN_DR4/](http://staff.ustc.edu.cn/~xbdong/Data_Release/blueAGN_DR4/); it will be available via the link to the machine-readable table on the MNRAS website.

Table 2. Hα and Hβ Broad-Line Profile Measurements

| Object               | FWHM  | \(\sigma_{line}\) | AI   | SI   | KI1  | FWHM  | \(\sigma_{line}\) | AI   | SI   | KI1  |
|----------------------|-------|-------------------|------|------|------|-------|-------------------|------|------|------|
| 000710.01+005329.0   | 9165.5| 4798.8            | −0.16| 0.93 | 0.38 | 9165.5| 4798.8            | −0.16| 0.93 | 0.38 |
| 000834.72+003156.1   | 1953.0| 1415.8            | 0.07 | 1.08 | 0.40 | 1953.0| 1415.8            | 0.07 | 1.08 | 0.40 |
| 001224.02−102226.2   | 4225.2| 2236.0            | 0.01 | 1.05 | 0.53 | 4225.2| 2236.0            | 0.01 | 1.05 | 0.53 |
| 001247.93−084700.4   | 4710.4| 3646.0            | 0.35 | 1.15 | 0.26 | 4710.4| 3646.0            | 0.35 | 1.15 | 0.26 |
| 002840.69−102145.0   | 1371.8| 1525.8            | 0.05 | 1.13 | 0.36 | 1371.8| 1525.8            | 0.05 | 1.13 | 0.36 |
| 004319.74+005115.3   | 12630.6| 5827.4           | −0.02| 1.01 | 0.71 | 12630.6| 5827.4           | −0.02| 1.01 | 0.71 |

Note. — Col. 1, object name in J2000.0. FWHM and line dispersion (\(\sigma_{line}\)) in unit of km s\(^{-1}\). Asymmetry index (AI) defined as in De Robertis (1985); shape index (SI) as in Boroson & Green (1992); kurtosis index (KI1) in Marziani et al. (1996); see §3.2.3. All parameters are derived from the model broad lines. Table 2 is now available in its entirety at [http://staff.ustc.edu.cn/~xbdong/Data_Release/blueAGN_DR4/](http://staff.ustc.edu.cn/~xbdong/Data_Release/blueAGN_DR4/); it will be available via the link to the machine-readable table on the MNRAS website.
Table 3. Summary of Spearman Rank Correlation Tests $^a$

|                     | $\text{H} \alpha^b/\text{H} \beta^b$ | $\alpha_{\lambda,1}$ |
|---------------------|--------------------------------------|----------------------|
| $L_{5100}$          | 0.115 (0.015)                       | 0.457 (1.0 $\times 10^{-6}$) |
| $L_{\text{bol}}/L_{\text{Edd}}$ $^b$ | $-0.051$ (0.281)                    | 0.073 (0.123)         |
| $M_{\text{BH}}$ $^b$ | 0.093 (0.049)                       | 0.187 (6.8 $\times 10^{-5}$) |
| $R_i$ $^c$          | 0.205 ($< 10^{-4}$)                 | 0.044 (0.381)         |
| $P_{20,\text{cm}}$ $^c$ | 0.209 ($< 10^{-4}$)                 | 0.144 (0.004)         |
| FWHM $^d$           | 0.078 (0.008)                       | 0.075 (0.116)         |
| $\sigma_{\text{line}}$ $^d$ | 0.099 (0.027)                      | 0.121 (0.011)         |
| skewness $^d$       | $-0.203$ (1.5 $\times 10^{-5}$)     | $-0.077$ (0.103)      |
| kurtosis $^d$       | $-0.047$ (0.324)                    | $-0.055$ (0.242)      |
| $AI$ $^d$           | $-0.020$ (0.673)                    | 0.024 (0.619)         |
| $SI$ $^d$           | $-0.002$ (0.974)                    | 0.129 (0.006)         |
| $KI1$ $^d$          | $-0.151$ (0.001)                    | $-0.070$ (0.138)      |
| $KI2$ $^d$          | 0.047 (0.320)                       | $-0.032$ (0.502)      |
| $\alpha_{\text{ox}}$ $^e$ | $-0.089$ (0.147)                    | 0.138 (0.024)         |
| $\alpha_{\lambda,1}$ | $-0.109$ (0.022)                    |                     |

$^a$ For each entry, we list the Spearman rank correlation statistic ($\rho$) and the probability of the null hypothesis ($P_{\text{null}}$) in parenthesis. If no censored data (upper limits) are present, $\rho$ is equal to the Spearman’s rank correlation coefficient $r_s$.

$^b$ The black hole masses are calculated using the formalism presented in Vestergaard & Peterson (2006, their equation 5) with H$\beta^b$ FWHM listed in Table 2; Eddington ratios ($L_{\text{bol}}/L_{\text{Edd}}$) are calculated assuming that the bolometric luminosity $L_{\text{bol}} \approx 9L_{5100}$ used for normal QSOs (Kaspi et al. 2000, Elvis et al. 1994).

$^c$ Using 404 sources covered by FIRST, of which 336 are upper limits.

$^d$ Computed based on the model H$\beta$ broad-line profiles.

$^e$ Using 268 sources matched with ROSAT; $\alpha_{\text{ox}}$ values are brought from Anderson et al. (2007).