H$\beta$ PROFILES IN QUASARS: EVIDENCE FOR AN INTERMEDIATE-LINE REGION

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Accepted for publication in ApJ (Letters).

ABSTRACT

We report on a systematic investigation of the H$\beta$ and Fe II emission lines in a sample of 568 quasars within $z < 0.8$ selected from the Sloan Digital Sky Survey. The conventional broad H$\beta$ emission line can be decomposed into two components—one with intermediate velocity width and another with very broad width. The velocity shift and equivalent width of the intermediate-width component do not correlate with those of the very broad component of H$\beta$, but they do resemble Fe II. Moreover, the width of the very broad component is roughly 2.5 times that of the intermediate-width component. These characteristics strongly suggest the existence of an intermediate-line region, whose kinematics seem to be dominated by infall, located at the outer portion of the broad-line region.

Subject headings: galaxies: nuclei — (galaxies:) quasars: emission lines — (galaxies:) quasars: general — galaxies: Seyfert — line: profiles

1. INTRODUCTION

The geometry and kinematics of the broad-line region (BLR) in active galactic nuclei (AGNs) have been studied for about three decades but the details are far from well understood. It is widely accepted that the BLR is stratified: high-ionization lines originate from small radii and low-ionization lines arise further out (Collin-Souffrin & Lasota 1988). This stratification picture is supported by the results of reverberation mapping, which show that lines of different ionization have different lags (e.g., Peterson & Wandel 1999). The dependence of the systemic velocities of the emission lines on ionization (e.g., Gaskell 1982; Sulentic et al. 2000a; Richards et al. 2002; Shang et al. 2007) suggests that the BLR may originate from a wind and a disk (e.g., Leighly & Moore 2004, and references therein). However, the profiles of the broad emission lines often contain multiple velocity components, suggesting that the structure of the BLR may be more complex than can be described by a simple stratification or wind + disk model.

It has been known that the broad H$\beta$ line profiles are generally not well described by a single Gaussian. Two Gaussians (e.g., Netzer & Trakhtenbrot 2007) or a Gauss-Hermite function (e.g., Salviander et al. 2007) are often used. Additionally, the profiles show great diversity from object to object. Sources with narrower H$\beta$ lines tend to have stronger line wings, while those with broader H$\beta$ lines are dominated by the line core (e.g., Sulentic et al. 2002). Some sources have asymmetric and shifted H$\beta$ profiles, suggesting that the BLR has a structure more complex than a single virialized component. The H$\beta$ profile of QO 208, for example, has an additional redshifted H$\beta$ component of intermediate width that closely resembles the kinematics of Fe II (Marziani et al. 1993). Additional evidence that the BLR contains two or more kinematically distinct components comes from differential variability between the line core and wing (e.g., Ferland et al. 1990; Peterson et al. 2000). The existence of an intermediate-line region and a very broad-line region for H$\beta$ emission was suggested by some previous studies (e.g., Brotherton 1996; Sulentic et al. 2000b).

In a recent spectral decomposition of a large sample of quasars selected from the Sloan Digital Sky Survey (SDSS), Hu et al. (2008, hereinafter Paper I) find that the majority of quasars show Fe II emission that is both redshifted and narrower than H$\beta$. Moreover, the magnitude of the Fe II redshift correlates inversely with the Eddington ratio. These characteristics suggest that Fe II originates from an exterior portion of the BLR, whose dynamics may be dominated by infall. These findings offer fresh insights into the structure of the BLR.

In light of the trends associated with Fe II emission, we expect that a portion of the H$\beta$-emitting gas may be related to an inflowing component too. In this Letter, we systematically study the H$\beta$ profiles of SDSS quasars to try to answer two questions: do all quasars have an intermediate-width H$\beta$ component similar to QO 208, and, if so, is this component also associate with the Fe II emission? We show that the conventional broad H$\beta$ line actually consists of two kinematically linked components, one of which originates from the same region that emits Fe II.

2. SAMPLE AND DATA ANALYSIS

Our sample is selected from the SDSS Fifth Data Release (Adelman-McCarthy et al. 2007) quasar catalog (Schneider et al. 2007). We choose objects with redshifts $z < 0.8$ to ensure that [O III] $\lambda$5007 lies within the SDSS spectral coverage. We also require a signal-to-noise ratio (S/N) > 10 in the restframe wavelength range 4430–5550 Å (covering H$\beta$, [O III], and the most prominent features of optical Fe II emission) and that no more than 1/3 of the pixels are masked by the SDSS pipeline in this region. 7601 quasars satisfy these criteria. The spectral analysis, whose details are described in Paper I, involves fitting a continuum model in a set of windows devoid of strong emission lines that consists of (1) a single power law, (2) Balmer continuum supplemented...
with high-order Balmer emission lines, and (3) a pseudo-continuum due to blended Fe II emission. The full width at half-maximum (FWHM) and shift of Fe II are measured from the continuum decomposition. After subtracting the continuum model, the H β line is decomposed into narrow (H βNC) and broad (H βBC) components. H βNC is forced to have the same profile as [O III], a shift of up to 600 km s^{-1} relative to [O III], and an intensity constrained to lie between 1/20 and 1/3 of that of [O III]. H βBC is modeled using a Gauss-Hermite function (van der Marel & Franx 1993), whose best fit yields FWHM(H βBC). The rest frame is defined by the peak of the [O III] λ5007 (see Paper I for more details).

Although the Gauss-Hermite function provides a good and convenient mathematical description of the H β profile, for the purpose of this Letter—investigating whether there is an intermediate-width H β component associated with Fe II emission—we use the following simpler method to fit H β. First, we use only one Gaussian to model the broad H β line (hereinafter the single-Gaussian model). Then we fit broad H β with two Gaussians (hereinafter the double-Gaussian model), an intermediate-width component (H βIC) and a very broad component (H βBC). In both models, H βNC is fitted in the same way as in Paper I. First, we compare the χ^2 of the double-Gaussian model and the Gauss-Hermite. There are 630 sources with χ^2 20% larger in the double-Gaussian model than in the Gauss-Hermite model (Hao et al. 2005); this means that the double-Gaussian fit is still inadequate for these sources. Then, for the sources that can be well fitted by the double-Gaussian model, we compare the reduced χ^2 of the double-Gaussian and single-Gaussian model, and use the F-test (Lupton 1993, Chapter 12.1) to calculate how significantly the double-Gaussian model improves the fit. Whether a source needs two Gaussians or not depends on its H βBC width. Figure 1 shows the probability P that the double-Gaussian model cannot improve the fit, as a function of FWHM(H βBC). The 2435 sources below the dashed line (~ 32% of the whole sample) require two Gaussians at a significance greater than 3 σ. For sources with FWHM(H βBC) > 5000 km s^{-1}, one Gaussian is enough to describe the profile of H βBC. This is consistent with Collin et al. (2006), who find that the ratio FWHM/σ (σ is the line dispersion) of H βBC depends on its line width (see their Fig. 3). For sources with broader H βBC, this ratio is close to 2.35, the value for a single Gaussian. As discussed later, this means that broader sources have a weaker H βIC component.

We use Monte Carlo simulations to determine the detection threshold of H βBC. We generate artificial H β lines using two components [FWHM(H βBC)] is set to 2.5 FWHM(H βBC) as shown in Fig. 5, fit it using a single and a double Gaussian, and then calculate the probability P as before. The EW ratio of H βBC/H βIC is increased progressively until 1 − P exceeds 99.73%. (All EW measurements refer to the continuum at 5100 Å.) The critical EW ratio of H βBC/H βIC depends on S/N, as shown in Figure 1. In order to detect an H β component with an EW that is 10% larger than the EW of H βBC, the S/N should be larger than 22.5. Thus, in the analysis below, we remove all sources with (1) S/N < 22.5, (2) χ^2 of double-Gaussian 20% larger than the χ^2 of Gauss-Hermite and 1 − P > 99.73%, and (3) EW(Fe II) < 25 Å (to insure that the Fe II measurements are as reliable as those in Paper I).

There are 510 sources with FWHM(H βBC) > 5000 km s^{-1}, and 568 sources, respectively. Note that the fraction of sources that require a double-Gaussian model (811/1499 ≈ 54%) is larger than the fraction when the S/N threshold is 10 (2435/7601 ≈ 32%), consistent with the simulations above: fainter H βBC can be detected with higher S/N. The analysis below focuses on the most stringent subset of 568 sources (~ 38% of the sources with S/N > 22.5). The reduced χ^2 for the double-Gaussian model fit has a median value of 1.004.

To constrain the relative strengths of Fe II emission associated with the very broad and intermediate-width components, we generated simulated spectra using two Fe II components, and then fit them using only one component, whose width is fixed to that of the input intermediate-width component. The EW of the input very broad component is increased progressively until the reduced χ^2 of the fit exceeds 1 σ from the expect value. For a typical Fe II EW of 75 Å and S/N ≈ 25 in our final sample, the flux ratio of Fe II between the input very broad component and intermediate-width component is ~0.3. This is the upper limit of the Fe II emission coming from the very broad component.

Figure 2 shows the emission-line fitting and Fe II emission measurement for three typical sources. Example a is an extreme case that has a large Fe II redshift (1533±24 km s^{-1}) and H β with an isolated red peak. The Fe II in example b is a moderately redshifted (590±98 km s^{-1}), and its H β core shows only a strong red asymmetry rather than another peak. A more common situation is seen in example c, in which Fe II and H βBC have no shift and the H β profile is symmetrical. Table 1 lists the measurements of the three sources shown in Figure 2.

3. RESULTS AND DISCUSSIONS

We find that H βIC and Fe II emission have similar kinematics. The similarity can be seen not only in individual sources, but also statistically for the whole sample. From examples a to c in Figure 2 the H β profiles change progressively while the Fe II shifts become lower and lower. Figure 3a shows a strong correlation between H βIC and Fe II shifts. Pearson’s correlation coefficient rP is 0.22, and the probability P of a chance correlation is < 1 × 10^{-5}. H βBC and Fe II have approximately the same shifts. The widths of H βBC and Fe II are also well correlated and roughly equal (Fig. 3b); rP = 0.48 and P < 1 × 10^{-5}. Except for some sources to the upper left of the solid lines whose errors are large, the majority of
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Fig. 2.— Examples of Fe II measurement and emission-line fitting for (a) SDSS J094603.94+013923.6, (b) SDSS J092008.22+032245.4, and (c) SDSS J103859.58+422742.2. For each source, the top panel shows multi-Gaussian fitting for Hβ and [O III]. Hβ VBC is in green and Hβ IC is in magenta. The two blue dashed lines mark the rest-frame wavelength of Hβ and [O III] λ5007. The magenta dotted line is the position of Hβ at the same velocity as Fe II. Note the consistency between the Hβ IC peak and the dotted line. Hβ NC and [O III] are in blue. The red line is the sum of each component. The bottom panel shows the emission-line spectrum after subtracting the power-law continuum. The green portions of the spectrum denote the windows for fitting the Fe II emission, whose model is given in red. The blue dashed line marks the peak of Fe II λ4924 at zero velocity shift.

Table 1

| SDSS Name       | z     | Fe II | Hβ IC | Hβ VBC |
|-----------------|-------|-------|-------|--------|
|                 |       | EW (Å) | FWHM (km s⁻¹) | Shift (km s⁻¹) | EW (Å) | FWHM (km s⁻¹) | Shift (km s⁻¹) | χ² |
| 094603.94+013923.6 | 0.220 | 60±1  | 1543±55 | 1533±24 | 54±1  | 1428±18 | 1754±7 | 5.066 |
| 092008.22+032245.4 | 0.334 | 45±2  | 2548±251 | 590±98  | 27±2  | 2281±103 | 589±42 | 0.715 |
| 103859.58+422742.2 | 0.221 | 72±1  | 1297±40  | −10±18  | 13±1  | 1259±71  | −16±26 | 1.361 |

Note.— Table 1 is available in its entirety electronically.

Fig. 3.— Correlations between (a) Fe II and Hβ IC shifts and (b) Fe II and Hβ IC widths. The solid diagonal lines denote that Fe II and Hβ IC have the same shifts and widths. The contours in panel (a) show the density of the data points.

Fig. 4.— Plots of (a) Fe II vs. Hβ VBC shifts and (b) Fe II vs. Hβ VBC widths. The two lines have different shifts and widths. The two components have different shifts and widths. The solid line in panel (b) denotes FWHM(Hβ VBC) = 2.5 FWHM(Hβ IC).

Fig. 5.— Plots of (a) Hβ VBC vs. Hβ IC shifts and (b) Hβ VBC vs. Hβ IC widths. The two components have different shifts and widths. The two components have different shifts and widths. The solid line in panel (b) denotes FWHM(Hβ VBC) = 2.5 FWHM(Hβ IC).

The observational results described above suggest a scenario in which the conventional BLR consists of two components—an intermediate-line region (ILR) and a very broad-line region (VBLR). If both regions are virialized, so that \( R \propto v^{-2} \), then the ILR is about 2.5 or 6.25 times farther from the center than the VBLR. Because of its redshift, the kinematics of the ILR may be dominated by infall. Hβ emis-
mission emerges from both the ILR and VBLR, while most of the Fe II emission comes from the ILR.

The ILR and VBLR defined in this paper are essentially similar to those described in Corbin (1998), Brotherton (1996), and Sulentic et al. (2000b), but differ from those in Brotherton et al. (1994) or Sulentic & Marziani (1999), which refer to the C IV-emitting region. Note that the ILR and VBLR of the Hβ-emitting region are distinct from those of the C IV-emitting region because the C IV ILR usually has the systemic redshift while the C IV VBLR shows a blueshift.

The lack of correlation between the EWs of Hβ/IC and Hβ/IV (Fig. 6b) strongly suggests that the two components are emitted from different regions. If both are photoionized, they must have different covering factors. The relative strength between Hβ/IC and Hβ/IV determines the final Hβ profiles. In Figure 11 sources broader than ~5000 km s⁻¹ can be fitted well using one Gaussian. This trend can be interpreted in our two-component BLR scenario. It is well known that sources with broad Hβ tend to have weak Fe II/Hβ (e.g., Boroson & Green 1992; Sulentic et al. 2000). The ILR is weak in these systems because Fe II is weak. Their profiles show little deviation from a single Gaussian under the typical S/N level of SDSS spectra. The composite spectra of sources with large Fe II redshifts, on the other hand, do show red asymmetry in the Hβ profiles (see Fig. 13 of Paper I). The variation in the relative strength of the Hβ/IV and Hβ/IC components in different sources reflects the competition between the two components, although they apparently do so in such a manner that their kinematics remain coupled.

It is of interest to note that the strengths of Hβ/IC and Fe II are not correlated (Fig. 6b). The wide range of Fe II/Hβ/IC ratios reflects either the complexity of the excitation mechanism of Fe II emission (e.g., Baldwin et al. 2004, and references therein) or large variations in quasar metallicities (e.g., Netzer & Trakhtenbrot 2007).

4. SUMMARY

We have studied the profiles of the Hβ emission line using a large sample of quasars selected from SDSS. Comparing the Hβ profiles with the properties of Fe II emission given in Paper I, we deduced the existence of two Hβ emission regions—an intermediate-line region and a very broad-line region. The observational evidence can be summarized as follows:

1. The velocity shifts and widths of the Hβ intermediate-width component are approximately the same as those of Fe II, indicating that they originate from the same region. However, the Fe II/Hβ/IC ratios vary greatly from object to object, reflecting variations in either metal abundance or excitation conditions in the Fe II-emitting region.

2. The velocity width of the very broad component of Hβ is roughly 2.5 times larger than that of the intermediate-width component, but no correlation exists between their radial velocities. The equivalent widths of the two components are also unrelated, suggesting that they have very different covering factors and geometry. The conventional BLR seems to consist of two different, physically distinct regions. We suggest that the intermediate-width component of Hβ and Fe II trace an infalling region in the outskirts of the BLR, likely located in between the molecular torus and the accretion disk.

The properties of the Hβ-emitting region discussed here, in conjunction with those of Fe II emission summarized in Paper I, offer important new constraints on models of the broad emission-line regions. This will be the subject of a forthcoming paper.

We appreciate extensive discussions among the members of the IHEP AGN group. We thank an anonymous referee for helpful comments. This research is supported by NSFC via NSFC-10325313, 10733010 and 10521001, and by CAS via KJCX2-YW-T03.

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