Quasars with Anomalous H\(_\beta\) Profiles. I.

Demographics

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(Received 2012 September 6; accepted 2013 April 3)

Abstract

The H\(_\beta\) emission line in a typical Type I quasar is composed of a broad base and a narrow core, with the core velocity characteristic of narrow-line region emission, and line-fitting routines typically assume this picture. We test the effects of removing this constraint, and find a substantial group of Type I quasars in the Sloan Digital Sky Survey catalog with H\(_\beta\) emission line cores broader than 1200 km s\(^{-1}\), above the velocity believed possible for gas in the quasar narrow-line region. We identify this group of “anomalous H\(_\beta\) quasars” (AHQs) as a distinct population because of a variety of spectral and photometric signatures common to these AHQs but atypical of other quasars. These features are similar to some aspects of narrow-line Seyfert 1s and correlations identified by Eigenvector 1, but also contain distinct features that make it difficult to classify AHQs. We demonstrate that AHQs comprise at least 11% and most likely approximately one quarter of the SDSS Type I quasar population at 0.2 < z < 0.8. For AHQs, the [O III]\(\lambda\) 4959, 5007 profile is often better fit by de-linking it from the H\(_\beta\) core, while a more standard linked fit produces a tight correlation between narrow- and broad-line velocities. We find that [O III] in AHQs sometimes has a standard narrow-line profile and other times matches the H\(_\beta\) core, but is rarely in between the two, implying that the broadened core emission arises from a distinct physical region. Another feature of AHQs is a diminished [O II] line, which might indicate a connection between AHQs and the interstellar mediums of their host galaxies, through reduced photoionization or star formation. We find that it is difficult to produce AHQs using the current quasar standard model.

Key words: accretion, accretion disks — black hole physics — galaxies: evolution — galaxies: nuclei — galaxies: quasars: general

1. Introduction

Although quasars are luminous enough to be detected at large distances, they are too small to be resolved into multiple spatial elements except at very short distances (e.g., Marconi et al. 2006) or when lensed by a foreground object (Sluse et al. 2011). As a result, our best tool for mapping the region around the central supermassive black hole in higher-redshift active galactic nuclei has been spectroscopy. Each spectral line is associated with a specific ionization potential, and the shape of the line corresponds to the peculiar velocity profile of the emitting gas, complicated by parameters such as densities, abundances, temperatures, and effects of radiative transfer. There is a long history of studying quasar emission lines and their correlations (cf. Boroson & Green 1992), much of which has helped to develop our standard model for Type I quasars (Sulentic et al. 2000; Gaskell 2009). In this paper, we describe a new class of quasars with distinct spectroscopic features that do not appear to be fit easily with that standard model.

The standard picture built from existing data consists, from the black hole outward, of (cf. Peterson 1997):

- The central black hole.
- A hot accretion disk, beginning near the “innermost stable circular orbit” (ISCO), typically a few Schwarzchild radii away with an exact radius dependent upon the spin of the central black hole. The accretion disk and corona are believed to emit the quasar continuum.
- The “broad-line region” (BLR), ~0.1–1 pc away, from which high-velocity gas produces correspondingly broad spectral emission lines, in the typical FWHM range of 2000–20000 km s\(^{-1}\). Prominent emission lines visible in optical spectra at z > 0.5 include, from ionization potential placing them nearest to the central black hole, C IV, a broad component of H\(_\beta\), and Mg II. In quasar virial mass estimators (McLure & Jarvis 2002; McLure & Dunlop 2004; Vestergaard & Peterson 2006; Wang et al. 2009; Onken & Kollmeier 2008; Risaliti et al. 2009; Rafiee & Hall 2010), the velocities of BLR gas are assumed to be predominantly virial in order to use Kepler’s laws to infer the mass of the central black hole. However, C IV in particular may also be substantially
broadened by radiation pressure and quasar outflows (Marconi et al. 2009; Netzer & Marziani 2010; Marziani & Sulentic 2011; Netzer 2009).

- The “narrow-line region” (NLR), \( \sim \) kpc away, from which lower-velocity gas produces correspondingly narrower spectral emission lines, with a typical FWHM of approximately 500 km s\(^{-1}\), and in some cases higher velocities due to thermal or other effects. This FWHM might correspond to typical velocities for gas in the interstellar medium being photoionized by the central black hole. Prominent narrow lines in the optical include the [O \textsc{iii}] fine structure doublet, a narrow component of H\(\beta\), and usually [O \textsc{ii}].

- A surrounding host galaxy. For quasars, the galactic starlight is typically too faint compared to the quasar to be detected directly, but galactic spectral lines are often present, including both absorption lines and, for many galaxies, a narrow [O \textsc{ii}] emission line believed to be associated with star formation. In a typical quasar spectrum, the [O \textsc{ii}] emission is likely dominated by photoionization due to a nonthermal continuum as opposed to star formation.

For some individual active galactic nuclei, reverberation mapping (Bentz et al. 2009; Peterson et al. 2004) has been able to confirm the inner portion of this picture, out to the H\(\beta\) broad emission line. In a time series of spectra for the same object, an increase in the continuum luminosity is followed, often hundreds of days later, by a similar flare in C\textsc{iv} and then H\(\beta\). Assuming that the flare propagates outward at the speed of light, the delay can be used to infer a radius to BLR spectral lines.

It should be noted, however, that this simple picture is merely a broad overview of features common to most quasars. Most individual quasars are observed to deviate from this model in any of a wide variety of ways, particularly where high-quality spectra are available and particularly outside of the broad-line region.

There have also been hints that for some quasars, this simple picture might be more clearly wrong. The Boroson and Green (1992) principal component analysis uncovered Eigenvector 1, indicating that for some quasars, changes in specific broad spectral lines are correlated with changes in specific narrow lines. The population of narrow-line Seyfert 1 galaxies contain active nuclei with no traditional broad-line component, but with an intermediate-velocity component up to \( \sim 2000\) km s\(^{-1}\) (Komossa 2008). It is unclear whether this intermediate component is a broadened narrow-line region, a weak, high-radius broad-line region, or something else entirely. Similarly, some quasars contain an intermediate H\(\beta\) component (Hu et al. 2008a). Even the [O \textsc{iii}] narrow line (A 4959, 5007) has been observed to occasionally be broader than 1000 km s\(^{-1}\) (Marziani et al. 1996; McIntosh et al. 1999).

The [O \textsc{iii}] fine structure doublet is an especially useful indicator for properties of Seyfert galaxies and other low-luminosity active galactic nuclei (AGNs) (Hao et al. 2005). [O \textsc{iii}] is a forbidden line that can only be produced in low-density gas where there are not enough free electrons to allow competing transitions. As such, [O \textsc{iii}] lines are typically found around AGN only in the narrow line region, as interstellar medium gas is lower-density than gas in the broad-line region. Common line-fitting techniques for the nearby H\(\beta\) line rely upon the assumption that the widths of the narrow H\(\beta\) component and [O \textsc{iii}] lines are identical, in order to disentangle the complicated combination of spectral lines surrounding H\(\beta\). The [O \textsc{iii}] lines, in turn, are typically assumed to be narrow based upon previous studies (Hao et al. 2005). For example, the Shen et al. (2008) virial mass catalog fit the H\(\beta\) broad component along with a narrow component linked to the [O \textsc{iii}] line width and at a maximum FWHM of 1200 km s\(^{-1}\).

Although fitting one Gaussian to each of these narrow lines, with a common width, is currently a standard practice, there is ample evidence that the underlying physics may be more complicated. Forbidden lines at higher ionization potentials do show broader velocity profiles than those with lower ionization potentials (Whittle 1985; De Robertis & Osterbrock 1984), indicating that the narrow-line region may not be monolithic. [O \textsc{iii}], a narrow line heavily studied just because it is typically strong and available in the optical up to \( z \approx 0.8 \), may be asymmetric with multiple components (Zamanov et al. 2002; Boroson 2005). This might be further evidence of an intermediate-line region, or of outflows (cf. Hall et al. 2002; Ho 2009).

Motivated by these examples of broader H\(\beta\) cores and non-Gaussian narrow-lines, in this work we examine the effects of removing the 1200 km s\(^{-1}\) bound from Shen et al. (2008). If the H\(\beta\) line is indeed composed predominantly of one broad and one narrow component as expected theoretically, removing this bound should have no substantial effect. Shen et al. (2011) model complex line shapes by adding a third Gaussian and even fourth in an attempt to describe the H\(\beta\) profile. Instead, we find and describe a set of quasars for which the \( \chi^2/\text{DOF} \) is substantially lowered when fit with a broadened “narrow” component of H\(\beta\) (section 2), but also that these two components are still sufficient to describe the entire H\(\beta\) profile; a third component is not necessary.

It turns out these “anomalous H\(\beta\)” quasars (AHQs, see section 3) comprise a distinct population, with a wide variety of properties common to all AHQs but atypical of other quasars. These properties are discussed in section 3, and include many of the characteristics previously reported by Boroson and Green (1992) and Hu et al. (2008a), as well as several properties characteristic of narrow-line Seyfert 1s, despite our study focusing on Type 1 quasars often containing a 10000 km s\(^{-1}\) broad H\(\beta\) component. In addition, we show that AHQ spectra have several additional, previously unreported properties characteristic of this new population. We consider whether these properties might be an artifact of our fitting routines in section 4. Finally, AHQs seem not to be fit easily with the standard AGN model, and possible explanations are considered in section 5, as well as issues of nomenclature. It is currently unclear how AHQs should be classified, but likely that a physical model will demonstrate how to fit them with existing quasar nomenclature.
2. Anomalous H\(\beta\) Profiles

Fitting techniques in current use typically assume that the H\(\beta\) core (i.e., the narrower component) and [O\textsc{iii}] both come from the narrow-line region, so that the two can be linked. Methods for linking them include three steps: fitting the [O\textsc{iii}] line, using it as a template for a narrow H\(\beta\) component, and fitting the two components simultaneously. Because one of the main recent uses of quasar H\(\beta\) emission has been as a virial mass indicator, we will begin our investigation by using the technique on which the SDSS Value Added Catalog (Shen et al. 2011, 2008) and calibration of Mg II virial masses against H\(\beta\) (McLure & Dunlop 2004) are based:

1. Using the catalog redshift, we select the spectrum at rest wavelengths \([4435,4700]\) and \([5100,5535]\) Å and simultaneously fit the sum of a power-law continuum and an Fe template (Bruhweiler & Verner 2008) convolved with a Gaussian of variable width.

2. With the continuum and iron lines removed, the H\(\beta\) line is fit with two Gaussians and the [O\textsc{iii}]\(\lambda\) 4959,5007 doublet with a pair of Gaussians; the [O\textsc{iii}] doublet is constrained to have the 3:1 amplitude ratio physically required by the fine structure transitions involved and the two [O\textsc{iii}] widths identical to the width of the H\(\beta\) narrow component. Typical uncertainties are 2\%–15\% in both H\(\beta\) velocities, with more luminous quasars and broader components typically best determined.

3. The final result is checked for contamination by nearby He i lines. If He i contamination is detected, we construct a new line fit with He i removed. This check is not part of the Shen et al. (2008) fitting prescription.

The Shen et al. (2011) catalog includes best fits for objects with very poor signal-to-noise and low-amplitude lines. We discard objects with very low H\(\beta\) equivalent width, where a fit containing no H\(\beta\) line had a better \(\chi^2/\text{DOF}\) than a fit containing an H\(\beta\) line. Although the Fe ii width is often similar to the H\(\beta\) broad component, they are not usually identical (Hu et al. 2008b). As a result, this is not required in our fitting, and for many AHQs, the two have very different velocities. Because the Fe ii amplitude is typically far smaller than the stronger of narrow H\(\beta\) and [O\textsc{iii}], alternative templates yield similar results. A sample end result (the first well-measured example sorted by right ascension) is shown in figure 1.

In Shen et al. (2008), the “narrow” component of H\(\beta\) and [O\textsc{iii}] are constrained to be narrower than 1200 km s\(^{-1}\). However, if H\(\beta\) is indeed predominantly composed of two nearly-Gaussian components, one broader than 1200 km s\(^{-1}\) and another narrower than 1200 km s\(^{-1}\) and produced with the same peculiar velocity as [O\textsc{iii}], this constraint is unnecessary, at least for quasar spectra with high signal-to-noise ratios.

Surprisingly, though, this constraint turns out to have been quite important, because removing this constraint, while otherwise reproducing the technique used in the Shen et al. (2008) catalog, produces a substantial population of objects with “narrow lines” fit as broader than 1200 km s\(^{-1}\). In figure 1(bottom), the quasar SDSS J00554.61+153833.8 is shown to exhibit “narrow” lines with a FWHM of 1860 km s\(^{-1}\). Further, this is not an isolated example, but rather part of a large class of objects with a broadened H\(\beta\) narrow component. In the Shen et al. (2011) catalog, 30.4\% of objects with discernible H\(\beta\) broad lines are measured to contain “narrow” lines broader than 1000 km s\(^{-1}\). It is convenient for the purpose of this paper to give this group of objects a label, although it is unclear what the proper nomenclature should be. For reasons discussed in section 3 and subsection 5.2, we will hereafter refer to this group of objects as “correlated” quasars, or anomalous H\(\beta\) quasars (AHQs).

2.1. Separating [O\textsc{iii}] and the H\(\beta\) Core in AHQs

A closer examination of objects where these “narrow” lines are measured as being broader than 1000 km s\(^{-1}\) reveals a mismatch between the [O\textsc{iii}] and H\(\beta\) core profiles (figure 2). Fitting the [O\textsc{iii}] line and the core of H\(\beta\) independently for these objects produces a better fit. Requiring [O\textsc{iii}] and the H\(\beta\) core to have identical profiles produces a 1940 km s\(^{-1}\) FWHM, but independent fits reveal a 2600 km s\(^{-1}\) FWHM for the H\(\beta\) core and 1310 km s\(^{-1}\) for the pair of [O\textsc{iii}] lines. Although [O\textsc{iii}] is narrower than the H\(\beta\) core, after de-linking the two lines, a population of objects with [O\textsc{iii}] greater than 1200 km s\(^{-1}\) still exists.

It is expected that the H\(\beta\) core should arise from the same narrow-line region as [O\textsc{iii}]\(\lambda\) 4959, 5007, and that they should therefore have the same profile. There are a variety of different fitting methods for exploring that expected link, including fitting the [O\textsc{iii}] profile independently and searching for an H\(\beta\) component of the same width, looking for an H\(\beta\) component with a profile fully identical to [O\textsc{iii}], and the simultaneous fit for narrow H\(\beta\) and [O\textsc{iii}] used in Shen et al. (2008) and McLure and Dunlop (2004). Surprisingly, we find that for AHQs, none of these is a good description of the observed spectra because the H\(\beta\) core has a different, higher-FWHM profile than [O\textsc{iii}].

It is likely that this broadened H\(\beta\) core does not represent a broadened narrow-line component. Typically the narrow-line region H\(\beta\) component has a smaller amplitude than [O\textsc{iii}], while AHQs are characterized by suppressed narrow-line emission. Rather, AHQs appear to contain two broad H\(\beta\) components, both broader than narrow lines such as [O\textsc{iii}], and no discernible narrow-line H\(\beta\) component. At the same time, [O\textsc{iii}] can be broader than 1000 km s\(^{-1}\), as shown in figure 2, and appears to be broader than 1000 km s\(^{-1}\) for approximately 10\% of the quasars in the SDSS catalog.

We note that although previous SDSS line catalogs (Hao et al. 2005; Shen et al. 2008, 2011) have not reported a substantial sample of AHQs, objects with [O\textsc{iii}] broader than 1000 km s\(^{-1}\) have been found in smaller surveys. Marziani et al. (1996) found an [O\textsc{iii}]\(\lambda\) 5007 FWHM over 1100 km s\(^{-1}\) for 6 of 52 low-redshift AGNs. In a sample of 32 high-luminosity quasars at \(2.0 < z < 2.5\), higher redshifts than the AHQs reported in this work. McIntosh et al. (1999) found 12 with [O\textsc{iii}]\(\lambda\) 5007 FWHM \(> 1200\) km s\(^{-1}\), and another six between 1000 and 1200 km s\(^{-1}\), finding a strong correlation between [O\textsc{iii}] FWHM and quasar luminosity. Forster et al. (2001) point out that the average [O\textsc{iii}] FWHM is 1150 km s\(^{-1}\) for radio-loud and 1160 km s\(^{-1}\) for radio-quiet quasars in the McIntosh et al. (1999) sample. What we report is that these quasars with broadened [O\textsc{iii}] are a part of a larger class
of quasars with broader H\(\beta\) cores than even these broadened [O\textsc{iii}] lines.

Although removing the link between the H\(\beta\) core and [O\textsc{iii}] produces a better description of the spectral line, for the remainder of this work (except for subsection 4.3) we will present fits linking the two lines. We do so primarily for three reasons:

1. Standard line fitting techniques expect the H\(\beta\) core and [O\textsc{iii}] to have identical profiles. Continuing to link the two lines demonstrates that our measurement of anomalous H\(\beta\) cores does not arise from a fundamental change in fitting technique, but solely from removing the artificial constraint on H\(\beta\) core velocity used in Shen et al. (2008).

2. Because [O\textsc{iii}] is narrower than the H\(\beta\) core for AHQs, the combined fit underestimates the H\(\beta\) core velocity. Since this work focuses on reporting broad H\(\beta\) cores, this underestimate yields a conservative AHQ fraction.

3. Existing catalogs, including SDSS value added catalogs (Shen et al. 2011, 2008), link the two lines. Doing the same in our results below allows a direct comparison between our work and existing catalogs.

In short, future line catalogs for AHQs will likely avoid linking the H\(\beta\) core and [O\textsc{iii}] profiles. However, because this work presents a surprising conclusion, it is presented by using the most conservative technique available, underestimating both individual H\(\beta\) core FWHMs and the overall AHQ fraction. We also illustrate the effects of de-linked line fitting on our main result in subsection 4.3.

3. AHQ Properties

The core of H\(\beta\) is typically a narrow line and emitted from a region with low enough density to also emit forbidden lines such as [O\textsc{iii}] and [Ne\textsc{v}], implying that these quasars with broader H\(\beta\) cores (AHQs) might have atypical structure. Thus, the investigation into AHQs is begun by determining whether they are atypical in any other ways, perhaps accompanied by other distinguishing features that might help to provide an explanation.

Indeed, a comparison between the broad H\(\beta\) and narrower component FWHMs shows two populations (figure 3): one with a narrow-line H\(\beta\) core apparently uncorrelated with the H\(\beta\) broad-line width and another with a broader H\(\beta\) core that is well correlated with the broad H\(\beta\) component. It is unclear whether this correlation indicates two distinct, correlated physical regions or whether the correlation in figure 3 is instead a nonphysical artifact of the standard line fitting technique for H\(\beta\) and [O\textsc{iii}]. We consider this question and other fitting techniques further in subsections 2.1 and 4.3. What is clear, however, is that the standard fitting technique divides quasar
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Table 1. Properties of quasars in the SDSS DR7 catalog.*

| σ (km s⁻¹) | FWHM | Color | N | Frac. “Best” N | Frac. BAL† | Fe II (arb.) | log Lbol |
|------------|------|-------|---|-------------|-----------|-------------|---------|
| 100–200    | 235–471 | Black | 3549 | 0.217 | 1162 | 0.217 | 0.0033 | 1.59 | 45.41 |
| 200–300    | 471–706 | Black | 4941 | 0.303 | 1018 | 0.274 | 0.0050 | 2.14 | 45.51 |
| 300–400    | 706–942 | Red   | 2309 | 0.141 | 657 | 0.123 | 0.0098 | 3.25 | 45.61 |
| 400–500    | 942–1177 | Red  | 1366 | 0.084 | 420 | 0.078 | 0.0069 | 4.14 | 45.68 |
| 500–600    | 1177–1413 | Yellow | 1086 | 0.067 | 394 | 0.074 | 0.0084 | 7.10 | 45.72 |
| 600–700    | 1413–1648 | Green | 1018 | 0.062 | 432 | 0.081 | 0.0065 | 9.37 | 45.82 |
| 700–800    | 1648–1884 | Cyan  | 743 | 0.045 | 321 | 0.060 | 0.0116 | 10.48 | 45.90 |
| 800–900    | 1884–2119 | Blue  | 424 | 0.026 | 207 | 0.039 | 0.0249 | 11.96 | 46.00 |
| 900–1000   | 2119–2355 | Magenta | 227 | 0.014 | 110 | 0.021 | 0.0284 | 13.75 | 46.01 |

* Properties of quasars in the SDSS DR7 catalog binned by Hβ core width, including the fraction showing broad absorption in Mg II (Shen et al. 2011) and the best-fit Fe II amplitude (arbitrary units).
† Broad absorption line.

Because low-density gas is required to allow the forbidden transitions producing the narrow [O III], the narrow-line region is often assumed to lie far from the central black hole. A very strong outflow reaching the narrow-line region could increase the velocities of [O III] (as can be seen in some but not all AHQs) and the narrow component of Hβ, and would at the same time also increase the velocity of the broad Hβ component coming from the broad-line region closer to the central black hole.

This second, diagonal branch of figure 3 appears to include the “intermediate line” quasar sample previously reported by Hu et al. (2008a) using a smaller sample of SDSS quasars. Hu et al. (2008a) found a similar fraction of AHQs to the ~30% reported in our work. By relating the AHQ branch to the standard quasars, we now find that these two classes may be more difficult to distinguish than previously thought. As indicated in figure 3, a cut at ~1200 km s⁻¹ is sufficient to remove standard quasars from an AHQ population, but objects with low FWHM of both Hβ components, classed in our study as standard quasars, might instead lie on a continuation of the AHQ branch, or might be a combination of some objects with standard and some objects with AHQ physics in their broad-line regions. If so, the true AHQ population would comprise more than 30% of the SDSS catalog, and some AHQs would have been well-fit in the Shen et al. (2011) catalog. This possibility is discussed further in subsection 5.2.

For further investigation, we divide the SDSS DR7 sample into bins by Hβ core width, as given in table 1. Quasars with standard narrow lines are most common, with the population peaking near the expected 500 km s⁻¹ line FWHM. However, 30.4% of quasars have Hβ core velocities greater than 1000 km s⁻¹, and in nearly one quarter of quasars these velocities are above the Shen et al. (2008) limit of 1200 km s⁻¹. Although figure 3 indicates that there are two populations of quasars, the quasar fraction decreases monotonously at velocities above the peak. This may indicate that quasars are not necessarily either AHQs or “standard” quasars, but rather can also exist in an intermediate state. Anomalous narrow lines are accompanied, on average, by an increased luminosity. However, AHQs are also increasingly likely to contain broad absorption lines as measured from Mg II in the Shen et al. (2011) catalog.

Fig. 3. Comparison of the narrow-line FWHM and Hβ broad-component FWHM for quasars in the SDSS DR7 catalog. Narrower velocities are accompanied by a wide range of Hβ widths, but AHQ narrow-line velocities are well-correlated with broad Hβ, increasing with increasing broad Hβ width. Contours are drawn at equally spaced number densities. (Color online)
For a variety of reasons, our best fit may not be a good match for even a well-measured SDSS spectrum, and this is one of the limitations of any automated line-fitting prescription with a small number of free parameters. For well-measured spectra where narrow Hβ and [O III] have similar, Gaussian profiles, our fit is generally good. However, many quasars best-fit with standard “narrow” lines have non-Gaussian profiles, and many anomalous Hβ quasars show a mismatch between the Hβ and [O III] profiles (subsection 2.1). In such cases, our fitting routine linking the two will be typically dominated by the higher-amplitude of narrow Hβ and [O III], which typically is [O III] for quasars with a standard set of narrow line and Hβ for AHQs (figure 4, further described below).

Some AHQs showing a mismatch between the Hβ core and [O III] may be objects with a broad blue [O III] wing component tied to the Hβ core and in addition to the [O III] narrow component, similar to those discussed in Zhang et al. (2011). Quasars with ~2000 km s^{-1} Hβ cores and standard [O III] lines are certainly anomalous, but might have a different cause from AHQs in which [O III] also has a discernable broad component.

We produce a “best” sample of quasars for which (1) the overall fit $\chi^2$/DOF is good and (2) the $\chi^2$/DOF for the ~50–150 pixels within 2$\sigma$ of the Hβ core and [O III] is within 0.5 of the total $\chi^2$/DOF. As shown in table 1, this sample has a slightly larger AHQ fraction than the overall catalog. A very conservative lower bound on the true AHQ fraction would be 11%, the fraction of quasars out of the entire sample that are AHQs in the “best” sample. A much more likely explanation is that ~11% of quasars are AHQs in which the broadened Hβ core profile is accompanied by a somewhat broadened [O III] profile, while an additional ~20% of quasars are AHQs with Hβ broadened but [O III] suppressed and unbroaded.

Spectra within each bin from table 1 are coadded to examine the average dependence of spectral lines on Hβ core FWHM. Each spectrum is first smoothed to the resolution of the SDSS spectrograph, then normalized to the monochromatic 5100 Å flux, and then averaged. Subtracting the best-fit continuum and Fe II template results in the spectral lines shown in figure 4.

As indicated by figure 3, for typical Hβ core profiles (black, red) in figure 4 an increase in FWHM is not associated with strong changes in the broad component of Hβ. However, broader Hβ core profiles, as shown in AHQs (remaining colors), are associated with an increase in width of Hβ as well as increasing Hβ line flux. When the [O III] width increases, it is associated with a declining amplitude, and in total a nearly constant equivalent width.

Several other spectral features are also responsive to increased Hβ core width (figure 5).

The continuum tilt increases for AHQs, making them bluer than other quasars. This bluer tilt occurs despite a higher broad absorption line (BAL) fraction among AHQs (table 1), which indicates AHQs might be on average dustier than other quasars. Perhaps this continuum slope is explained by AHQs having a higher temperature, also consistent with their higher average luminosity. AHQs also show stronger Fe II lines (see also table 1 of Boroson & Green 1992). An effort to find AHQ indicators available at other redshifts where [O III] is unavailable finds that [Ne v] broadens along with [O III], while [S II] does not (Steinhardt & Silverman 2011).

The stronger and broader Hβ line might provide evidence that the nature of the quasar broad-line region is changing, whether due to a strong outflow or to other accretion physics. However, the Mg II line (figure 5, top left) does not increase in width or in equivalent width in AHQs. Since Mg II has an ionization potential placing it at a larger radius from the central black hole (Peterson 1997), one possible explanation might be an outflow propagating only partway through the broad-line region.

However, the [O I] $\lambda$ 3727 Å line appears sensitive to these changes (figure 5). [O I] originates in both narrow-line region gas around the quasar and star formation in the host galaxy (Ho 2005; Kim et al. 2006). If broadened [O III] seen in some AHQs is evidence of an outflow broadening the entire narrow-line region, then any [O I] coming from near the quasar would also be broadened. The [O I] amplitude is declining in figure 5, but the line width is not increasing.

The decline in [O I] amplitude indicates that the combination of [O I] from all sources, including star formation, diminishes with increasing Hβ core width. One intriguing possibility is that star formation in AHQ hosts is quenched by outflows from the central black hole. It is also possible that all quasars inhibit star formation, and that the reduction in [O I] flux between standard Type I and AHQ quasars is due to a reduction in the photoionized [O I] in the narrow-line region.

The [O I] centroid appears to shift between different bins in figure 5. Although this could be interpreted as a skew in [O I], the redshift is determined primarily by the highest-equivalent width lines. If Hβ is skewed in AHQs (as indicated in figure 4), the result may be a systematically incorrect redshift, resulting in locating low-amplitude lines such as [O I] at the wrong rest wavelength. If the narrow component is blueshifted while the broad component lies at the velocity of the host galaxy, it might induce this sort of skew. This effect may make it difficult...
to determine high-precision redshifts of AHQs, as their broad emission lines are skewed and their galactic lines are difficult to measure due to their small amplitude.

If this redshift error leading to an [O II] offset is systematic and uniform for fixed narrow-line width, the average decrease in [O II] amplitude will be well-indicated by the coadded spectrum. However, if the offset is nonuniform, high-amplitude lines with different centroids may be coadded to produce a low-amplitude, broader line. Therefore, we fit the [O II] line directly and investigate its properties. As with our Hβ and [O III] fits, we first fit a combination of continuum and broadened Fe II template, then find the best-fit Gaussian for the leftover line profile. We find that the [O II] equivalent width declines by a factor of 2.25 for AHQs compared to standard quasars. The best-fit [O II] width remains to be typical of a narrow galactic emission line, and the decreased line flux comes from a decrease in [O II] amplitude. For low-amplitude [O II], noise is often incorporated into the best-fit line profile, so the true decline may be larger.

4. Dependence of AHQs on Fitting Techniques

Because of the long history of studying quasar spectra, a report of a large, new spectroscopic class of quasars discovered via spectral line fitting should meet with appropriate skepticism, and it is important to consider whether AHQs might just be an artifact of fitting techniques. Ultimately, the Hβ-[O III] complex arises from complicated physics but is fit with a small number of parameters in an automated way, without the underlying model being adjusted individually for tens of thousands of quasars in the SDSS DR7 and future catalogs. As a result, most fits should contain errors. By choosing

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**Fig. 5.** Comparison of coadded quasar spectra at different narrow-line widths binned and colored as given in table 1. For shorter wavelengths, only spectra at sufficiently high redshift were coadded. At top left, the Mg II region. At top right, the [O II] region. (Color online)
a technique previously used by McLure and Dunlop (2004) and Shen et al. (2008), we hope to have avoided introducing any novel line-fitting errors. However, we should highlight two specific dangers.

4.1. Continuum Fitting

Errors in continuum fitting could result in incorrectly determining the properties of broad spectral lines, either missing the broad component of Hβ if too much flux is considered as part of the continuum or introducing a false broad component by under-fitting the continuum. Although for \( \sim 500-1000 \, \text{Å} \) windows the continuum is well-fit by a power law, the slope of that power law changes between the Mg II and Hβ region in composite spectra (Vanden Berk et al. 2001), so it must be locally determined. However, most of the pixels near Hβ are contaminated by either Fe II or strong spectral emission lines. Our fitting technique solves this problem by fitting simultaneously for Fe II emission and the continuum. An alternative technique would involve choosing a window free of Fe II contamination, such as 5080–5100 Å (Forster et al. 2001), and using these windows to fit the continuum alone. However, in an AHQ with broadened [O III], 5080 Å may not be free of [O III] contamination, so this window could also provide an erroneous continuum slope.

By simultaneously fitting Fe II and continuum, we fit hundreds of SDSS pixels with four parameters, resulting in a well-determined fit. However, although the continuum fits exhibited in figures 1 and 2 appear reasonable, it is difficult to prove that any individual spectrum has been well-fit. Fortunately, it is the broad, rather than the narrow, component of Hβ that will be strongly affected by errors in continuum fitting. Our report of a large population of AHQs relies on fitting the Hβ narrow component, and thus should not be susceptible to errors in continuum fitting.

4.2. Iron Contamination

Although Fe II is a larger problem when fitting Mg II rather than Hβ, there are also Fe II lines extending near [O III]. Further, the strength of iron lines increases strongly in AHQs (table 1). As with continuum fitting, Fe II contamination should not be a problem when determining whether an object is some type of AHQ, as the narrow Hβ component is stronger than Fe II and well-measured. However, the combination of strongly suppressed [O III] and augmented Fe II emission is more likely to result in errors by fitting [O III]Å 5007.

The presence of stronger iron lines does make it easier to detect and fit Fe II. Further, although there are several different Fe II templates available, they are typically derived from the spectra of objects with narrower Fe II lines, such as 1 Zw 1 (Bruhweiler & Verner 2008). Because these templates are then convolved with a broad Gaussian to simulate Fe II with a FWHM of thousands of km s\(^{-1}\), differences between templates are minimized, so alternative templates produce a similar AHQ sample.

The reduction from the full AHQ sample to the “best” sample presented in section 3 uncovered a large population of AHQs in which [O III] was suppressed but not broadened. Perhaps what we have fit as suppressed and broadened [O III] in these other cases is instead dominated by strong Fe II emission at broad-line region velocities. Because several AHQs show not just a broadened [O III]Å 5007 line but also equally broad [O III]Å 4959, for some objects [O III] is unambiguously broader than 1000 km s\(^{-1}\) (figure 2). In other objects, a combination of He I contamination and highly suppressed [O III]Å 4959 might make an alternative explanation involving Fe II more plausible.

The Fe II FWHM is often linked to the broad Hβ component FWHM. However, in AHQs with broadened [O III], the [O III] FWHM is instead linked to the Hβ narrow component, an apparent mismatch. Because AHQ broad-line regions appear to behave anomalously in several ways compared to broad-line regions in standard quasars, perhaps iron emission is also different. Iron contamination is therefore a plausible concern when fitting [O III] for some AHQs, but cannot be responsible for miscategorizing objects as AHQs based upon the core Hβ.

4.3. De-Linking [O III] and Hβ

As described in subsection 2.1, one way in which the standard fitting technique used in this paper seems clearly inadequate for AHQs lies in linking the core Hβ profile with the profile of nearby [O III] lines. For the reasons given earlier, we have presented our main results using a more standard fitting technique. For quasars with a standard narrow-line region, the [O III] and Hβ core profiles are indeed similar, so that de-linking them has a negligible effect. However, for AHQs de-linking the two profiles often results in the detection of broader Hβ core than the [O III] width.

Using a linked fit, AHQs appeared as a diagonal branch comprising at least 30% of quasars (figure 3). By de-linking the Hβ narrow component from [O III] (figures 6 and 7), we find that for some quasars, both the Hβ core and [O III] are broadened, but there are also many objects for which the Hβ core is broadened but [O III] is at a typical narrow-line velocity of <1000 km s\(^{-1}\).

That there is a population of AHQs when fitting the [O III] line independently (figure 7), similarly in figure 3, demonstrates that the broadened [O III] in AHQs is not simply an artifact of tying the [O III] profile to Hβ. Further, in quasars with broadened [O III], its velocity is correlated with broad Hβ. Thus, the apparent connection between the dynamics of gas emitting [O III] and broad-line region gas strongly influenced by the central black hole must also be physical rather than an artifact of our line-fitting techniques. We note that for all other quasars, the de-linked fits produce the standard result that the dynamics of the narrow-line region are (nearly) independent of those of the broad-line region.

For the Hβ line, de-linking the fits also provides a similar picture to figure 3, but now places far more quasars on the AHQ branch in figure 6. Since Fe II contamination is a concern when fitting the wings of the [O III] profile but not for Hβ, we conclude that Fe II cannot provide an explanation for AHQs. We also note that figure 6 is similar for different flux ratios between the two Hβ components, including where the narrower component has similar flux to the broader component and where there is a large disparity.

Because [O III] is typically stronger than the Hβ core, the FWHM for the linked fit is usually dominated by [O III], and thus quasars in which the Hβ core is broad but [O III] is narrow
appear on the standard quasar branch in figure 3. Our estimate using linked fitting that approximately 30% of quasars are AHQs therefore is an underestimate for Hβ, and instead is closer to the fraction of quasars with both broadened Hβ cores and [O III]. Finally, we note that even when fitting [O III] independently of the Hβ profile, there appear to be two distinct branches. It appears that when Hβ has a broadened core, [O III] emission is possible at a typical narrow-line velocity, possible at the Hβ core velocity, but impossible at a velocity in between those two. When Hβ is well-described by two tightly correlated components, it is unclear whether this indicates two distinct regions with correlated dynamics or one region with a complex profile that can be fit with two correlated Gaussians. This evidence from [O III] seems to indicate that when Hβ has a broadened core, the core emission may physically arise from a distinct region, which sometimes lies at a low enough density to allow [O III] emission.

4.4. Modeling Hβ With Two Gaussians

In this work, we choose to model the Hβ line as a pair of Gaussians, and each of the two [O III] lines as one Gaussian. This is in keeping with standard practice for large catalogs (cf. Shen et al. 2011, 2008; McLure & Dunlop 2004; Rafiee & Hall 2010). Even some past works using more complicated fitting prescriptions reported their results using two Gaussians (Hu et al. 2008a). As such, if the correct interpretation of this result turns out to be merely that the two-Gaussian fit is faulty for ~30% of quasars, it would still be important to understand and correct for this problem, and that correction would change the results of existing statistical studies of the SDSS quasar population using Hβ line fitting, including virial mass catalogs.

However, the question remains as to whether two Gaussian components is a good representation of the Hβ line, particularly for AHQs. When only one component of an AHQ is allowed to be broader than 1200 km s⁻¹, effectively the entire line shape is modeled as one Gaussian, where the fitting in this work uses two. Fitting two broad Gaussians to a line shape closer to one Gaussian, but not exactly Gaussian, might lead to fitting composed of the dominant Gaussian and a second, correlated Gaussian that would be artificial and representative of line non-Gaussianity. So, is one Gaussian actually a better fit for AHQs? For that matter, is a third Gaussian an even better fit, as reported by Hu et al. (2008a)?

The simplest measure of question whether two Gaussians provide a better fit is to examine the χ²/DOF for each fit. We consider the part of the spectrum within 2σ of the peak, as defined by the broadest component. For all quasars, the χ²/DOF averages 1.31 for two-Gaussian fits and 1.70 for one-Gaussian fits. For AHQs, two-Gaussian fits average 1.30 while one-Gaussian fits average 2.02. Adding a third Gaussian, however, provides no such substantial help; a three Gaussian fit reduces the χ²/DOF from 1.31 to 1.29 for all quasars and, like the two-Gaussian fit, averages 1.30 for AHQs. Thus, it is clear that the second-strongest component of the Hβ line shape is strong, while the third-largest is much weaker. A two-Gaussian fit therefore seems reasonable, although the correct line shape may not contain Gaussians at all; a correct fit should produce a χ²/DOF of 1. However, errors in SDSS are likely correlated between neighboring pixels (McDonald et al. 2006).
so the reported uncertainties used in producing these values for $\chi^2$ may not be trustworthy. This $\chi^2$ analysis is a good sanity check on our fitting technique, but is certainly not proof that the lines are being fit well.

Ultimately, fitting lines is an art, there are many complex prescriptions that can be used to produce higher-quality fits for individual spectra, and it is unrealistic to tailor individual fits for 100000 spectra in SDSS, or even more in future surveys. We believe that the best we can do as scientists is to use public data and encourage other experts to use alternative prescriptions for H$\beta$. It appears very difficult to fit AHQs well with one broad component and one component under 1200 km s$^{-1}$ in FWHM.

In general, there are many errors arising from fitting the spectrum of a complex object with a simplistic model containing little physics and a small number of parameters. These errors will likely result in some incorrect fits, and it would be difficult to believe reported H$\beta$ core widths to within 1%. However, many AHQs have H$\beta$ cores with FWHM measured at over 2000 km s$^{-1}$, and even a rudimentary fit “by eye” to the H$\beta$ lines displayed in figures 1 and 2 cannot accommodate more typical H$\beta$ core FWHM of under 1000 km s$^{-1}$. These details of line-fitting are important when, for example, using precision line measurements to produce a quasar virial mass. However, they cannot be responsible for overestimating the H$\beta$ core width by such a large factor in 30% of the SDSS quasar catalog.

5. Discussion

We report a new class of Type I quasars with broadened H$\beta$ cores. These quasars (AHQs) include over 1/4 of all $\sim$16000 SDSS quasars for which H$\beta$ is well-measured ($z < 0.8$). However, finding AHQs in previous line-fitting catalogs of SDSS quasars has not been reported for two reasons: (1) selection and fitting routines currently assume that the H$\beta$ core has the same profile as [O III], and that both are narrow lines, which is not true for AHQs, and (2) H$\beta$ lines that cannot be fit well with one broad and one narrow component have been modeled with additional Gaussians and more complex profiles (Shen et al. 2011), rather than simpler, two-component model used in this work.

The existence of these AHQs now necessitates a reexamination of other selection criteria in SDSS and similar surveys. In particular, the presence of a strong, narrow [O III] line is often a strong component of Type II quasar and Seyfert galaxy selection, since broader lines may not be present. Any type II AHQs or AHQ Seyferts would likely be selected against during the production of such catalogs.

Other AGNs with anomalous narrow lines in several previous examples have been reported. These include Seyferts with broadened or skewed [O III] (cf. Xu & Komossa 2011), as well as quasars with multiple broad H$\beta$ components (Hu et al. 2008a), with the broader broad component redshifted with regard to the narrower one (Sulentic et al. 2002; Collin et al. 2006).

AHQs, however, not only show two well-centered broad components but represent approximately one quarter of the SDSS quasar catalog at $z < 0.8$, with thousands of examples. As such their origin is a compelling puzzle. The spectra of these quasars provide enough evidence to analyze several possible explanations:

Could AHQs be created by an outflow into the narrow-line region? Given that outflows are a common property of most quasars (Elvis 2000), it would not be surprising to find that a large population exists with discernable evidence for possible nonvirial gas motion in the broad-line (and narrow-line) region. Although there is a slight skew to [O III] and the narrow component of H$\beta$ in coadded AHQ spectra (figure 4), the lines are mostly symmetric. Thus, any outflow must be similarly symmetrical, meaning that light from both sides of the outflow is visible. Otherwise, these lines would be more strongly skewed, just as strong asymmetric outflows can skew C$\ IV$ emission (Shen et al. 2008).

Moreover, Mg II, which emanates from the outer portion of the broad-line region, does not increase in width in AHQs (figure 5). The narrow-line region, containing [O III] and presumably the H$\beta$ core, lies further from the central black hole than the broad-line region. Thus, since any outflow does not extend past the edge of the broad-line region, AHQs are not created by an outflow into the narrow-line region. The broad component of H$\beta$ also comes from the broad-line region, but its ionization potential places it closer to the central black hole than Mg II. Therefore, an outflow that does not reach Mg II-emitting gas could still be responsible for higher velocities in gas producing the broad component of H$\beta$. An alternative option might be an outflow, larger than the accretion disk, that is able to emit H$\beta$ (and, presumably, C$\ IV$), but unable to emit Mg II.

Could AHQs be created by H$\beta$ core emission from virialized gas in the broad-line region? Some AHQs contain not just a broadened H$\beta$ core, but also show [O III] broader than 1000 km s$^{-1}$ (figure 2). As a forbidden line, [O III] requires a low density. In a typical Type I quasar, the broad-line region is too dense to allow [O III] emission, which is why [O III] does not have a prominent broad-line component. In AHQs, the line flux from H$\beta$ and Mg II, both emitted in the broad-line region is comparable to or larger than other Type I quasars. So, the broad-line region density is unlikely to be substantially lower. Further, if [O III] and the narrow component of H$\beta$ are in the broad-line region, where is the broad component of H$\beta$ located? Nevertheless, many AHQs show a broadened H$\beta$ core and suppressed [O III] emission, a combination more suitable for broad-line emission.

One way to test this picture is to consider the evidence from virial mass estimates. As described in Steinhardt and Silverman (2011), the H$\beta$ broad component yields a systematically larger mass estimate than Mg II for AHQs. Unlike H$\beta$, Mg II is not strongly correlated with changes in [O III] for AHQs, and therefore Mg II is likely the better mass indicator. For agreement, the H$\beta$ broad component must be placed at less than half of the radius inferred from the continuum luminosity–broad-line region radius relation calibrated by reverberation mapping. If the H$\beta$ narrow component and [O III] were instead placed at that radius, it would result in virial masses 1–2 dex below those produced using Mg II. Thus, H$\beta$ core emission from virialized broad-line region gas does not seem to fit the available evidence, although some
Could AHQs be typical Type I quasars viewed only from certain angles where an outflow is seen most clearly? \([\text{O II}]\) emission comes in part from star formation and in part from larger radii than \([\text{O III}]\), the latter due to its lower ionization state. Thus, \([\text{O II}]\) emission sharply declining (figure 5) with broadened \(\text{H}\beta\) cores seems to indicate that AHQs lie in host galaxies, or at least \(\sim\) kpc scale central regions, with different properties than other Type I quasars. This would not happen merely due to geometry. Indeed, it is a puzzle that the \([\text{O II}]\) line indicates a connection between the host galaxy and the quasar, while the unchanging Mg II indicates that the connection is not directly due to a direct outflow.

Could AHQs be a pre-turnoff phase of the quasar duty cycle? The decreased \([\text{O II}]\) equivalent width, coming from a combination of star formation and narrow-line region gas, might indicate a reduced supply of gas and dust to the central black hole, perhaps further reduced by a strong outflow. This, in turn, could cause the central quasar to go quiescent, with AHQs an intermediate phase as the quasar turns off. However, the average luminosity of AHQs is actually higher than other quasars (table 1). An upcoming luminosity decrease would not necessarily render the quasar quiescent, and the response time to a reduced inflow \(\sim\) kpc away is long. Nearby, AHQs might actually have more dust available than average Type I quasars, as they are more likely to contain broad absorption lines (table 1). This picture also does not yet explain the broadened \(\text{H}\beta\) and \([\text{O III}]\) lines.

So, although several scenarios present themselves, none yet seems able to fit all of the available evidence.

5.1. AHQs and Feedback

There is known to be a link between the properties of lower-luminosity active galactic nuclei and their hosts (Kauffmann et al. 2003; Silverman et al. 2009; Schawinski et al. 2010; Cardamone et al. 2010). Although coevolution of the quasar and its host galaxy has long been expected and even assumed, direct evidence for this idea has not yet been forthcoming, primarily because the quasar dominates its host and because the peak quasar number density lies at \(z \sim 2\), where resolving the host galaxy as separate from the quasar cannot be done with current ground-based instruments and where the quasar itself, the accretion disk, and the broad-line region cannot be resolved with any existing instruments.

One particularly striking feature of AHQ quasars is the strong link in coadded AHQ spectra (figure 5) between \([\text{O III}]\), produced either in nearby heated interstellar medium or closer to the central black hole, and \([\text{O II}]\), produced in photoionization \(\sim\) kpc from the black hole and in star formation in the host galaxy. The correlation between AHQs and their hosts appears to be evidence of some sort of feedback or linked evolution. Further work, including a physical model of that link, is needed to understand whether we are seeing feedback, coevolution, or perhaps some other process that, as a byproduct, quenches star formation, broadens \(\text{H}\beta\) core, and sometimes even broadens the \([\text{O III}]\) line.

5.2. Nomenclature

One of the difficulties in reporting on quasars with anomalous \(\text{H}\beta\) cores has come when we choose the terminology, particularly for objects in which \([\text{O III}]\) is also broader than \(1000 \text{ km s}^{-1}\). In many ways, a better description might invoke an unsatisfying combination such as “anomalous narrow-line,” “broad narrow-line,” or even “broad narrow \(\text{H}\beta\),” in describing these quasars. Alternatively, perhaps they might be named by analogy with Seyfert nomenclature (e.g., Narrow-line Sy1). It was even pointed out to the authors that with AHQs comprising as much as 30% of the quasar catalog, their \(\text{H}\beta\) profiles aren’t really anomalous. The root problem is that a set of lines conventionally referred to as “narrow” are often found at velocities typically termed “broad,” and it may be difficult to satisfactorily describe these objects without altering common terminology. We have chosen to describe these objects as “anomalous \(\text{H}\beta\)” in an effort to avoid this debate, and it is our hope that future work will produce a physical understanding of AHQs and allow a name representative of their origin rather than their spectra.

It should also be noted that the selection of AHQs in this study has been entirely based upon spectroscopic criteria, i.e., their \(\text{H}\beta\) narrow component is anomalously broad. A more natural categorization might be based upon the physics of their broad-line regions. For example, quasars might be classed as either virial (VQ) or nonvirial (NVQ) based upon their broad-line regions. As discussed in followup work, many AHQs appear to have nonvirial broad-line regions (Steinhardt & Silverman 2011). One might guess that quasars on the diagonal branch of figure 3 might be NVQs, while quasars on the horizontal branch are VQs, with the quasars in the lower-left intersection of the two branches perhaps consisting of a mixture of both VQs and NVQs. In this interpretation, what we have currently labeled our AHQ sample would consist mostly of NVQs with a few VQs mixed in, while our “standard” quasar sample would consist mostly of VQs but with a substantial number of NVQs as well at lower-left.

This work has defined AHQs as a population for which standard assumptions about the broad- and narrow-line regions appear to be false. This is a useful definition because line-fitting catalogs are often predicated upon these assumptions, and for AHQs an amended technique must be used. The best definition would simultaneously divide quasars spectroscopically and physically. However, if additional spectral properties cannot break the degeneracy in the lower-left of figure 3, it may be even possible that multiple categorizations are required.

The authors would like to thank Steve Balbus, Tim Brandt, Forrest Collman, Martin Elvis, Jeremy Goodman, Daryl Haggard, Julian Krolik, Greg Novak, Jerry Ostriker, Guido Risaliti, Malte Schramm, Ohad Shemmer, Yue Shen, David Spiegel, Michael Strauss, and Todd Thompson for valuable comments. This work was supported by World Premier International Research Center Initiative (WPI Initiative), MEXT of Japan.
References

Bentz, M. C., Peterson, B. M., Netzer, H., Pogge, R. W., & Vestergaard, M. 2009, ApJ, 697, 160
Boroson, T. A., & Green, R. F. 1992, ApJS, 80, 109
Bruhweiler, F., & Verner, E. 2008, ApJ, 675, 83
Cardamone, C. N., Urry, C. M., Schawinski, K., Treister, E., Brammer, G., & Gawiser, E. 2010, ApJ, 721, L38
Collin, S., Kawaguchi, T., Peterson, B. M., & Vestergaard, M. 2006, A&A, 456, 75
De Robertis, M. M., & Osterbrock, D. E. 1984, ApJ, 286, 171
Elvis, M. 2000, ApJ, 545, 63
Forster, K., Green, P. J., Aldcroft, T. L., Vestergaard, M., Foltz, C. B., & Hewett, P. C. 2001, ApJS, 134, 35
Gaskell, C. M. 2009, New Astron. Rev., 53, 140
Hall, P. B., et al. 2002, ApJS, 141, 267
Hao, L., et al. 2005, AJ, 129, 1795
Ho, L. C. 2005, ApJ, 629, 680
Ho, L. C. 2009, ApJ, 699, 638
Hu, C., Wang, J.-M., Ho, L. C., Chen, Y.-M., Bian, W.-H., & Xue, S.-J. 2008a, ApJ, 683, L115
Hu, C., Wang, J.-M., Ho, L. C., Chen, Y.-M., Zhang, H.-T., Bian, W.-H., & Xue, S.-J. 2008b, ApJ, 687, 78
Kauffmann, G., et al. 2003, MNRAS, 346, 1055
Kim, M., Ho, L. C., & Im, M. 2006, ApJ, 642, 702
Komossa, S. 2008, Rev. Mex. Astron. Astrofis., Ser. Conf., 32, 86
Marconi, A., Axon, D. J., Maiolino, R., Nagao, T., Pietrini, P., Risaliti, G., Robinson, A., & Torricelli, G. 2009, ApJ, 698, L103
Marconi, A., Pastorini, G., Pacini, F., Axon, D. J., Capetti, A., Macchetto, D., Koekemoer, A. M., & Schreier, E. J. 2006, A&A, 448, 921
Marziani, P., & Sulentic, J. W. 2012, New Astron. Rev., 56, 49
Marziani, P., Sulentic, J. W., Dultzin-Hacyan, D., Calvani, M., & Moles, M. 1996, ApJS, 104, 37
McDonald, P., et al. 2006, ApJS, 163, 80
McIntosh, D. H., Rieke, M. J., Rix, H.-W., Foltz, C. B., & Weymann, R. J. 1999, ApJ, 514, 40
McLure, R. J., & Dunlop, J. S. 2004, MNRAS, 352, 1390
McLure, R. J., & Jarvis, M. J. 2002, MNRAS, 337, 109
Netzer, H. 2009, ApJ, 695, 793
Netzer, H., & Marziani, P. 2010, ApJ, 724, 318
Onken, C. A., & Kollmeier, J. A. 2008, ApJ, 689, L13
Peterson, B. M. 1997, An Introduction to Active Galactic Nuclei (Cambridge, UK: Cambridge University Press)
Peterson, B. M., et al. 2004, ApJ, 613, 682
Rafiee, A., & Hall, P. B. 2011, MNRAS, 415, 2932
Risaliti, G., Young, M., & Elvis, M. 2009, ApJ, 700, L6
Schawinski, K., et al. 2010, ApJ, 711, 284
Shen, Y., et al. 2011, ApJS, 194, 45
Shen, Y., Greene, J. E., Strauss, M. A., Richards, G. T., & Schneider, D. P. 2008, ApJ, 680, 169
Silverman, J. D., et al. 2009, ApJ, 696, 396
Sluse, D., et al. 2011, A&A, 528, A100
Steinhardt, C. L., & Silverman, J. D. 2011, arXiv:1109.1554
Sulentic, J. W., Marziani, P., & Dultzin-Hacyan, D. 2000, ARA&A, 38, 521
Sulentic, J. W., Marziani, P., Zamanov, R., Bachev, R., Calvani, M., & Dultzin-Hacyan, D. 2002, ApJ, 566, L71
Vanden Berk, D. E., et al. 2001, AJ, 122, 549
Vestergaard, M., & Peterson, B. M. 2006, ApJ, 641, 689
Wang, J.-G., et al. 2009, ApJ, 707, 1334
Whittle, M. 1985, MNRAS, 216, 817
Xu, D., & Komossa, S. 2011, in Proc. Narrow-Line Seyfert 1 Galaxies and their place in the Universe, PoS(NLS1), ed. L. F. Board et al. (Trieste: SISSA), 6
Zamanov, R., Marziani, P., Sulentic, J. W., Calvani, M., Dultzin-Hacyan, D., & Bachev, R. 2002, ApJ, 576, L9
Zhang, K., Dong, X.-B., Wang, T.-G., & Gaskell, C. M. 2011, ApJ, 737, 71