ABSTRACT

Estimates of the mass of super-massive black holes (BHs) in distant active galactic nuclei (AGNs) can be obtained efficiently only through single-epoch (SE) spectra, using a combination of their broad emission line widths and continuum luminosities. Yet the reliability and accuracy of the method and the resulting mass estimates, \( M_{\text{BH}} \), remain uncertain. A recent study by Croom using a sample of Sloan Digital Sky Survey, 2dF QSO Redshift Survey, and 2dF-SDSS LRG and QSO Survey quasars suggests that line widths contribute little information about the BH mass in these SE estimates and can be replaced by a constant value without significant loss of accuracy. In this Letter, we use a sample of nearby reverberation-mapped AGNs to show that this conclusion is not universally applicable. We use the bulge luminosity \( L_{\text{Bulge}} \) of these local objects to test how well the known \( M_{\text{BH}} - L_{\text{Bulge}} \) correlation is recovered when using randomly assigned line widths instead of the measured ones to estimate \( M_{\text{BH}} \). We find that line widths provide significant information about \( M_{\text{BH}} \), and that for this sample, the line width information is just as significant as that provided by the continuum luminosities. We discuss the effects of observational biases upon the analysis of Croom and suggest that the results can probably be explained as a bias of flux-limited, shallow quasar samples.

Key words: galaxies: active – quasars: emission lines

Online-only material: machine-readable table

1. INTRODUCTION

Super-massive black holes (BHs) at the center of galaxies are believed to play a fundamental role in the evolution of galaxies. Accreting BHs or active galactic nuclei (AGNs) are thought, for example, to be responsible for the quenching of star formation in galaxies needed to explain the existence of the blue cloud and the red sequence (e.g., Granato et al. 2004; Di Matteo et al. 2005; Hopkins et al. 2005) and for heating gas near the centers of galaxy clusters to stop gas accretion onto the central galaxies (e.g., Croton et al. 2006). This makes characterizing the masses and accretion rates of the BH population across cosmic time crucial to understanding the evolution of galaxies and clusters.

Direct dynamical measurements of the masses of BHs are, however, possible only for nearby quiescent galaxies using spatially resolved velocity measurements inside (or close to) the BH’s sphere of influence (e.g., Merritt & Ferrarese 2001; Gültekin et al. 2009). Fortunately, AGNs provide a completely different means of directly estimating \( M_{\text{BH}} \) through reverberation mapping (RM; Blandford & McKee 1982; Peterson 1993). Here, it is assumed that the gas responsible for the broad-line emission is virialized and that the broad-line velocity widths are related to the orbital speed of the gas around the BH. Estimates of \( M_{\text{BH}} \) are then obtained by combining the width of the emission lines with an estimate of the distance from the BH to the broad-line region \( R_{\text{BLR}} \). Since AGNs are typically variable, \( R_{\text{BLR}} \) is estimated using the time it takes for the broad-emission lines to respond to changes in the accretion-disk luminosity.

While the RM technique can in principle be used for sources at any distance, it is time consuming, and has been impractical for luminous and distant objects whose variability timescales are long due to their high luminosity (e.g., Vanden Berk et al. 2004; MacLeod et al. 2010) and time dilation. Local RM observations have, however, shown that \( R_{\text{BLR}} \) is tightly correlated with the luminosity of the accretion disk (e.g., Kaspi et al. 2000; Bentz et al. 2009b). This allows one to estimate \( R_{\text{BLR}} \) directly from the luminosity, and hence estimate \( M_{\text{BH}} \) from the single-epoch (SE) spectra used to determine the line widths. In practice, SE \( M_{\text{BH}} \) estimates are obtained by means of

\[
M_{\text{BH}} = f \frac{(\Delta v)^2 L_{\lambda}^5}{G},
\]

where \( \Delta v \) is the velocity width of a given broad-emission line, \( L_{\lambda} \) is the luminosity of the continuum at an associated wavelength \( \lambda \) (in \( \text{Å} \)), \( \alpha \approx 1/2 \) but may depend weakly on \( \lambda \), \( G \) is the gravitational constant, and \( f \) is a dimensionless factor that accounts for the geometry and inclination of the BLR and the characterization of the line width used in defining the relation. The two most common line width characterizations are the FWHM and the line dispersion \( (\sigma_v) \); see, e.g., Peterson et al. 2004). The most common combinations of broad lines and continuum luminosities used are H\(\beta \) and \( L_{\text{3000}} \) (\( \alpha = 0.519 \), Bentz et al. 2009b) at low redshift, and Mg\(\text{II} \) with \( L_{\text{3000}} \) (\( \alpha = 0.47 \), McLure & Jarvis 2002) or C IV with \( L_{\text{1550}} \) (\( \alpha = 0.53 \), Vestergaard & Peterson 2006) at higher redshifts, where these lines appear at observed-frame optical wavelengths.

Recently, Croom (2011, hereafter C11) used a large sample of quasars from the Sloan Digital Sky Survey (SDSS, York et al. 2000).
properties are summarized in Table 1. Unfortunately, few AGNs exist with dynamical measurements of $M_{BH}$, rendering such a test infeasible at present. Studies of quiescent galaxies, however, have determined that there is a strong correlation between the mass of the central BH and the luminosity of the spheroidal component of its host galaxy (e.g., Marconi & Hunt 2003; Graham 2007, 2012). So while we lack dynamical estimates of $M_{BH}$ for comparison, we can assess the

2. ARE LINE WIDTHS IMPORTANT FOR ACCURATE BH MASS ESTIMATES?

In order to understand the importance of line widths in SE $M_{BH}$ estimates, we use a sample of 34 nearby AGNs observed in RM campaigns with bulge luminosity measurements at 5100 Å, $L_{\text{Bulge}}$, by Bentz et al. (2009a) using the Hubble Space Telescope. Although the target selection is somewhat arbitrary, the sample is approximately volume-limited, as luminous, distant sources are generally avoided in RM studies due to cosmological time dilation and their intrinsically longer variability timescales. The inherent difficulty in measuring bulge luminosities of distant AGNs further constrains the sample distance. The sample properties are summarized in Table 1.

Every object in our sample has been the subject of at least one RM observational campaign, and many for two or more. For each object we use the mean optical spectrum of each RM campaign, and we treat each of the 62 mean spectra as independent objects. While there is typically not enough variability from a single object within an RM campaign to treat each individual spectrum as an independent data point, it is a good approximation to assume that each observational campaign provides an independent measurement. Although for any one object the dynamic range in luminosity is limited, Peterson et al. (2004) and Bentz et al. (2007) show that RM $M_{BH}$ estimates of NGC 5548, the most studied source, are consistent between campaigns ($\Delta \log M_{BH} \approx 0.14$ dex). Table 1 also lists the number of individual spectra used to build each mean spectrum.

The host-corrected AGN continuum luminosities at 5100 Å, $L_{5100}$, are taken from Bentz et al. (2009a), while the broad Hβ FWHM and $\sigma_i$ measurements are taken directly from the references listed in Table 1. While this leads to some heterogeneity in the recipes used to make the line width measurements, the (typically) extremely high S/N of the mean spectra minimizes the resulting systematic errors (Denney et al. 2009a). The distributions of the sample in Hβ FWHM, continuum $L_{5100}$, bulge $L_{\text{Bulge}}$, and estimated BH mass are shown in Figure 1.

The ideal test to determine whether the velocity widths hold information about the BH mass would compare these SE mass estimates to dynamical $M_{BH}$ measurements for the same objects. Unfortunately, few AGNs exist with dynamical measurements of $M_{BH}$, rendering such a test infeasible at present. Studies of quiescent galaxies, however, have determined that there is a strong correlation between the mass of the central BH and the luminosity of the spheroidal component of its host galaxy (e.g., Marconi & Hunt 2003; Graham 2007, 2012). So while we lack dynamical estimates of $M_{BH}$ for comparison, we can assess the

![Figure 1. Distribution of the physical properties of our sample of nearby AGNs. The panels show the distribution of the $L_{5100}$ AGN continuum luminosities (left), broad Hβ FWHM (middle left), SE $M_{BH}$ estimates (middle right), and 5100 Å bulge luminosities $L_{\text{Bulge}}$ (right).](image-url)
reliability of $M_{BH}$ estimates simply by using $L_{\text{Bulge}}$ as a proxy and studying how well they hold to the $M_{BH}$–$L_{\text{Bulge}}$ correlation.

We estimate SE BH masses for each object by means of Equation (1), using the mean continuum luminosity at 5100 Å and either the FWHM or the $\sigma_I$ line width characterization of the mean H$\beta$ spectrum. We evaluate the correlation strength between $M_{BH}$ and $L_{\text{Bulge}}$ using the Spearman rank-order coefficient, $r_S$, finding a value of $r_S^0 = 0.69 (0.63)$ when using the FWHM ($\sigma_I$) for the mass estimates. Given the number of data points, the probability of obtaining such a value of $r_S^0$ in the absence of a correlation is $P_{\text{ran}} = 7.4 \times 10^{-10} (5.4 \times 10^{-10})$. As expected, our SE $M_{BH}$ estimates are very well correlated with the luminosity of the spheroidal component of their host, suggesting that these SE estimates can be quite accurate.

The amount of information obtained by using accurate line-width estimates can then be tested by re-estimating $r_S$ using $M_{BH}$ estimates obtained with randomly selected values for the line widths. In practice, we randomly re-distribute the measured line widths across the objects in our sample 500 times, essentially bootstrap-resampling the observed FWHM distribution, estimating $r_S$ for each realization. In this procedure, we never assign a measurement its true line width, although doing so does not alter our main conclusions. Figure 2 shows the resulting distribution of the $r_S$ coefficients compared with the value obtained before modifying the original line widths, $r_S^0$. We only show the results for the FWHM, as those using $\sigma_I$ are very similar. Note that $r_S^0$ is significantly above the distribution obtained by randomizing the line widths. If we view the values of $r_S$ as Gaussian random numbers, the true value is $4.3 \sigma$ from the mean of the random trials. The mean value of $r_S = 0.309$ ($P_{\text{ran}} = 1.5\%$) in the random trials is eight orders of magnitude less significant than that obtained using the real FWHM estimates. This demonstrates that line widths provide very significant information about $M_{BH}$ and that accurate line width estimates are crucial for accurate SE $M_{BH}$ estimates in this sample. This is illustrated in the top right panel of Figure 2, which shows the spread in BH mass ratio obtained by combining all 500 random realizations. The difference in the estimated $M_{BH}$ is strongly peaked but also with broad wings, with a standard deviation of 0.65 dex. We find similar results if we include each source only once.

Using the same formalism, we can also investigate the importance of the continuum luminosity for SE $M_{BH}$ estimates by randomizing the continuum luminosities rather than the line width estimates. The resulting $r_S$ distribution is also shown in Figure 2, and it looks very similar to that obtained by randomizing the line widths. This is not surprising, as in our sample the ~2 dex dynamic range in $L_{5100}^{1/2}$ is similar to that of FWHM$^2$ (see Figure 1). The mean Spearman rank-order coefficient of the randomized distributions is $r_S = 0.293$ ($P_{\text{ran}} = 2.1\%$) so, for this sample, accurate line widths are just as important as accurate luminosities for SE $M_{BH}$ estimates. Finally, as a cross-check, one can also estimate the probability that the $M_{BH}$–$L_{\text{Bulge}}$ correlation could randomly arise in our sample. We randomize the sample in both $L_{5100}$ and the FWHM, and, as expected, we find an $r_S$ distribution consistent with no correlation. The mean of the distribution is $r_S = -1.7 \times 10^{-3}$, implying $P_{\text{ran}} = 99\%$.

3. DISCUSSION

Unless the results of the previous section are not applicable at higher redshift, which is physically implausible, we must now look into the possibility that C11’s results are either due to the low S/N of the spectra or a conspiracy between the surveys and the shape and evolution of both the QSO luminosity and Eddington ratio distributions that leaves the observed line widths in a nearly redshift-independent distribution. We note that the sample of C11 is overwhelmingly dominated by SDSS observations, accounting for 100%, 71%, and 86% of the H$\beta$, Mg $ii$, and C $iv$ measurements, respectively. For simplicity, the following discussion focuses solely on the SDSS data.

Denney et al. (2009a) have shown that H$\beta$ line width estimates can be significantly in error for low S/N spectra, with systematic and random error components that scale with S/N. The errors are small for S/N ~ 20, but at a typical S/N ~ 5, Denney et al. (2009a) observed a shift of 0.10 dex to larger BH masses, and the dispersion increased by 0.12 dex. While in principle this shift could be due to either errors in the line widths or continuum luminosities, $L_{5100}$ is quite insensitive to S/N and $M_{BH}$ only depends on its square root (Equation (1)). Thus, the errors in $M_{BH}$ found by Denney et al. (2009a) should be dominated by uncertainties in the line width measurements induced by poor S/N.

Given these results, we then consider whether the SDSS data are simply too noisy. We investigated this possibility using a stacking analysis of the SDSS QSO spectra. We use C $iv$ because it has a clean local continuum, and is the line most affected by systematic issues in low S/N spectra (see, e.g., Assef et al. 2011). While this is not ideal, since our discussion and the results of Denney et al. (2009a) have focused solely on H$\beta$, it is still useful since C11 reached identical conclusions for all three of the main QSO broad-emission lines used for $M_{BH}$ estimates (H$\beta$, Mg $ii$, and C $iv$). The details and analysis of these stacked spectra, as well as for Mg $ii$, are presented by S. Frank et al. (2012, in preparation). The stacks are produced by averaging approximately 7200 QSO SDSS spectra from the sample of Shen et al. (2008, hereafter S08) in the redshift range.
1.857 < z < 3.118 and in the small absolute magnitude range −27.6 mag < M_i < −26.6 mag, divided into 33 bins of FWHM as measured by S08. SDSS quasar redshifts are determined from all possible absorption and emission lines, minimizing the effects of possible C iv blueshifts upon z (see Adelman-McCarthy et al. 2008 for details). In the selection process, known BALQSOs were rejected as they can significantly bias the resulting combined spectra. Before stacking, each individual spectrum is corrected for Galactic reddening using the extinction map of Schlegel et al. (1998), shifted into the rest frame, and normalized by the flux near a rest-frame wavelength of 1700 Å. The resulting spectra are then continuum subtracted and averaged, and the FWHM is measured directly from the stacked spectra. Our results are qualitatively insensitive to whether we use the median or averaged stacked spectra.

Figure 3 compares the FWHM measured from the stacked spectra with the mean and median FWHM estimates of S08 in each bin. We find that the FWHM of the mean spectra agrees with the mean/median of the individual estimates. Note, however, that they are moderately biased, particularly at the high-velocity end. These issues are explored further by S. Frank et al. (2012, in preparation). We have also repeated the process for different bins of M_i, and find qualitatively similar results for all absolute magnitudes. Overall, we consider it unlikely that the line width measurements are noisy enough to explain the C11 results, since on average they retain the information of the high S/N stacks, and C iv is the line that is most likely to be affected by systematic biases. Furthermore, we note that C11 use the inter-percentile value to characterize the line widths for Mg ii and C iv, and these should be more robust at lower S/N than the FWHM.

Thus, we are left with the conclusion that the narrow and apparently unevolving distribution of line width measurements in the C11 sample (see his Figure 1) is caused by a combination of evolution in the Eddington ratio distribution, the quasar luminosity function (QLF), and the SDSS selection function. For example, Figure 4 shows the distribution of Mg ii line widths from S08, selected because they span the broadest range of redshifts. With the simplifying approximation that α = 1/2 in Equation (1), the line width is given by

\[
\Delta \nu \propto \frac{L^{1/4}}{\ell_{\text{Edd}}}.
\]

where \(\ell_{\text{Edd}}\) is the Eddington ratio. We know from Kollmeier et al. (2006) that the \(\ell_{\text{Edd}}\) distribution of broad-line quasars is narrow. For these bright SDSS AGNs, the steep QLF (\(dn/dL \propto L^{-3.1}\) for \(z < 2.4\), Richards et al. 2006) means that at any given redshift half of quasars are within 0.35 mag of the survey flux limit, corresponding to a velocity spread of only 0.035 dex (8%) if we neglect the narrow width of the \(\ell_{\text{Edd}}\) distribution. Thus, at fixed redshift we should expect a narrow velocity distribution.

The distribution of \(\Delta \nu\) also shows little evolution with redshift. Note that the luminosity of objects at the flux limit evolves as \(L_{\text{min}} \propto \Gamma(z)^2\), where \(\Gamma(z) = D_L(z) (1+z)^{-0.28} \sim z^{0.07}\) for our cosmology and a mean quasar spectral slope of \(f_\nu \propto \nu^{-0.44}\) (Vanden Berk et al. 2001). Hence, at fixed \(\ell_{\text{Edd}}\), the apparent evolution of their associated line widths is \(\Delta \nu \propto \Gamma(z)^{-1/2} \sim z^{0.54}\). If we compare this “passive” evolution rate to that observed for Mg ii (Figure 4), we find that the differences are already surprisingly small. Taken at face value, the difference between the “passive” evolution model and the observed FWHM \(\propto \Gamma^{0.16}\) implies an evolution in the Eddington ratio of \(\ell_{\text{Edd}} \propto \Gamma^{0.68} \sim z^{0.73}\). Hence, the slow evolution of \(\Delta \nu\) may be related to quasar “downsizing” (e.g., Cowie et al. 2003). Whether the slow evolution is due to general changes in the accretion rates with z or evolution in \(\ell_{\text{Edd}}\) as a function of \(M_{\text{BH}}\) is a complex problem beyond the scope of this Letter. Recent modeling of the QLF and observed \(\ell_{\text{Edd}}\) distributions by Shankar et al. (2011) suggest that \(\ell_{\text{Edd}}\) likely evolves in both...
manner, increasing with increasing \( z \) and decreasing \( M_{\text{BH}} \). That the net result would be to leave almost no apparent evolution is then simply a coincidence. Adding the significant noise in the line-width measurements of low S/N spectra may further blur the signs of a weak evolution with redshift. Since line widths are clearly essential for \( SE_{\text{M}_{\text{BH}}} \) estimates in the local reverberation-mapped sample, this seems to be the most natural explanation of the C11 result. We conclude that line widths are as important as continuum luminosities for determining accurate BH masses, but that the evolution of the QSO population likely conspires with the survey flux limit to conceal this in shallow surveys such as SDSS.

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