BLACK HOLE MASS, VELOCITY DISPERSION, AND THE RADIO SOURCE IN ACTIVE GALACTIC NUCLEI

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ABSTRACT

The recent discovery by Gebhardt et al. and Ferrarese & Merritt of a correlation between nuclear black hole mass $M_{bh}$ and stellar velocity dispersion $\sigma_v$ in elliptical galaxies and spiral bulges has raised the question whether such a relationship exists for active galactic nuclei (AGNs). Estimates of $M_{bh}$ for many AGNs, made using reverberation mapping techniques, allow exploration of the relationship between black hole mass, the host galaxy, and the energetics of nuclear emission. However, since only a few AGNs have both $M_{bh}$ and $\sigma_v$ measurements, we use the [O iii] $\lambda$5007 emission-line widths on the assumption that for most AGNs the forbidden line kinematics are dominated by virial motion in the host galaxy bulge. We find that a relation does exist between $M_{bh}$ and the [O iii] line width for AGNs, which is similar to the one found by Gebhardt et al., although with more scatter, as expected if secondary influences on the gas kinematics are also present. Our conclusion is that both active and inactive galaxies follow the same relationship between black hole mass and bulge gravitational potential.

Monitoring the variability of the continuum and emission-line fluxes in broad-line AGNs shows that the two are highly correlated, linking emission on scales of kiloparsecs with the nuclear energy source.

Subject headings: galaxies: kinematics and dynamics — galaxies: nuclei — galaxies: Seyfert — quasars: general

1. INTRODUCTION

In the standard model for an active galactic nucleus (AGN), radiant energy is released through accretion onto a supermassive ($10^6$–$10^9 M_{\odot}$) black hole. However, until recently, there have been few mass estimates for nuclear black holes in AGNs. Kinematic studies of nuclear gas disks (e.g., Harms et al. 1994) and stellar dynamical studies, using high spatial resolution ground-based spectroscopy (e.g., Kormendy 1988), and more recently with the Space Telescope Imaging Spectrograph (STIS; e.g., Bower et al. 2000), have produced numerous central mass estimates mostly for normal galaxies. However, in application to AGNs these techniques are severely limited. Since roughly one galaxy in a hundred has a luminous active nucleus, even the nearest examples are relatively distant, reducing the effective spatial resolution. Furthermore, stellar dynamical techniques require high signal-to-noise ratio measurements of stellar absorption features, which are often lost in the glare of a bright active nucleus. Also, emission lines from ionized gas at small radii can be influenced by relativistic jets or winds associated with the AGN.

These difficulties can be overcome, however, using reverberation mapping techniques (e.g., Netzer & Peterson 1997). Monitoring the variability of the continuum and emission-line fluxes in broad-line AGNs shows that the two are highly correlated but that the emission lines lag behind the continuum by times ranging from days to months. The lag is best explained as a light travel time effect and can be used to estimate the size of the broad-line region (BLR). If one further assumes that the BLR kinematics are largely Keplerian, one can use the line widths as a characteristic velocity and in turn determine the total mass contained within the BLR. Strong evidence for Keplerian motion exists for at least one well-studied Seyfert galaxy, NGC 5548. Results for several different emission lines, each with different lags and therefore spanning a range of distances from the nucleus, give consistent values for the central mass (Peterson & Wandel 1999). Reverberation studies have now yielded $M_{bh}$ estimates for numerous Seyfert 1 galaxies and quasars (e.g., Kaspi et al. 2000). However, there have been some claims that the masses determined from these variability studies are systematically low (Wandel 1999; Ho 1999).

Recent work has focused on the distributions of black hole properties and the relationship to their host galaxies. Kormendy (1993) first found a correlation between $M_{bh}$ and the mass of the spheroidal component $M_{bul}$ (see also Kormendy & Richstone 1995). In a comprehensive study using ground-based spectroscopy and Hubble Space Telescope (HST) imaging, Magorrian et al. (1998) presented strong evidence in support of the $M_{bh}$-$M_{bul}$ relation. More recently, two studies (Gebhardt et al. 2000a; Ferrarese & Merritt 2000) reported relationships between $M_{bh}$ and $\sigma_v$, the stellar velocity dispersion obtained within a large aperture extending to the galaxy effective radius, thus insensitive to the influence of the black hole. The correlation between these two parameters is remarkably strong, suggesting a link between the formation of the bulge and the development of the black hole.

In this Letter we combine reverberation mapping measurements of $M_{bh}$ in AGNs with narrow-line region (NLR) gas and bulge stellar kinematic measurements corresponding to motion well beyond influence of the black hole to compare the nuclei of active and normal galaxies. We also investigate the possibility of a correlation between black hole mass and the radio luminosity in AGNs. Section 2 describes the data collected from the literature. Section 3 presents the $M_{bh}$-$\sigma_v$ relation for AGNs. In § 4 we consider the relationship between $M_{bh}$ and the radio luminosity, and in § 5 we summarize our conclusions.

2. DATA

We start with all AGNs with black hole masses, measured by the reverberation mapping technique: 17 Seyfert 1 galaxies (as compiled by Wandel, Peterson, & Malkan 1999) and 17 PG quasars (Kaspi et al. 2000). For most of the galaxies, we use the black hole masses tabulated by Kaspi et al. (2000), evaluated using the mean H$\beta$ profile width; $M_{bh}$-values for three galaxies (Mkn 279, NGC 3516, and NGC 4593) were taken from Ho (1999). For as many objects as possible we obtained published measurements of $\sigma_v$, FWHM($\text{O}_{iii}$), and the radio flux.
The adopted values are presented in Table 1. For the Seyfert galaxies, FWHM$_{[OIII]}$ is taken from Whittle (1992a). For the quasars, FWHM$_{[OIII]}$ values were adopted only if the spectroscopy was of medium to high resolution ($R > 1500$); $\sigma_*$ in AGN host galaxies has been determined using spectral regions around both the Ca II triplet and Mg b. The values used here have been published in Smith, Heckman, & Illingworth (1990), Terlevich, Díaz, & Terlevich (1990), and Nelson & Whittle (1995, for references on individual galaxies). Radio luminosities are from Whittle (1992a) for Seyfert galaxies and from Kellerman et al. (1989) for PG quasars. We have scaled observations at 5 GHz assuming a power-law index of 0.7 and assume $H_0 = 80$ km s$^{-1}$ Mpc$^{-1}$. We also calculate $R$, the ratio of the radio to optical flux, using the mean continuum luminosities from Kaspi et al. (2000).

We point out that the stellar and gas kinematic measurements are from small-aperture observations typically covering 2$''$–3$''$, somewhat smaller than the apertures used to measure $\sigma_*$. Nevertheless, we can be confident that these measurements are unaffected by the presence of the black hole. First, since the AGNs are at larger distances than the normal galaxies for which $M_{\text{bh}}$ has been determined, the aperture typically corresponds to physical scales of a kiloparsec or more, actually comparable to the bulge effective radius. Second, Nelson & Whittle (1996) found that Seyfert galaxies were offset from the Faber-Jackson relation ($M_{\text{bul}} \propto \log \sigma_*$) for normal galaxies in the sense of having lower velocity dispersions than normal galaxies of the same $M_{\text{bul}}$. Their interpretation was that Seyfert galaxy bulges have lower M/L ratios than normal spiral galaxies, exactly the opposite of what one would expect if the stellar kinematics were strongly influenced by a massive nuclear black hole.

3. THE $M_{\text{bh}}$-$\sigma_*$ RELATION FOR AGNs

Recently, Gebhardt et al. (2000b) included Seyfert galaxies in their plot of $\sigma_*$ versus $M_{\text{bh}}$ (in some cases choosing different values for $\sigma_*$ than in Table 1) and concluded that AGNs show no significant difference from the overall relation. Unfortunately, $\sigma_*$-values are available in the literature for only a handful of the AGNs with reverberation mapping estimates for $M_{\text{bh}}$. Therefore, a definitive comparison of AGNs and normal galaxies is not possible with these data. However, Nelson & Whittle (1996) have shown that for the majority of Seyfert galaxies, a moderately strong correlation between FWHM$_{[OIII]}$ and $\sigma_*$ exists, indicating roughly equal absorption and emission-line widths. Thus, the [O III] $\lambda 5007$ profiles are dominated by virial motion in the bulge potential. As might be expected, a fair amount of real (i.e., not due to measurement error) scatter does exist. Nelson & Whittle (1996) used the deviation from purely virial gas motion to investigate possible secondary influences on the NLR kinematics.
Their results confirmed conclusions from previous studies (e.g., Whittle 1992b, 1992c) that the interaction of NLR gas with a relatively strong kiloparsec-scale linear radio source can produce nonvirial gas acceleration. They also found a weak tendency for interacting systems and mergers to have broader emission lines than expected from purely virial motion, an issue that may be important in quasars, which are more likely to be interacting systems (McLeod & Rieke 1995). Thus, keeping the issue of secondary influences on the NLR kinematics in mind, we can proceed with the idea that the primary influence on the forbidden line widths in AGNs is the bulge potential.

In Figure 1 we plot FWHM \([\text{O}III]\)/2.35, or \(\sigma_p\), versus \(M_{bh}\). Filled symbols show the values of FWHM \([\text{O}III]\) for the galaxies in Table 1: circles for Seyfert galaxies and squares for PG quasars. Plus signs show AGNs for which \(\sigma_a\) measurements exist, and triangles show \(M_{bh}\) and \(\sigma\) from Gebhardt et al. (2000a). The similarity in the trends between the data from Table 1 and the Gebhardt et al. (2000a) sample is striking. The solid line is the relation determined by Gebhardt et al. (2000a), and the shorter dashed line is our fit to the AGN, using the ordinary least-squares bisector (Isobe et al. 1990), which gives good results for large uncertainties in both variables. The correlation for the AGN is moderately strong \([R = 0.51, P(\text{null}) = 0.5\%]\) with a slope 3.7 \pm 0.7 and intercept \(-0.5 \pm 0.1\). The AGN relation is slightly shifted to larger widths for a given \(M_{bh}\) than the Gebhardt et al. (2000a) relation and is more scattered. Also, there seems to be no statistical difference between the distributions of Seyfert galaxies and quasars.

The slope on the fit agrees well with that found by Gebhardt et al. (2000a, 2000b), who derived a different value than Ferrarese & Merritt (2000; 3.75 as opposed to 4.8). Gebhardt et al. (2000a, 2000b) discuss various explanations for the difference in the two values. Although our result supports a shallower slope, an analysis using stellar velocity dispersion instead of emission-line width would be more conclusive.

We can be more quantitative about the similarity of the relation for elliptical galaxies and that for the AGN by considering the origin of the scatter. The mean 1 \(\sigma\) error bar in log \(M_{bh}\) plotted in the upper left, is 0.17/\(-0.20\), while the rms deviation of the filled symbols in Figure 1, relative to the Gebhardt et al. (2000a, 2000b) relation, is 0.55. Since we expect that emission-line widths can be determined to accuracies of \(-10\%\) for the spectral resolution of the observations, we expect that a large component of the scatter is not due to measurement error but reflects real deviations, perhaps indicating secondary influences on NLR kinematics. If we calculate the difference from the Gebhardt et al. (2000a, 2000b) relation, this time in log FWHM \([\text{O}III]\), we find a small offset, \(\Delta\) log FWHM \([\text{O}III]\) = 0.06, with a distribution of rms width 0.14. Nelson & Whittle (1996) used differences in emission- and absorption-line widths, \(\Delta W \equiv \log \text{FWHM}_{\text{[OIII]}} - \log \text{FWHM}_{\text{[OII]}}\), to investigate nonvirial influences on emission-line kinematics. For their entire Seyfert sample, they found \(\Delta W = 0.0\) and an rms width of 0.2. Excluding interacting galaxies and objects with relatively luminous linear radio sources, they found \(\Delta W = -0.1\), thus slightly narrower emission lines than absorption lines, and an rms width of 0.13. Thus, it is reasonable that the scatter and the small offset indicate nonvirial contributions to the line widths in some objects. The fact that the rms deviation is comparable to what found in Nelson & Whittle (1996) is consistent with this interpretation. Unfortunately, the current sample includes no Seyfert galaxies with strong linear radio sources and, as a result of their larger distances, the radio maps for the quasars are mostly unresolved on kiloparsec scales (see, e.g., Kellerman et al. 1994; Kukula 1998). Therefore, no strong statements regarding nonvirial gas kinematics can be made.

The relationship between \(M_{bh}\) and the FWHM \([\text{O}III]\) in AGNs is precisely what we would expect if AGNs follow the \(M_{bh},\sigma_a\) relation and if the primary influence on NLR kinematics is the bulge gravitational potential. Although one might point out that the AGNs plotted with \(\sigma_a\) do seem to lie systematically below the relation, the reality of such a shift based on only seven objects is not compelling. Our primary conclusion is that the relationship between the mass of the central dark object and the depth of the gravitational potential in AGNs is the same as for normal galaxies. Clearly, more velocity dispersion measurements for AGNs are needed. However, in fainter objects detailed studies of the \([\text{O}III]\) emission-line profiles accounting for nonvirial kinematic components could provide a valuable substitute.

These results seem to conflict with previous reports that AGNs have lower black hole–to–bulge mass ratios than normal galaxies (Wandel 1999) or alternatively that the reverberation...
mapping estimates of $M_{bh}$ are systematically low (Ho 1999). Figure 1 suggests that neither of these is correct and that the differences must lie in the values of $M_{bol}$. A number of factors may have contributed to this apparent disagreement. First, the $M_{bol}$-$L_\text{bol}$ relation derived by Gebhardt et al. (2000a, 2000b) has been evaluated using only stellar dynamical black hole mass estimates from three-integral modeling. The result is that the black hole masses are about a factor of 3 lower than the ones published by Magorrian et al. (1998), which were used in Wandel (1999). Second, Nelson & Whittle (1996) found that Seyfert galaxies are offset from the Faber-Jackson relation for normal galaxies having brighter bulges by on average about 0.6 at the same velocity dispersion. More generally, bulge-disk decomposition is a difficult task even for normal, nearby galaxies. The problem is compounded in Seyfert 1 galaxies by their smaller apparent bulge sizes due to larger mean distances and the bright point-source component. Thus, much of the discrepancy can be resolved by acknowledging that as much or greater uncertainty exists in the bulge luminosity of Seyfert galaxies as exists in the estimates of $M_{bh}$ by any of the available techniques.

4. RADIO LUMINOSITY AND BLACK HOLE MASS IN AGNs

Using reliable measurements of black hole mass in AGNs, we can compare parameters related to the energetics of AGNs with the size of the central engine. For example, Kaspi et al. (2000) found a strong correlation between the black hole mass and the mean optical continuum luminosity, with the dependence $M \propto L^{1/3}$, suggesting that more luminous AGNs radiate at a larger fraction of the Eddington luminosity. Nelson & Whittle (1996) found a correlation between $\sigma$ and the radio luminosity at 1415 MHz ($L_{1415}$) in Seyfert galaxies. This relation was linked to previously known correlations between radio power and absolute blue luminosity (Meurs & Wilson 1984; Edelson 1987; Whittle 1992c) and between radio power and [O iii] line width (e.g., Whittle 1985). They speculated that the origin of such a correlation might result from the correlation of $M_{bh}$ with bulge mass and that the radio sources associated with larger central engines might be correspondingly more luminous. In Figure 2 we plot $L_{1415\text{MHz}}$ versus $M_{bh}$ using different symbols for radio-loud ($R > 8.0$; plus signs), radio-intermediate ($1.0 < R < 8.0$; open circles), and radio-quiet ($R < 1.0$; filled circles) AGNs. The criteria are chosen rather arbitrarily but nevertheless demonstrate some interesting differences. The solid line shows a fit to the most radio-quiet group. The correlation is quite strong [$R = 0.82, P(\text{null}) = 0.003\%$, with a slope 0.84 ± 0.12]. A fit including radio-intermediate data (not shown) is somewhat weaker [$R = 0.58, P(\text{null}) = 0.1\%$, and a fit to the entire sample is weaker still [$R = 0.40, P(\text{null}) = 2\%$]. The results suggest that at least in radio-quiet AGNs, the radio luminosity, emitted on kiloparsec scales, is linked to the mass of the nuclear black hole. Moreover, Laor (2000) has presented compelling evidence that radio loudness is dependent on $M_{bh}$. Nelson & Whittle (1996) noted other explanations for their result, including higher ambient pressure in larger bulges, leading to increased radio emissivity. We cannot distinguish between these possibilities, and it is possible that both effects work together to produce the observed correlation.

5. SUMMARY

Using the assumption that NLR kinematics are predominantly due to virial motion in the host galaxy potential, we find that AGNs follow a relation between $M_{bh}$ and $\sigma$ similar to normal galaxies. Although the AGN black hole masses are determined using reverberation mapping, we find no significant differences with results from studies using stellar dynamical techniques. Satisfied that the black hole masses in AGNs are reliable, we can begin to examine the relationship of black hole mass with other properties of AGNs. As an example, we have found that the radio luminosity in radio-quiet AGNs is correlated with black hole mass relating parameters determined on vastly different size scales.

I would like to thank Donna Weistrop for her support and comments on a draft of this Letter. This work was supported in part by NASA under contract NAS5-31231.

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