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The Effect of Radiation Pressure on Virial Black Hole Mass Estimates and the Case of Narrow-Line Seyfert 1 Galaxies

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THE EFFECT OF RADIATION PRESSURE ON VIRIAL BLACK HOLE MASS ESTIMATES
AND THE CASE OF NARROW LINE SEYFERT 1 GALAXIES

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ABSTRACT

We consider the effect of radiation pressure from ionizing photons on black hole (BH) mass estimates based on the application of the virial theorem to broad emission lines in AGN spectra. BH masses based only on the virial product $\Delta V^2 R$ and neglecting the effect of radiation pressure can be severely underestimated especially in objects close to the Eddington limit. We provide an empirical calibration of the correction for radiation pressure and we show that it is consistent with a simple physical model in which BLR clouds are optically thick to ionizing radiation and have average column densities of $N_{\rm H} \sim 10^{23}\,{\rm cm}^{-2}$. This value is remarkably similar to what is required in standard BLR photoionization models to explain observed spectra. With the inclusion of radiation pressure the discrepancy between virial BH masses based on single epoch spectra and on reverberation mapping data drops from 0.4 to 0.2 dex rms. The use of single epoch observations as surrogates of reverberation mapping campaigns can thus provide more accurate BH masses than previously thought. Finally, we show that Narrow Line Seyfert 1 (NLS1) galaxies have apparently low BH masses because they are radiating close to their Eddington limit. After the radiation pressure correction, NLS1 galaxies have BH masses similar to other broad line AGNs and follow the same $M_{\rm BH}$-$\sigma_{\rm e}/L_{\rm sph}$ relations as other active and normal galaxies. Radiation forces arising from ionizing photon momentum deposition constitute an important physical effect which must be taken into account when computing virial BH masses.

Subject headings: radiation mechanisms: general — galaxies: active — galaxies: fundamental parameters — galaxies: nuclei — quasars: emission lines — galaxies: Seyfert

1. INTRODUCTION

In the last few years, it has become increasingly clear that supermassive black holes (BH) are an essential element in the evolution of galaxies. The key observational evidence of a link between a BH and its host galaxy is provided by the tight correlations between BH mass and luminosity, mass, velocity dispersion and surface brightness profile of the host spheroids (Kormendy & Richstone 1995; Gebhardt et al. 2000; Ferrarese & Merritt 2000; Marconi & Hunt 2003; Graham & Driver 2007). The link between BH and host galaxy is probably established by the feedback of the accreting BH, i.e. the active galactic nucleus, on the host galaxy itself (e.g. Silk & Rees 1998; Granato et al. 2004; Di Matteo et al. 2005; Croton et al. 2006, and references therein).

In order to fully understand the implications of BH growth on the evolution of the host galaxies it is fundamental to measure BH masses in large samples of galaxies from zero to high redshifts. Direct BH mass estimates based on stellar and gas kinematics are possible only in the local universe and their complexity does not allow their application to large samples (e.g. Ferrarese & Ford 2005; Marconi et al. 2006). The limit of the local universe can be overcome with the reverberation mapping (RM) technique (see, e.g.,

Peterson & Bentz 2006 for a recent review) which provides an estimate of the Broad Line Region (BLR) average distance from the BH ($R_{\rm BLR}$). The BH mass can thus be derived using the virial theorem, $M_{\rm BH} = f\Delta V^2 R_{\rm BLR}/G$, where ΔV is the width of the broad emission line and f is a scaling factor which depends on the physical properties of the BLR (e.g. Peterson & Wandel 2000). Although this technique is potentially plagued by many unknown systematic errors (Krolik 2001;Collin et al. 2006), BH masses from reverberation mappping are in agreement with the $M_{\rm BH}$-$\sigma_{\rm e}$ relation of normal galaxies (e.g. McLure & Dunlop 2002). However, this technique is very demanding in terms of telescope time and it can be applied only to a few objects especially at high redshifts (Peterson et al. 2004; Kaspi et al. 2007). The radius-luminosity relation discovered by Kaspi et al. (2000) shows that continuum luminosity can be used as a proxy for $R_{\rm BLR}$ (Kaspi et al. 2000, 2005; Bentz et al. 2006b). From the spectrum of a broad line AGN it is therefore possible to obtain a single epoch (SE) BH mass estimate.

One of the most important sources of uncertainty in virial $M_{\rm BH}$ estimates is the scaling factor f. Onken et al. (2004) have provided an estimate of f assuming that the AGN in the RM database of Peterson et al. (2004) follow the $M_{\rm BH}$-$\sigma_{\rm e}$ relation of normal galaxies (Tremaine et al. 2002; Ferrarese & Ford 2005). The factor f by Onken et al. (2004) is only applicable to estimates of the virial product based on RM (see Peterson et al. 2004 for more details). Building on the results by Onken et al. (2004), Vestergaard & Peterson (2006) have calibrated scaling relations for SE virial $M_{\rm BH}$ estimates which combine the width of broad Hβ with the luminosities of λL_λ at 5100Å.

Overall, SE virial estimates are commonly used to estimate BH masses in large sample of galaxies from zero to high redshifts (e.g. Willott et al. 2003; McLure & Dunlop 2004;

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Vestergaard 2004; Jiang et al. 2007) and are deemed accurate only from a statistical point of view on large samples of objects since a single measurement can be wrong even by a factor of ~ 10 (e.g. Vestergaard & Peterson 2006).

There are three important considerations which are suggested by the results presented in the above papers. First, SE virial BH masses of a few objects (e.g. high z, high L quasars or Narrow Line Seyfert 1 galaxies) imply they radiate near or above the Eddington limit. The virial theorem is based on the assumption that the system is gravitationally bound and this might be violated in super-Eddington sources where the outward force due to radiation pressure overcomes gravitational attraction. Second, even when $L < L_{\rm Edd}$, one should take into account that the radiation force partially compensates gravitational attraction. In the standard accretion disk model, the source of ionizing photons can be considered point-like at the distance of the BLR (see however Collin & Huré 2001 for a different point of view) and the radiation force scales as r^{-2} mirroring the radial dependence of the BH gravitational attraction. Thus BLR clouds are effectively being pulled by a smaller effective BH mass and all present virial mass estimates for objects close to their Eddington limit, where radiation pressure is not considered, might be underestimated. Finally, the Eddington limit is computed assuming that the radiation pressure is due only to Thomson scattering of photons by free electrons. As supported by reverberation mapping, by the radius-luminosity relation and other observational evidences (e.g. Blandford et al. 1990), BLR clouds are almost certainly photoionized. Thus BLR clouds are subject to radiation forces arising from the deposition of momentum by ionizing photons which can substantially exceed that due to scattering.

The importance of radiation pressure due to ionizing photons and its possible effects on virial BH masses has already been mentioned in a few papers (e.g. Mathews 1993; Gaskell 1996) but seem to have not been considered in detail subsequently. This effect might be particularly important in Narrow Line Seyfert 1 galaxies which are believed to accrete close to their Eddington limit. Indeed, they are characterized by small BH masses compared to other AGNs and to the $M_{\rm BH}$-$L_{\rm sph}/\sigma_{\rm e}$ relations (e.g. Mathur et al. 2001). It has also been noted that the distance of NLS1 galaxies from the $M_{\rm BH}$-$L_{\rm sph}/\sigma_{\rm e}$ relations is larger for objects with larger Eddington ratios (Grupe & Mathur 2004) suggesting that smaller BHs are growing faster. Alternatively, this might be an indication that that virial BH mass are underestimated in the high $L/L_{\rm Edd}$ regime.

In this paper we investigate the effect of radiation pressure on virial BH mass estimates. In § 2 we present a simple physical model for the radiation pressure effect on virial BH mass estimates. In § 3 we calibrate the effect of radiation pressure on virial BH masses adapting the procedures of Onken et al. (2004) and Vestergaard & Peterson (2006). In § 4 we apply our corrected virial BH mass estimates to Narrow Line Seyfert 1 galaxies and show that these galaxies are indeed consistent with the $M_{\rm BH}$-$\sigma_{\rm e}/L_{\rm sph}$ relations, showing that BHs are not abnormally small. Finally, we discuss our results and draw our conclusions in § 5.

2. THE EFFECT OF RADIATION PRESSURE ON VIRIAL BLACK HOLE MASS ESTIMATES: A SIMPLE PHYSICAL APPROACH

We will explore the effect of radiation pressure on BLR clouds using a simplified model which assumes that (i) each cloud is optically thick to ionizing photons but optically thin
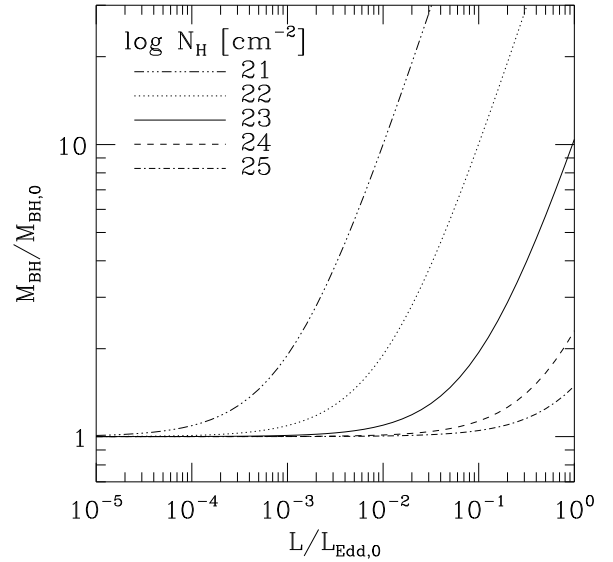

FIG. 1.— The ratio between virial BH masses taking into account radiation pressure ($M_{\rm BH}$) and those based only on the virial product ($M_{\rm BH,0}$) is plotted against the classical Eddington ratio based on $M_{\rm BH,0}$. $M_{\rm BH}/M_{\rm BH,0}$ is thus the correction factor which should be applied to BH mass estimates based only on the virial product. $N_{\rm H}$ is, on average, the total column density of each BLR cloud along the direction to the ionizing source.

to scattering processes, (ii) the Thomson cross-section is representative of all scattering processes involving free or bound electrons and (iii) both recombination and scattered photons are 'isotropically' re-emitted. These assumptions are valid if $Uc/\alpha_{\rm B}(H) < N_{\rm H} < 1/\sigma_{\rm T}$ where $N_{\rm H}$ is the total cloud column density along the direction to the ionizing source, U is the ionization parameter, $\alpha_{\rm B}(H)$ is the 'case-B' recombination coefficient for hydrogen and $\sigma_{\rm T}$ is the Thomson cross-section. For typical conditions in the BLR ($T_{\rm e} \simeq 2 \times 10^4\,{\rm K}$, $U \simeq 0.01$, e.g. Netzer 2006) $1.2 \times 10^{21}\,{\rm cm}^{-2} < N_{\rm H} < 1.5 \times 10^{24}\,{\rm cm}^{-2}$.

The total force acting on a cloud in the outward radial direction and due to radiation pressure is

$$F = \int_0^{+\infty} {\rm d}\nu\, \frac{L_\nu}{4\pi r^2 c}(1 - {\rm e}^{-\tau_\nu})\Delta A \qquad (1)$$

where L_ν is the luminosity of the AGN continuum emission, r is the cloud distance from the ionizing source, τ_ν is the optical depth of absorption/scattering processes and ΔA is the cloud surface exposed to the AGN radiation. Scattering is important only for non-ionizing photons therefore, under the above assumptions, it is possible to write:

$$F = \frac{L_{\rm ion}}{4\pi r^2 c}\Delta A + \frac{L - L_{\rm ion}}{4\pi r^2 c}\sigma_{\rm T} N_{\rm H}\Delta A \qquad (2)$$

where the two terms are the radiation forces due to absorption of ionizing photons and Thomson scattering, respectively, $L_{\rm ion}$ is the total luminosity of the AGN ionizing continuum, $h\nu > 13.6\,{\rm eV}$ (see, e.g., Peterson 1997; Krolik 1999) and $N_{\rm H}$ is, on average, the total column density of each BLR cloud along the direction to the ionizing source. The contribution to the radiation force from the absorption of line photons is negligible for the optically thick clouds considered here (see, e.g., the seminal paper by Castor et al. 1975).

Taking into account the total radiation force acting on each cloud and assuming that the BLR is a bound system, it is possible to derive a modified version of the classical virial theorem which takes into account radiation as well as gravitational forces. Approximating the cloud mass as $\sim m_{\mathrm{p}} N_{\mathrm{H}} \Delta A$ the modified expression for the virial BH mass M_{BH} is:

$$M_{\mathrm{BH}} = f \frac{V^2 r}{G} + \frac{L}{L_{\mathrm{Edd},\odot}} \left[1 - a + \frac{a}{\sigma_{\mathrm{T}} N_{\mathrm{H}}} \right] \mathrm{M}_\odot \qquad (3)$$

where f is a geometrical factor which takes into account the geometry of the BLR, $L_{\mathrm{Edd},\odot}$ is the classical Eddington luminosity for a solar mass object and $a = L_{\mathrm{ion}}/L$. This expression has a physical meaning as long as the system is bound, i.e. as long as the radiation force on BLR clouds is smaller than gravity. In formulae

$$L < \frac{L_{\mathrm{Edd},0}}{\left[1 - a + a/(\sigma_{\mathrm{T}} N_{\mathrm{H}}) \right]} \qquad (4)$$

where $L_{\mathrm{Edd},0}$ is the classical Eddington luminosity. Neglecting momentum injection by ionizing photons ($a = 0$) we recover the classical relation $L < L_{\mathrm{Edd},0}$. Using M_{BH} from Eq. 3 to compute $L_{\mathrm{Edd},0}$, it should be noticed that for $L \to \infty$, $L/L_{\mathrm{Edd},0} \to 1/\left[1 - a + a/(\sigma_{\mathrm{T}} N_{\mathrm{H}}) \right]$ and $L/L_{\mathrm{Edd},0}$ will always be less than or equal to 1. This is a consequence of the assumption of gravitationally bound BLR which allowed us to write Eq. 3. Therefore, it is not possible to establish whether a system is above Eddington by using virial BH mass estimates, since they are themselves based on the assumption of a sub-Eddington system.

In order to quantify the effect of the radiation force correction we write Eq. 3 as

$$M_{\mathrm{BH}} = M_{\mathrm{BH},0} \left[1 + \frac{L}{L_{\mathrm{Edd},0}} \left(1 - a + \frac{a}{\sigma_{\mathrm{T}} N_{\mathrm{H}}} \right) \right] \qquad (5)$$

where $M_{\mathrm{BH},0}$ is the standard virial BH mass computed without taking into account radiation pressure. In Fig. 1 we show the behavior of $M_{\mathrm{BH}}/M_{\mathrm{BH},0}$ as a function of $L/L_{\mathrm{Edd},0}$ and for different values of N_{H}. The $a = L_{\mathrm{ion}}/L$ bolometric correction has been computed following Marconi et al. (2004) and is on average $a \simeq 0.6$ in the $10^{10} - 10^{12} \mathrm{L}_\odot$ luminosity range. For $N_{\mathrm{H}} = 10^{23} \mathrm{cm}^{-2}$ and $L/L_{\mathrm{Edd},0} > 0.1$, $M_{\mathrm{BH}}/M_{\mathrm{BH},0}$ varies between 2 and 10. This can be much larger for smaller column densities of BLR clouds but values at low N_{H} should be taken with caution since the adopted formula is valid only if the cloud is optically thick to ionizing photons, i.e. $N_{\mathrm{H}} > Uc/\alpha_{\mathrm{B}}(H) \simeq 1.2 \times 10^{21}(U/0.01) \mathrm{cm}^{-2}$. The correction factor remains small (< 2) only for column densities $N_{\mathrm{H}} > 10^{24} \mathrm{cm}^{-2}$. Clearly the correcting factor critically depends on the N_{H} value which sets the total cloud mass and thus the relative importance of gravitational attraction with respect to radiation pressure. Overall, this figure suggest that neglecting the effect of radiation pressure might result in M_{BH} values which are underestimated even by a factor ~ 10.

Virial estimates of BH masses are based on the assumption that the BLR is gravitationally bound to the BH and that outflowing motions are negligible. In recent years, building upon observational evidence for outflows in the BLR, alternative models have been proposed in which part of the BLR is in the form of a disk wind (e.g. Murray & Chiang 1995; Chiang & Murray 1996; Elvis 2000; Collin & Huré 2001; Proga et al. 2000; Proga 2007; Everett 2005 and references therein). This possibility has generated a debate about the reliability of virial BH masses (e.g. Peterson & Wandel 2000;

Krolik 2001; Onken & Peterson 2002; Collin et al. 2006; Vestergaard & Peterson 2006) which is beyond the scope of this paper. Nevertheless, virial BH mass estimators are widely used, and in order to investigate the effect of radiation pressure on such estimates, we must necessarily start from the same set of assumptions for our simple model.

3. THE EFFECT OF RADIATION PRESSURE ON VIRIAL BLACK HOLE MASS ESTIMATES: AN OBSERVATIONAL APPROACH

The simple physical approach presented in the previous sections suggests that virial BH mass estimates can be written as a function of observed quantities as

$$M_{\mathrm{BH}} = f \frac{V^2 R}{G} + g \left(\frac{L_{5100}}{10^{44} \, \mathrm{erg \, s}^{-1}} \right) \mathrm{M}_\odot \qquad (6)$$

where L_{5100} represents λL_λ at 5100Å. After Eq. 3, g corresponds to

$$g = 6.0 \times 10^6 \left(\frac{b}{9.0} \right) \left(1 - a + \frac{a}{\sigma_T N_{\mathrm{H}}} \right) \qquad (7)$$

where $b = L/L_{5100}$ is the bolometric correction at 5100Å. Following Marconi et al. (2004), the L/L_{5100} bolometric correction is on average $b \simeq 9.0$ in the $10^{10} - 10^{12} \mathrm{L}_\odot$ luminosity range. f and g are free unknown parameters which depend on the physical and geometrical properties of the BLR. In particular the g factor critically depends on the assumed N_{H} value which determines the cloud mass and thus sets the relative importance of gravity and radiation pressure.

A correction for the radiation force which is proportional to L is more general than the simple physical model presented in the previous section therefore, in order to avoid *a-priori* assumptions on the values of the physical parameters characterizing BLR clouds, we can determine f and g following a procedure similar to Onken et al. (2004) and Vestergaard & Peterson (2006). Thus our model will only provide a simple physical interpretation of the empirical g values.

3.1. *Black hole masses from reverberation mapping data*

Onken et al. (2004) considered the AGNs from the reverberation mapping database by Peterson et al. (2004) with measured stellar velocity dispersion. They used the time lag of the broad lines for R and the velocity dispersion of the *r.m.s.* spectra for V. They determined f by assuming that the AGNs in their sample follow the M_{BH}-σ_{e} relation for normal galaxies.

We first update the RM database by Peterson et al. (2004) with the newer estimates of BLR time lags for NGC 4151 (Bentz et al. 2006a), NGC 4593 (Denney et al. 2006) and NGC5548 (Bentz et al. 2007). We exclude from the database PG1211+143 and IC4329A because their time lags are not reliable (Peterson et al. 2004). When possible, we correct the average AGN luminosities $\lambda L_\lambda (5100$ Å$)$ for the host galaxy contamination following Bentz et al. (2006b). We consider the host galaxy velocity dispersions by Onken et al. (2004) and we supplement them with the data by Nelson et al. (2004) for Mrk 279 and Dasyra et al. (2007) for PG1229+204, PG1426+015, PG1617+175 and PG2130+099.

f and g are then derived by finding the minimum of:

$$\chi^2 = \sum_i \frac{\left[(\log M_{\mathrm{BH}})_i - (\log M_{\mathrm{BH}})_{0,i} \right]^2}{(\delta \log M_{\mathrm{BH}})_i^2 + (\delta \log M_{\mathrm{BH}})_{0,i}^2 + \Delta \Sigma^2} \qquad (8)$$

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TABLE 1
CALIBRATION OF RM VIRIAL MASSES

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Database	f	$\log g$	$\Delta_{\rm res}$
Onken2004[†]	5.5 (+1.9;−1.5)	−10*	0.39
Onken2004	5.2 (+1.6;−1.2)	−10*	0.39
Updated	4.8 (+1.5;−1.3)	−10*	0.52
Updated (Fam1)	**3.1 (+1.3;−1.5)**	**7.6 (+0.3;−0.3)**	0.50
(Fam2)	4.3 (+1.2;−1.1)	< 2	

[†] $\Delta\Sigma = 0.0$ as in Onken et al. (2004). * Fixed fit parameter.

where $(\log M_{\rm BH})_i$ is the log BH mass of the i-th object which depends on f and g, $(\log M_{\rm BH})_{0,i} = \alpha + \beta \log(\sigma_{\rm e}/200\,{\rm km\,s^{-1}})_i$ is the expected mass value from the $M_{\rm BH}$-σ relation (Tremaine et al. 2002; Ferrarese & Ford 2005). $\sigma_{\rm e}$ is the stellar velocity dispersion of the host spheroid, $(\delta \log M_{\rm BH})_i$ is the error on $(\log M_{\rm BH})_i$ based on the errors on V^2, R and $\delta(\log \sigma_{\rm e})_i$ is the error on $\log(\sigma_{\rm e}/200)_i$. At variance with Onken et al. (2004), we allow for an intrinsic dispersion of the $M_{\rm BH}$-σ relation, $\Delta\Sigma$, which we assume equal to 0.25 dex (e.g. Tremaine et al. 2002; Marconi et al. 2004; Tundo et al. 2007). We follow a standard χ^2 minimization and we estimate errors on the parameters with the bootstrap method (Efron & Tibshirani 1994) with 1000 realizations of the parent sample. As shown by Onken et al. (2004) the use of the Ferrarese & Ford (2005) or Tremaine et al. (2002) version of the $M_{\rm BH}$-$\sigma_{\rm e}$ relation provides consistent results; therefore, in the following we will focus only on the Tremaine et al. (2002) relation, $\alpha = 8.13 \pm 0.06$, $\beta = 4.02 \pm 0.32$.

The results of the fitting procedure are summarized in Table 1. We have considered the original Onken et al. (2004) database and the updated one. Errors on fit parameters are determined from the percentiles of the bootstrap results at the 68% confidence level around the median. Several considerations can be made from the results in Table 1. As a sanity check, we are able to reproduce the results by Onken et al. (2004) i.e. $f = 5.5 \pm 1.9$ (first table row). The fits shown in the second and third row indicate that when g is fixed and negligible, the use of the updated database or the use of an intrinsic dispersion for $M_{\rm BH}$-σ do not significantly change the f value. With the use of the updated database which has a larger number of objects, the scatter of the residuals is significantly increased. When g is free to vary, the bootstrap analysis shows that there are two distinct families of solutions: those where both f and g are determined and those where g is negligible and totally undetermined. The existence of two families of solutions from the bootstrap simulations is an indication that the dependence on luminosity can be inferred only from part of the sample, i.e. from the objects with the largest $L/L_{\rm Edd}$ ratios. In roughly 20% of the sample realizations the number of these objects is low, g is undetermined and the f values are consistent with the Onken et al. (2004) determination. The inclusion of the g parameter has the net effect of decreasing f, since the expected BH mass is fixed by the $M_{\rm BH}$-$\sigma_{\rm e}$ relation.

Our ability to determine an accurate empirical value of g is limited, as were previous efforts to determine f, by the size, composition and accuracy of the existing reverberation database. In particular, it currently contains few sources with high Eddington ratios, which provide the tightest constraints on g. With this caveat in mind, however, we provide a first estimate of $f = 3.1 \pm 1.4$ and $\log g = 7.6 \pm 0.3$ to compute $M_{\rm BH}$ from reverberation mapping data.

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TABLE 2
CALIBRATION OF SE VIRIAL MASSES

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$M_{\rm BH}$ from RM	$\log \tilde{f}$	$\log g$	$\Delta_{\rm res}$
$M_{\rm BH}$ from SE ($V_{H\beta}, L_{5100}$)			
$f = 5.5$; $\log g = -10$[†]	6.93 (+0.12;−0.13)	−10*	0.43
$f = 5.5$; $\log g = -10$	6.47 (+0.17;−0.22)	7.48 (+0.16;−0.25)	0.34
$f = 3.1$; $\log g = 7.6$	**6.13 (+0.15;−0.30)**	**7.72 (+0.06;−0.05)**	0.22
$M_{\rm BH}$ from SE ($V_{H\beta}, L_{H\beta}$)			
$f = 5.5$; $\log g = -10$[†]	6.69 (+0.12;−0.08)	−10*	0.46
$f = 3.1$; $\log g = 7.6$	**5.95 (+0.12;−0.17)**	**7.82 (+0.07;−0.09)**	0.27

[†] Original Onken et al. (2004) database. * Fixed fit parameter.

3.2. *Black Hole masses from single epoch spectra*

Vestergaard & Peterson (2006) considered the AGNs in the Peterson et al. (2004) database. They collected single epoch spectra for the same sources and used the FWHM of the broad lines as an estimate of V and the continuum or broad line luminosity to estimate R from the radius-luminosity relation of Bentz et al. (2006b). Then they determined the corresponding $\tilde{f}$ parameter (see Eq. 9 below) by rescaling the virial products from single epoch spectra to the BH masses determined following Onken et al. (2004).

We consider the database of single epoch measurements of $FWHM(H\beta)$ (hereafter $V_{H\beta}$), $L_{H\beta}$ and L_{5100} by Vestergaard & Peterson (2006) and following those authors we write the virial BH mass from single epoch measurements as:

$$M_{\rm BH}/{\rm M_\odot} = \tilde{f} \left(\frac{V_{H\beta}}{1000\,{\rm km\,s^{-1}}} \right)^2 \left(\frac{L_{5100}}{10^{44}\,{\rm erg\,s^{-1}}} \right)^{0.5} + g \left(\frac{L_{5100}}{10^{44}\,{\rm erg\,s^{-1}}} \right) \qquad (9)$$

where the proxy for V is now the FWHM of the Hβ line and the BLR radius R is given by the radius-luminosity relation with a slope of 0.50 ± 0.06. As before, the best $\tilde{f}$ and g values follow from χ^2 minimization as in Eq. 8 where $(\log M_{\rm BH})_{0,i}$ is now the BH mass from reverberation mapping computed according to Onken et al. 2004 ($f = 5.5$, $\log g = -10.0$) or to our new calibration ($f = 3.1$, $\log g = 7.6$). Obviously, the $\Delta\Sigma$ term has been removed.

The fit results are shown in Table 2 where, as before, we provide bootstrap errors. The fit results in the first row are the sanity check to show that we are able to reproduce the results by Vestergaard & Peterson (2006), who find $\log \tilde{f} = 6.91 \pm 0.02$ with an rms of 0.43. Our errors are larger because of bootstrap simulations, but they would be similar to the ones by Vestergaard & Peterson (2006) if we used the formal errors of the fit. In the second row we start from the assumption that virial masses from RM are computed following Onken et al. (2004), but we allow for a free g factor. The SE data are clearly able to provide an estimate of the g factor which turns out to be remarkably similar to what was found for the RM data. In the third row we start from virial RM masses computed with the best f and g values and there are two surprising results: first, the g value which turns out for SE virial masses is $\log g = 7.72 \pm 0.05$, perfectly consistent with that from RM virial masses, but with a much smaller uncertainty. Second, the dispersion of the residuals drops from ~ 0.4 to 0.2 dex. The latter result indicates that half of the

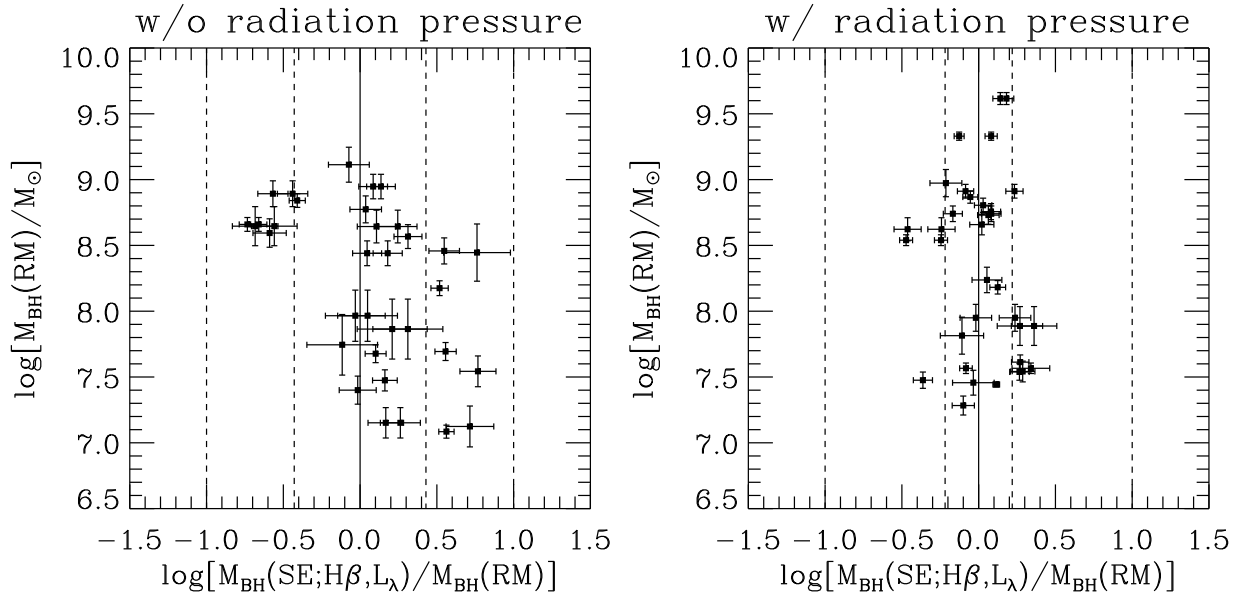## w/o radiation pressure   w/ radiation pressure

FIG. 2.— Comparison between SE and corresponding RM virial masses. Left panel: without taking into account radiation pressure (same as Fig. 8, right panel, of Vestergaard & Peterson 2006); the dispersion of the data along the x axis around the 0 value is 0.4 dex. Right panel: same as right panel but taking into account radiation pressure as described in the text (RM virial masses are also computed with the correction for radiation pressure); the dispersion is 0.2 dex. Error bars combine errors on RM and SE virial masses but are dominated by the former. Error bars are different in the left and right panels because of the different relative importance of virial products and luminosities in RM virial masses.

scatter of SE virial BH masses around RM ones is consistent with a need to take into account radiation pressure. The reduced scatter of the SE virial masses is also shown in Fig. 2 (right panel) and should be compared with the left panel in the same figure and Fig. 8 (right panel) of Vestergaard & Peterson (2006).

Wu et al. (2004) and Greene & Ho (2005b) have shown that it is also possible to use the luminosity of the broad Hβ instead of L_{5100} to avoid possible contamination of the AGN continuum emission from the host galaxy. Thus, following Vestergaard & Peterson (2006), we substitute L_{5100} with $L_{H\beta}$ in Eq. 9 to obtain SE virial masses from the broad Hβ line only. Inverting the $L_{H\beta} - L_{5100}$ relation by Greene & Ho (2005b) we can write

$$M_{\rm BH}/{\rm M}_\odot = \tilde{f}\left(\frac{V_{H\beta}}{1000\,{\rm km\,s^{-1}}}\right)^2\left(\frac{L_{H\beta}}{10^{42}\,{\rm erg\,s^{-1}}}\right)^{0.44}$$
$$+g\,0.732\left(\frac{L_{H\beta}}{10^{42}\,{\rm erg\,s^{-1}}}\right)^{0.883} \qquad (10)$$

The fit results are shown in Table 2. As before, we can reproduce the Vestergaard & Peterson (2006) calibration, $\log\tilde{f} = 6.67 \pm 0.03$, and the best fit which takes into account radiation pressure shows a significant drop in the dispersion of the residuals providing a best fit g value which is consistent with previous results.

3.3. *The average column density of BLR clouds*

The results in the previous sections show that it is possible to determine f and g both for RM and SE virial masses although it is difficult to accurately quantify their magnitude with the present data. The f values are smaller than those derived by Onken et al. (2004) and Vestergaard & Peterson (2006) because the final BH masses are still calibrated with the $M_{\rm BH}$-σ relation but part of the final $M_{\rm BH}$ value is accounted for by the effect of radiation pressure. Considering the effect of radiation pressure can significantly improve the agreement of SE and RM virial masses.

The two g values determined by (1) minimising the RM virial mass against the $M_{\rm BH} - \sigma_{\rm e}$ relation and (2) minimising the SE virial mass against the 'calibrated' RM mass are both consistent with a value $\log g \simeq 7.7$. Considering Eq. 7 we can derive the average $N_{\rm H}$ which is needed to obtain the g value determined empirically. With $\log g = 7.7$ and $a = 0.6$ we can derive $N_{\rm H} \simeq 1.1 \times 10^{23}\,{\rm cm^{-2}}$. This $N_{\rm H}$ value which we inferred by calibrating RM and SE virial BH masses is remarkably similar with the indications from photoionization modeling studies of the BLR. Within the framework of the standard BLR model, photoionization calculations can explain observed spectra only if BLR clouds are optically thick to ionizing radiation and adopted $N_{\rm H}$ are usually of the order of $10^{23}\,{\rm cm^{-2}}$ (e.g. Baldwin et al. 1995; Kaspi & Netzer 1999; Korista & Goad 2004 and references therein).

4. THE CASE OF NARROW LINE SEYFERT 1 GALAXIES

The nature of Narrow Line Seyfert 1 galaxies and their relation to 'normal' Seyfert 1 galaxies is still debated, but it is more or less generally believed that they are AGNs characterized by high accretion rates and small BH masses accounting for their smaller line widths (e.g. Pounds et al. 1995). Many different authors have undertaken the task of measuring virial BH masses in NLS1 galaxies and found that they are small compared to broad line AGNs with similar luminosities (e.g. Grupe 2004). The location of NLS1 on the $M_{\rm BH}$-$\sigma_{\rm e}/L_{\rm sph}$, however, is still hotly debated. Most authors suggest that NLS1 galaxies have small BHs compared to their host galaxies (e.g. Mathur et al. 2001; Grupe & Mathur 2004; Zhou et al. 2006; Ryan et al. 2007) while others find an overall agreement with the $M_{\rm BH}$-$\sigma_{\rm e}$ relation of normal galaxies (e.g. Botte et al. 2005; Komossa & Xu 2007). A picture is now emerging in which the BHs in NLS1 galaxies are now experiencing a rapid growth which will eventually lead them on the $M_{\rm BH}$-$L_{\rm sph}/\sigma_{\rm e}$ relations as other active and normal galaxies (e.g. Collin & Kawaguchi 2004; Mathur & Grupe 2005).

NLS1 galaxies are thus ideal targets to explore the effects of the newly calibrated expressions which take into account
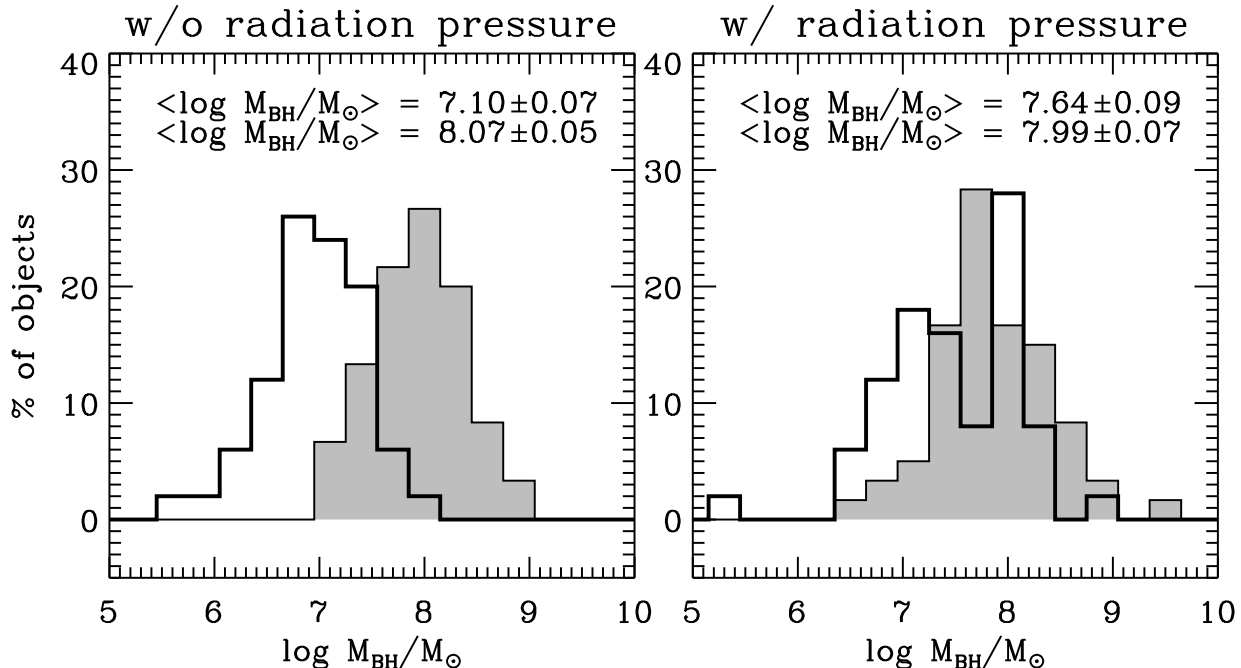
FIG. 3.— Distributions of BH masses for narrow line Seyfert 1 galaxies ($V_{H\beta} \leq 2000\,\mathrm{km\,s^{-1}}$, thick line) and 'normal' Seyfert 1 galaxies ($V_{H\beta} > 2000\,\mathrm{km\,s^{-1}}$, thin line with shaded area). Left panel: M_{BH} obtained with the scaling relations by Vestergaard & Peterson (2006). Right panel: M_{BH} obtained with the scaling relations which take into account radiation pressure. The numbers in the top left corners of both panels denote the mean and standard deviation of the mean ($\sigma/\sqrt{N}$) of narrow and broad Seyfert 1 galaxies.

radiation pressure. In particular, using our new calibrated expressions for virial BH masses, we will verify (i) whether BH masses of NLS1 galaxies are indeed small compared to other AGNs with similar luminosities and (ii) whether they lie below the M_{BH}-σ_e,L_{sph} relations.

We first test whether BH masses in NLS1 galaxies are on average smaller than those in 'normal' Seyfert 1 galaxies. We consider the complete, soft X-ray selected sample by Grupe et al. (2004) which is composed of 110 broad line AGNs with measured $V_{H\beta}$, $L_{H\beta}$ and L_{5100} and we compute virial BH masses using Eq. 9. In Fig. 3 we plot the distributions of M_{BH} obtained with the scaling relations by Vestergaard & Peterson (2006) (left panel) and with the scaling relations which take into account radiation pressure (right panel). The sample has been divided in two parts, narrow line Seyfert 1 galaxies ($V_{H\beta} \leq 2000\,\mathrm{km\,s^{-1}}$, thick line) and 'normal' Seyfert 1 galaxies ($V_{H\beta} > 2000\,\mathrm{km\,s^{-1}}$, thin line with shaded area). In the top left corners of both panels we report the mean and standard deviation of the mean ($\sigma/\sqrt{N}$) of narrow and broad Seyfert 1 galaxies. If radiation pressure is not taken into account, we recover the well known result that BH masses are a factor ~ 10 smaller in NLS1 galaxies. However, this difference is greatly reduced to a factor ~ 2 when radiation pressure is taken into account. The average BH mass of 'normal' Seyfert 1 galaxies is unchanged as expected since these objects are accreting at moderately low Eddington ratios compared to NLS1. It is beyond the scope of this paper to accurately determine the average BH mass of NLS1 with respect to Seyfert 1 galaxies, we only wish to point out that the effect of radiation pressure is very important and, when taken into account, BH masses of NLS1 galaxies are, on average, a factor 5 larger.

We now test whether NLS1 galaxies indeed lie below the M_{BH}-σ_e/L_{sph} relations. We consider only samples where σ_e or L_{sph} are measured directly because we want to avoid is-

sues connected with using σ_e surrogates like the dispersion of the [O III] line (e.g. Greene & Ho 2005a; Komossa & Xu 2007). We thus consider the samples of NLS1 galaxies by Botte et al. (2005) and Zhou et al. (2006) where σ_e are directly measured and the sample by Ryan et al. (2007), the only one for which accurate high resolution J and K photometry of the host spheroid is available. From Zhou et al. (2006) we take the sub-sample of 33 sources with z <0.1 for which either the host galaxy appears to be face on or the SDSS fiber aperture is dominated by galactic bulge contribution. This choice is motivated by the need to avoid bulge velocity dispersion values which are artificially increased by rotation of the galactic disks.

For the Botte et al. (2005) and Ryan et al. (2007) samples, we compute virial BH masses using the scaling relations by Vestergaard & Peterson (2006) and Eq. 9. Instead for the Zhou et al. (2006) sample we use Eq. 10, i.e. we use the luminosity of the broad Hβ as a proxy for R_{BLR}, since, due the latter selection criteria, λL_λ might be strongly contaminated by stellar light. The comparison with expected BH mass values from the M_{BH}-σ_e (Tremaine et al. 2002) and M_{BH}-L_{sph} (Marconi & Hunt 2003) are plotted in the Fig. 4: in the left panel we use the virial BH masses by Vestergaard & Peterson (2006) while in the right panel we use our new virial mass estimates which take into account radiation pressure. A more refined statistical analysis would be complicated by the heterogeneity of the data and is beyond the scope of this paper but it is clear that, although with a large scatter, NLS1 with 'old' virial BH masses are lying preferentially below the M_{BH}-σ_e relation defined by normal galaxies. When radiation pressure is taken into account in virial BH mass estimates, this tendency disappears or is strongly reduced. It is significant that the NLS1 galaxies with bulge luminosities by Ryan et al. (2007) are all lying below the expected M_{BH}-L_{sph} values while they are in good agreement with it after radiation pressure has
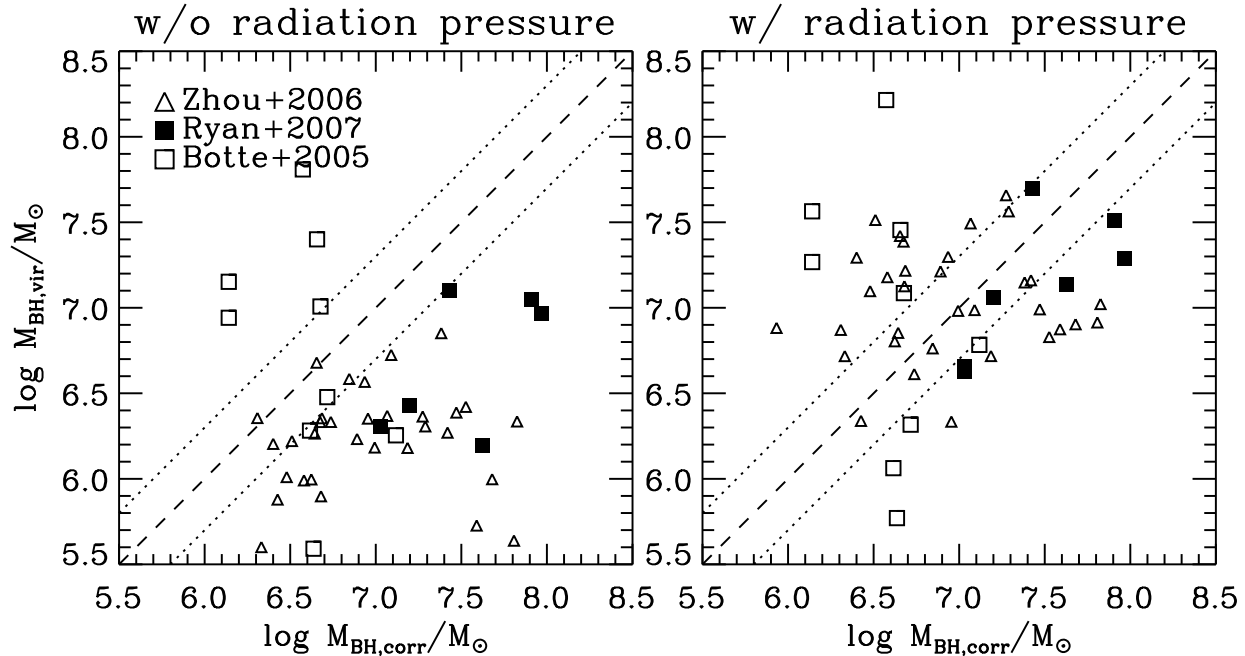
w/o radiation pressure

w/ radiation pressure

FIG. 4.— Comparison between virial BH masses ($M_{BH,vir}$) and those expected from the M_{BH}-σ_e or M_{BH}-L_{sph} correlations for normal galaxies ($M_{BH,corr}$, Tremaine et al. 2002; Marconi & Hunt 2003). Left panel: virial BH masses are computed using the calibrated relations by Vestergaard & Peterson (2006). Right panel: virial BH masses are computed using the relations derived in this paper which take into account radiation pressure.

been taken into account. This is confirmed by Fig. 5 where we plot the histogram of the distances from the M_{BH}-σ_e correlation for the data by Zhou et al. (2006). In the top left corner we report the mean and standard deviation of the mean ($\sigma/\sqrt{N}$) of residuals from the M_{BH}-σ_e correlation. If radiation pressure is not taken into account, NLS1 galaxies lie, on average, a factor ~ 5 below the correlation. However, after taking into account radiation pressure, virial BH masses are dispersed around the correlation.

The above findings do not constitute the definitive proof that radiation pressure provides a solution to the small BH mass problem in NLS1. We only show that our calibrated correction for radiation pressure is approximately of the right amount to bring NLS1 to lie on the M_{BH}-σ_e,L_{sph} correlations.

Finally, although it is not possible to establish whether a system is emitting above Eddington using virial BH masses (see § 2), the average increase of BH masses by 0.5-0.7 dex in NLS1 galaxies (from the Grupe et al. 2004 and Zhou et al. 2006 samples, respectively) implies a similar decrease of their classical $L/L_{Edd,0}$ ratios.

5. SUMMARY AND CONCLUSIONS

In this paper we have considered the effect of radiation pressure on virial BH mass estimates.

With a simple physical model, we have provided a correction for the effect of radiation pressure on virial products. This correction mainly depends on the average column density N_H of broad line clouds.

We have re-calibrated virial BH masses based on reverberation mapping data and single epoch spectra following a procedure analogous to Onken et al. (2004) and Vestergaard & Peterson (2006). With the caveat that it is difficult to accurately quantify the importance of radiation pressure with the present data, we find consistent values for the radiation pressure correction which, based on the above physical model, indicates an average $N_H \sim 10^{23}\,cm^{-2}$ for BLR clouds. This value is remarkably consistent with the BLR
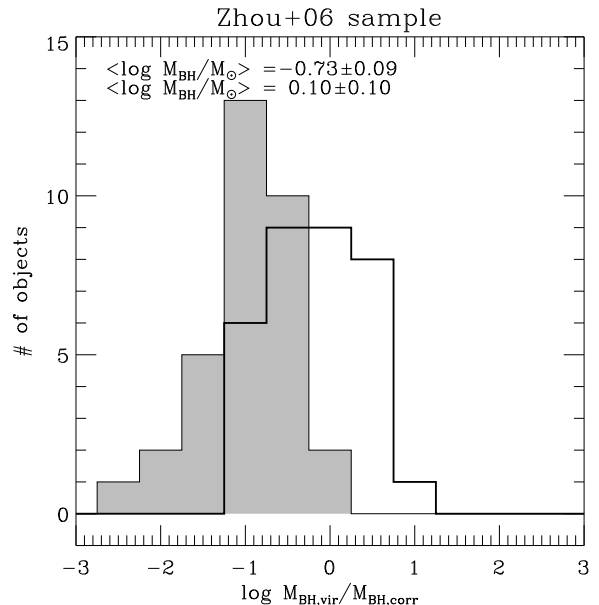
Zhou+06 sample

FIG. 5.— Histogram of the $M_{BH,vir}/M_{BH,corr}$ ratio for the Zhou et al. (2006) sample of 33 NLS1 galaxies (see text). Virial BH masses are computed using the calibrated relations by Vestergaard & Peterson (2006) (thin line with shaded area) and with the relations derived in this paper which take into account radiation pressure.

cloud column density required in photoionization models to explain the observed spectra.

When taking into account radiation pressure, the average rms scatter of the ratio between single epoch and reverberation mapping virial BH masses drops from 0.4 to 0.2 dex. The use of single epoch observations as surrogates of expensive reverberation mapping campaigns can thus provide more accurate virial BH masses than previously thought.

We have considered our newly calibrated virial BH mass relations for Narrow Line Seyfert 1 galaxies and we have shown

that, after taking into account radiation pressure, those galaxies seem to have BH masses similar to that of other broad line AGNs and and which follow the same $M_{\rm BH}$-$\sigma_{\rm e}$,$L_{\rm sph}$ relations as normal galaxies.

The small BH masses previously found in NLS1 can be attributed to the neglect of radiation pressure in objects radiating close to their Eddington limit.

Overall, the analysis presented in this paper clearly indicates that radiation forces arising from the deposition of momentum by ionizing photon constitute an important physical effect which must be taken into account when computing

virial BH mass estimates.

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