Refining the Radius–Luminosity Relationship for Active Galactic Nuclei

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Abstract.
We have measured the host-galaxy starlight contribution to four lower-luminosity AGNs (NGC 3516, NGC 4593, IC 4329A, and NGC 7469). We include these objects with new broad line region measurements for NGC 4151 and NGC 4593 to present a revised version of the radius–luminosity relationship for AGNs.

1. Introduction

The radius–luminosity ($R - L$) relationship is an extremely useful product that results from years of reverberation-mapping (variability) campaigns to study AGNs. It is the basis for estimates of black hole masses in objects where direct measurements are either not feasible or not practical.

Recently, Bentz et al. (2006a) presented a revised version of the $R - L$ relationship based on starlight-corrected luminosities for reverberation-mapped AGNs based on high-resolution Hubble Space Telescope (HST) imaging of the galaxy centers. The power law slope determined for this revised relationship was $\alpha = 0.52$, shallower than previously determined and consistent with naive photoionization arguments. This initial sample of starlight-corrected objects was 14, and several of the lower-luminosity objects that did not have imaging available were excluded from the fit of the $R - L$ relationship. In this work, we present an additional four objects (NGC 3516, NGC 4593, IC 4329A, and NGC 7469) with high-resolution HST imaging and measurements of the host-galaxy starlight contribution to their luminosity measurements. We also include new broad line region (BLR) radius measurements from the recent reverberation-mapping campaigns of NGC 4151 (Bentz et al. 2006b) and NGC 4593 (Denney et al. 2006). We reanalyze the fit to the $R - L$ relationship and present the resulting formula for estimating black hole masses based on the new $R - L$ calibration.

2. Observations and Host-Galaxy Flux Measurements

HST imaging of NGC 3516, NGC 4593, IC 4329A, and NGC 7469 was obtained throughout Cycle 14 (2005-2006). The observations, reduction methods, and galaxy fitting methods were similar to those described by Bentz et al. (2006a), but for completeness, we include a short description here.
Each object was observed with the Advanced Camera for Surveys (ACS) High Resolution Channel through the F550M filter (medium-band V). A set of graduated exposure times (120 s, 300 s, and 600 s) was employed to both acquire unsaturated images of the nucleus but also to achieve a reasonable signal-to-noise ratio in the outlying galaxy. Saturated pixels in the longer exposures were replaced with unsaturated pixels from shorter exposures that had been scaled by the exposure time difference. The corrected images were stacked and cleaned of cosmic rays and then transformed to account for the distortions of the ACS camera.

| Object   | Aperture (') | PA (°) | $f_{\lambda,\text{gal}}$ (5100Å) | $\lambda L_{\lambda,\text{AGN}}$ (5100Å) | Refs. |
|----------|--------------|--------|----------------------------------|----------------------------------|-------|
| NGC 3516 | 1.5 $\times$ 2 | 25     | $4.64 \pm 0.86$                  | 0.032 $\pm$ 0.026                 | 1,2   |
| NGC 4593 | 5 $\times$ 12.75 | 90     | $11.54 \pm 2.14$                | 0.044 $\pm$ 0.022                 | 3     |
| IC 4329A | 5 $\times$ 10   | 90     | $4.90 \pm 0.91$                  | 0.032 $\pm$ 0.038                 | 4     |
| NGC 7649 | 10 $\times$ 16.8 | 26.7   | $15.98 \pm 2.96$                | 0.135 $\pm$ 0.129                 | 5     |

References: 1. Onken et al. (2003), 2. Wanders et al. (1993), 3. Denney et al. (2006), 4. Winge et al. (1996), 5. Collier et al. (1998).

The final images were fit with two dimensional galaxy models using Galfit (Peng et al. 2002). A simultaneous fit of the disk, bulge, and central PSF was determined for each object. Once a satisfactory fit was found, the central PSF was subtracted, leaving a nucleus-free image of each galaxy. The original ground-based monitoring aperture was overlaid on each host galaxy image and the starlight within the aperture was summed to give the host-galaxy contribution to the flux measured for each AGN. Table 1 lists the aperture geometries and orientations for each of the four objects, along with the measured host galaxy flux and the resulting starlight-free luminosity of the AGN.

3. Recalibrating the $R - L$ Relationship

We combine the corrections above with those of Bentz et al. (2006a) and also replace previous reverberation-mapping results for the radii of the BLRs in NGC 4151 and NGC 4593 with the new results determined by Bentz et al. (2006b) and Denney et al. (2006). Multiple measurements for the same object were combined into a weighted mean. We then used the orthogonal least-squares analysis package GaussFit (McArthur et al. 1994) to determine the $R - L$ relationship for H$\beta$,

$$\log R_{\text{BLR}} = -22.198 + 0.539 \log \lambda L_{\lambda}(5100\text{Å})$$  \hspace{1cm} (1)

where $R_{\text{BLR}}$ is the average radius of the H$\beta$ BLR. This recalibration of the $R - L$ relationship is not significantly different from that determined by Bentz et al. (2006a), even with the inclusion of additional data points. Figure 1 shows...
the calibration determined above contrasted with the calibration determined by Kaspi et al. (2005), which does not include host-galaxy starlight corrections.

Removing the host-galaxy starlight component significantly reduces the scatter in the relationship, but also flattens the slope of the relationship considerably. This has the overall effect of biasing samples that use the \( R - L \) relationship to estimate black hole masses. The largest effect is for low-luminosity objects where black hole masses could be overestimated by a factor of \( > 3 \). The host-galaxy starlight is typically removed from flux measurements of low-luminosity objects before the black hole mass is estimated. However, it is also crucial to use an \( R - L \) relationship that has been determined after removal of the host-galaxy starlight from the population of objects providing the calibration.

To estimate black hole masses, the luminosity of the object is used in combination with the \( R - L \) relationship to estimate the radius of the BLR.
following equation gives the combination of the above determination for the $R - L$ relationship and the formula for calculating black hole masses:

$$\log M_{BH} = 0.808 + 0.539 \log L_{44} + 2 \log V + \log f. \quad (2)$$

Here, $L_{44}$ is the luminosity of the object in units of $10^{44}$ ergs s$^{-1}$, $V$ is the velocity width of the H$\beta$ emission line in km s$^{-1}$, and $f$ is a geometric factor. Onken et al. (2004) find that $\langle f \rangle = 5.5$ for the reverberation-mapped objects, where $V$ is measured as the second moment of the variable (RMS) line profile, $\sigma_{\text{line}}$. While this measurement of the line width is not possible for single epoch spectra, $\sigma_{\text{line}}$ may still be calculated from the mean line profile, and again $f = 5.5$ should be used. It is important when estimating black hole masses using the above equation to correct any FWHM measurements of the line profile by using the $f$ values determined by Collin et al. (2006) in their eq. 7.

4. Conclusions

Removing the host-galaxy contribution to luminosity measurements of reverberation-mapped AGNs substantially decreases the slope of the $R - L$ relationship. Failing to take the host galaxy starlight into account will serve to bias estimates of black hole masses that are based on the $R - L$ relationship, especially on the low luminosity end where the masses can be overestimated by a factor of $> 3$. The $R - L$ relationship has now been shown to hold across five orders of magnitude, with fairly low scatter. As such, it is a powerful diagnostic tool in that outliers from the relationship can be expected to have physical differences that cause them to be separated from the general population of AGNs.

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