RELATION BETWEEN BLACK HOLE MASS AND BULGE LUMINOSITY IN HARD X-RAY SELECTED TYPE 1 AGNS

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Abstract: Using I-band images of 35 nearby (\(z < 0.1\)) type 1 active galactic nuclei (AGNs) obtained with Hubble Space Telescope, selected from the 70-month Swift-BAT X-ray source catalog, we investigate the photometric properties of the host galaxies. With a careful treatment of the point-spread function (PSF) model and imaging decomposition, we robustly measure the I-band brightness and the effective radius of bulges in our sample. Along with black hole (BH) mass estimates from single-epoch spectroscopic data, we present the relation between BH mass and I-band bulge luminosity (\(M_{\text{BH}}-M_{\text{I,bul}}\) relation) of our sample AGNs. We find that our sample lies offset from the \(M_{\text{BH}}-M_{\text{I,bul}}\) relation of inactive galaxies by 0.4 dex, i.e., at a given bulge luminosity, the BH mass of our sample is systematically smaller than that of inactive galaxies. We also demonstrate that the zero point offset in the \(M_{\text{BH}}-M_{\text{I,bul}}\) relation with respect to inactive galaxies is correlated with the Eddington ratio. Based on the Kormendy relation, we find that the mean surface brightness of ellipticals and classical bulges in our sample is comparable to that of normal galaxies, revealing that bulge brightness is not enhanced in our sample. As a result, we conclude that the deviation in the \(M_{\text{BH}}-M_{\text{I,bul}}\) relation from inactive galaxies is possibly because the scaling factor in the virial BH mass estimator depends on the Eddington ratio.

Key words: black hole physics — galaxies: active — galaxies: Seyfert — quasars

1. INTRODUCTION

Supermassive black holes (SMBHs) are ubiquitous at the centers of massive galaxies, and their mass is tightly correlated with various physical properties of bulges, such as luminosity, stellar mass, and velocity dispersion \citep{Kormendy2013}. While these scaling relations imply a physical connection between SMBH and the host galaxy in terms of their formation and evolution, the physical origin of the scaling relations is still under debate. Energetic feedback from an active galactic nucleus (AGN) is one of the favored mechanisms to drive the co-evolution of SMBH and the host galaxy \citep[e.g.,][]{Di Matteo2005}. In this light, exploring the scaling relations in AGN is of great importance to unveil the origin of the BH-host relations.

Several scaling relations have been widely used to understand the causal connection between SMBHs and their host galaxies in active galaxies, thanks to the relative ease of estimating the BH mass of type 1 AGN, which exhibit blue continuum from the accretion disk and broad emission lines in the spectrum. For example, using the relation between BH mass and physical properties of the bulge (e.g., stellar velocity dispersion and bulge luminosity) from distant AGNs, previous studies argued that BH growth precedes galaxy growth \citep[e.g.,][]{Peng2006, Woo2008, Park2014}. Using AGN in the local universe, several studies reported that active galaxies deviate from inactive galaxies in the \(M_{\text{BH}}-M_{\text{I,bul}}\) relation, revealing that either BH mass is systematically undermassive or bulge luminosity is overluminous compared to normal galaxies \citep[e.g.,][]{Kim2008b, Kim2019}. On the other hand, a relation between the effective radius and the mean surface brightness within the effective radius \citep{Kormendy1977} has been extensively used to probe young stellar populations in host galaxies of nearby AGNs \citep[e.g.,][]{Kim2019, Zhao2019, Zhao2021}. For example, \cite{Kim2019} argued that bulges regardless of the bulge types in galaxies hosting type 1 AGNs tend to be brighter than normal galaxies inferred from the Kormendy relation, possibly due to recent star formation. However, using the same relation, \cite{Zhao2021} demonstrated that only pseudo-bulges in active galaxies are overluminous. Interestingly, this trend is consistent with the result for type 2 AGNs in \cite{Zhao2019}. Overall, different studies reached somewhat different conclusions regarding the stellar population in galaxies hosting AGNs, possibly due to the diverse sample properties and filters (\(R\) and \(I\)) used in the previous studies \citep[e.g.,][]{Zhao2019}.

Nevertheless, previous studies for nearby AGNs included some distant AGNs (\(z \leq 0.35 - 0.5\)), which can still be affected by cosmic evolution \cite[e.g.,][]{Bennert2009}.
Additionally, the sample was dominated by AGNs selected from the UV/optical survey (e.g., Schmidt & Green 1983; Lyke et al. 2020), possibly biased toward bright and less obscured AGNs. These factors can introduce some unknown biases in establishing the BH–host relation. In this study, we make use of relatively unbiased and nearby AGNs ($z < 0.1$) drawn from a hard X-ray survey (Koss et al. 2017). Moreover, the imaging data used in this study is obtained with uniform and consistent observations, which can allow us to explore the BH-host relation with a minimum bias due to the sample selection, cosmic evolution, and diverse imaging quality.

In this study, we revisit two scaling relations (BH mass–bulge luminosity and Kormendy relations) of nearby type 1 AGNs using $I$-band images obtained with Hubble Space Telescope (HST). In §2, we present the physical properties of the sample, and description of the observation and data reduction. In §3, we present the methods for the imaging decomposition. We present $M_{BH}$–$M_{bul}$ and Kormendy relations of our sample by comparing them with inactive galaxies in §4. In §5, we discuss the physical origins of systematic offsets in the scaling relations. A summary and conclusions are given in §6. We adopt the following cosmological parameters: $H_0 = 100 h = 67.8$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.308$, and $\Omega_{\Lambda} = 0.692$ (Planck Collaboration et al. 2016).

2. Sample and Data

2.1. Sample

Our sample contains nearby AGNs ($z < 0.1$) drawn from the 70-month Swift-BAT X-ray source catalog (Koss et al. 2017). We utilized images obtained with HST as a part of the gap-filler snapshot program (HST program 15444), in which the imaging survey of nearby hard X-ray selected AGNs was conducted (Kim et al. 2021). Due to less severe attenuation in the hard X-ray band, the parent sample is thought to be relatively unbiased in terms of obscuration, making the Swift-BAT observations and data reduction. In §2.6, we present the physical properties of the sample, and description of the observation and data reduction. In §3, we present the methods for the imaging decomposition. We present $M_{BH}$–$M_{bul}$ and Kormendy relations of our sample by comparing them with active galaxies in §4. In §5, we discuss the physical origins of systematic offsets in the scaling relations. A summary and conclusions are given in §6. We adopt the following cosmological parameters: $H_0 = 100 h = 67.8$ km s$^{-1}$ Mpc$^{-1}$, $\Omega_m = 0.308$, and $\Omega_{\Lambda} = 0.692$ (Planck Collaboration et al. 2016).

2.2. Observations and Data Reduction

The HST images were taken with the Wide Field Channel (WFC) of the Advanced Camera for Surveys (ACS). Its field of view ($202'' \times 202''$) is large enough to cover the target galaxies. To avoid contamination from the extended emission and maximize the light ratio of the host to the nucleus, we adopted the F814W filter, corresponding to $I$-band. We obtained two dithered images with an exposure time of 337 s for efficient removal of cosmic rays and correction for hot pixels. An additional image with an exposure of 5 s was acquired for each target to avoid the saturation of the bright nucleus.

The basic data reduction, which includes bias subtraction, flat-fielding, and correction for the charge-transfer efficiency, was performed using the Pyraf-based STSDAS package. Cosmic rays were removed from each exposure by adopting the l.a.cosmic algorithm developed by van Dokkum (2001). The spatial offset between the two long exposures was computed using the TweakReg task, and the two exposures were combined after the distortion correction using AstroDrizzle. The pixel size in the combined image is 0.05. The subarray images with short exposure time suffer heavily from a strong pattern noise in the bias, leaving a series of stripes in the raw images. To solve this problem, we removed this noise using ACS_DESTRIPE_PLUS (Grogin 2010). The saturated pixels at the AGN core in the long-exposure images were replaced by the corresponding pixels in the short-exposure images. Details of the observations and data reduction are described in Kim et al. (2021).

2.3. BH mass and Eddington Ratio

If the gas in the broad line region (BLR) is virialized, BH mass can be estimated from the combination of the velocity dispersion ($\sigma$) and the radius of the BLR ($R_{BLR}$) as $M_{BH} = f_{\sigma}^2R_{BLR}/G$, where $f$ is a scaling factor determined by the kinematics and structure of the BLR. Due to the tight correlation between $R_{BLR}$ and BH luminosity, BH luminosity can be a surrogate for $R_{BLR}$ (Kaspi et al. 2000; Bentz et al. 2013) but see Du et al. (2016). Fonseca Alvarez et al. (2020). Therefore, BH mass can be computed with the width and luminosity of the broad emission lines (H$\beta$ and H$\alpha$ in this study) derived from single-epoch spectra. However, the scaling factor ($f$) is somewhat uncertain and has been empirically determined by assuming that, for example, active galaxies follow the same BH mass–stellar velocity dispersion relation of inactive galaxies. Ho & Kim (2015) argued that the scaling factor ($f$) depends on the bulge types (i.e., classical bulge vs. pseudo-bulge). Therefore, in this study, we adopted two different scaling factors for the BH mass estimation according to their bulge types. We utilize the fluxes and widths of the broad H$\alpha$ emission, estimated from the decomposition of the optical
spectra \cite{2017ApJ...851..131K}. If the broad H\alpha emission is unavailable, we instead used the spectral measurements of broad H\beta emission. The conversion from the fluxes of broad emission lines to the luminosity at 5100 Å was performed using the conversion factors from \cite{2005ApJ...629L..79G}. The typical uncertainty on virial mass estimates is of \sim 0.4 dex \cite[e.g.,][]{2006MNRAS.368.1289V}.

Bolometric luminosities of AGNs are inferred from the hard X-ray luminosity estimated in the 14-195 keV band, corrected for absorption \cite{2017ApJ...844..148R}. For the bolometric correction, we adopted a single conversion factor of 8 (i.e., $L_{\text{bol}} = 8 \times L_{14-195\text{keV}}$; \cite{2017ApJ...844..148R}). The median Eddington ratio of the entire sample is 0.06.

3. Analysis

3.1. PSF Generation

To robustly estimate the bulge brightness in the images of type 1 AGNs, a careful decomposition of the bright nuclear component, modeled by a PSF, is essential. The PSF can be constructed in two different ways: (1) an empirical PSF derived from stars obtained in the same observing condition (e.g., filters and detectors); (2) a synthetic PSF modeled by TinyTim software \cite{TinyTim}. The TinyTim PSF has been widely used as it represents the central part of the PSF relatively well. However, it often underestimates the surface brightness in the halo of the PSF, which can naturally lead to the miscalculation of underlying host brightness \cite[e.g.,][]{2008ApJ...675..146K, 2021MNRAS.500.5406Z}. Therefore, in this study, we employed an empirical PSF to model the nucleus.

To generate the empirical PSF, we initially selected numerous sufficiently bright but unsaturated stars from the science images. Then, through visual inspection, extended sources and stars with close neighbors are manually excluded, finally with 44 stars remaining. We use IRAF to eliminate faint nearby sources around the target stars, adjust the scale among them, and combine the images for generating the PSF. By comparing the surface brightness profile of the generated PSF and those of individual stars obtained with ELLIPSE within IRAF, we confirmed that the profile in the central part of the PSF is well represented by the empirical PSF (Fig. 1). However, the wing of the PSF is rather dominated by noise, which can easily mimic the signal from the host galaxy. Therefore, to characterize the outer part of the PSF, we additionally utilized a moderately saturated star. To determine the relative scaling between the initial PSF and the saturated star, we modeled the 2D surface brightness profiles of both objects with the profile of the initial PSF using GALFIT \cite{2002ApJ...563..740P, 2010MNRAS.402.1681P}. During the fit, the saturated pixels and charge-bleeding regions near the PSF core were properly masked out. Finally, we constructed the full PSF by replacing the masked region in the image of the saturated star with the scaled initial PSF.

To validate the empirical PSF, we compared its surface brightness profile with that of the TinyTim PSF (Fig. 1). Although both PSFs are in good agreement with each other in the central region, we found that there are substantial differences between the two PSFs in the extended wings at $r > 1''$, as expected. This comparison demonstrates that the empirical PSF is more suitable for our study.

3.2. Image Decomposition

To investigate the photometric properties of bulges in our sample, we performed a 2D imaging decomposi-
Figure 2. Results of imaging decomposition with GALFIT. (a) In the top panel, surface brightness profiles of the original image (open circles), nucleus (dotted line), and bulge (red line) are displayed. If present, bar and disk are denoted by green dashed-dotted line and blue dashed line, respectively. Black solid line represents the surface brightness profile of the best-fit model. The bottom panel shows the residual. (b) Original image. (c) Best-fit model for the host galaxy without the nuclear component. (d) Residual image. All the images are shown with an asinh stretch.
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tion of the HST images using GALFIT ([Peng et al. 2002] 2010). Before conducting the fit, we manually masked neighboring objects and charge-bleeding trails due to saturation. For robust measurements, it is necessary to adequately model non-bulge components, such as the nucleus, disk, bar, and oval if present along with the bulge component. We employed the empirical PSF to approximate the nucleus. The sub-components of the host galaxies were modeled with S´ersic profiles. As an initial test, we fitted the host galaxy with a single S´ersic profile, where we either fixed the S´ersic index (n) as 1 or 4, or let it float as a free parameter. If there is no clear evidence of additional components (e.g., disk or bar) in the residual images, we conclude that the host is well fitted with the single S´ersic component (i.e., elliptical). For a sanity check for the goodness of the fit, we also utilized 1D surface brightness profiles of the original images and best models and their residuals (Fig. 2).

If any structures other than the bulge are revealed in the residual images, we refit the imaging data by adding S´ersic components: a S´ersic component with n = 1 for an exponential disk, a S´ersic component with n = 0.5 for a bar, and a S´ersic component with free n for an oval. If the fitting result is severely affected by the light from companion objects, we simultaneously fit them with S´ersic profiles for extended sources or PSFs for point sources. Finally, Fourier modes were additionally implemented to account for the lopsidedness of the host if the host galaxy is heavily disturbed. The detailed fitting results, including 1D surface brightness profiles, are displayed in Figure 2.

Owing to the bright nucleus and PSF mismatch, it is occasionally difficult to choose the best model for the host galaxy from the decomposition with GALFIT. In that case, the fitting result with the most physically meaningful parameters and a smaller reduced χ² value was selected as the best fit. For example, S´ersic models with a large S´ersic index (n > 8) or a tiny effective radius (Re < a few pixels) were not considered as reliable.

To estimate the uncertainty of the bulge luminosity, we adopted the recipe proposed by [Kim et al. 2017] based on imaging simulations. The uncertainty of the bulge luminosity was initially determined by the bulge-to-nucleus light ratio (0.3 mag for L_{bul}/L_{nuc} ≥ 0.2 and 0.4 mag for L_{bul}/L_{nuc} < 0.2). Then, an additional component (e.g., disk) for the host would increase the uncertainty by 0.1 mag. Additional uncertainty can be introduced from imperfect sky subtraction, which was done as part of the drizzling process. Because the field of view is sufficiently large for robust sky determination, the measurement error for the sky estimation is expected to be small. Nevertheless, to quantify the effect of sky uncertainty, we perform the decomposition by fixing the sky to 1σ and −1σ of the original sky value. This experiment often resulted in host components with unreliable structural parameters (e.g., extremely small or large S´ersic indices with large effective radii), but the impact on the bulge luminosity is modest, usually only within 0.2 mag. Note that PSF mismatch appears to be severe in a few targets (e.g., SWIFT J1132.9+1019A). However, because the bulges are large and bright, as shown in the radial profiles, the total bulge luminosity is only affected at the level of ~ 0.2 − 0.3 mag. In addition, such PSF mismatch was taken into account when estimating the error budget ([Kim et al. 2017]).

We applied a correction for Galactic extinction ([Schlafly & Finkbeiner 2011]). We performed k-correct using the method in [Chilingarian et al. (2010) and Chilingarian & Zolotukhin (2012)]. The color information of host galaxies is unknown. As a result, we adopt V − Ic color inferred from the morphological types of hosts ([Fukugita et al. 1995]), which are determined from visual inspection. For the nucleus, V − Ic = 0.6 is calculated from the QSO composite spectrum ([Vanden Berk et al. 2001]). The conversion of MF_{S14W} to M_I was not applied because the conversion factor is known to be negligible (< 0.05 mag; [Fukugita et al. 1995, Harris 2018]). Table 3 lists the photometric properties of the sample obtained through the imaging decomposition.

4. RESULTS

4.1. M_{BH}−M_{I, bul} Relation

To estimate the M_{BH}−M_{I, bul} relation for our sample, we employed a χ² minimization fit (modified FITEXY given in [Tremaine et al. 2002], which accounts for the measurement errors in both M_{BH} and M_{I, bul} and intrinsic scatter (σ)). We fit the M_{BH}−M_{I, bul} relation of the form

$$\log(M_{BH}/M_\odot) = \alpha M_{I, bul} + \beta.$$  

(1)

Given the small sample size, we fixed the slope to α = −0.57, which was derived from the inactive galaxies, and only solved for the zero point (β). To compute the M_{BH}−M_{I, bul} relation of the inactive galaxies in I-band from that in K-band ([Kormendy & Ho 2013], we used mass-to-light-ratio in K- and I-band inferred from B − V color ([Into & Portinari 2013]).

It appears that the AGNs in our sample tend to have a lower zero point compared to inactive galaxies (Fig. 3). To find the main driver of this offset, we divided the sample into two subgroups: one with a lower Eddington ratio than the median value (0.06) and one with a higher Eddington ratio than the median value. We find that AGNs with larger Eddington ratio systematically lie below those with smaller Eddington ratio in the M_{BH}−M_{I, bul} relation, indicating that the zero point depends on the Eddington ratio.

However, given the fact that hosts with classical bulges and pseudo-bulges follow a different M_{BH}−M_{I, bul} relation ([Kormendy & Ho 2013], it is essential to assess this trend by dividing the sample according to the bulge type ([Ho & Kim 2014]). In this light, we performed the bulge classification based on the S´ersic index (n) and B/T. Following the methods given in [Fisher & Drory (2008), Gadotti (2009) and Gao et al. (2020)], bulges with n > 2 and B/T > 0.2 (n ≤ 2 or B/T ≤ 0.2) are
classified as a classical bulge (pseudo-bulge). Furthermore, we computed the $M_{\text{BH}}-M_{I,\text{bul}}$ relation of inactive galaxies for different bulge types utilizing the data from Kormendy & Ho (2013). The $M_{\text{BH}}-M_{I,\text{bul}}$ relation of the pseudo-bulges has a substantially larger scatter ($\epsilon_0 \sim 0.63$ dex for the pseudo-bulge in inactive galaxies) compared to the classical bulges ($\epsilon_0 \sim 0.31$ dex), which can introduce a systematic bias in the comparison between the two bulge types (Tab. 1). Therefore, classical bulges and ellipticals are considered only for further analysis. By fixing the slope to that of classical bulges and ellipticals in inactive galaxies ($\sim -0.49$), we again find that AGNs with classical bulges or ellipticals lie systematically below the relation of inactive galaxies and the zero point offset is lower for objects with greater Eddington ratio. This observation confirms our previous finding for the entire sample, that the zero point depends on the Eddington ratio.

### 4.2. Kormendy Relation

There is an anti-correlation between the effective radius ($R_e$) and the mean surface brightness ($\langle \mu_I \rangle$) within the effective radius, known as the Kormendy relation [Kormendy 1977]. Here, we present the Kormendy relation for our sample. Fisher & Drory (2008), Gadotti (2009), and Gao et al. (2020) reported that classical bulges and pseudo-bulges are distinctive in the Kormendy relation, while classical bulges follow the Kormendy relation similar to that of ellipticals. Therefore, we investigated the Kormendy relations as a function of bulge type. We fit the Kormendy relation of the form

$$\langle \mu_I \rangle = \kappa \log(R_e/kpc) + \gamma,$$

where $\langle \mu_I \rangle$ is the $I$-band mean surface brightness in the units of mag arcsec$^{-2}$. We adopted the ordinary least squares bisector method for the fit as both parameters are independent [Isobe et al. 1999].

The Kormendy relation of inactive galaxies in the $I$ band is inferred from that in $R$ band given in Kim & Ho (2019). This process is done by assuming $R - I = 0.65$ for ellipticals and classical bulges, which is equivalent to the value for a galaxy of Hubble type Sab, and $R - I = 0.57$ for pseudo-bulges, which is equivalent to the value for an Scd spiral [Fukugita et al. 1995]. For the comparison, we also adopted the Kormendy relation of inactive ellipticals in the $I$ band. It was converted from that in $R$ band from Gao et al. (2020) by assuming $R - I = 0.70$ of an elliptical galaxy [Fukugita et al. 1995]. Figure 4 shows that, for ellipticals and classical bulges, there is little difference between the AGNs in our sample and those in inactive galaxies. However, for pseudo-bulges, the AGNs in our sample appear to systematically have brighter $\langle \mu_I \rangle$ compared to those in inactive galaxies at a given $R_e$. In both types, we found no evidence for a dependence of the Kormendy relation on Eddington ratio. The detailed fitting results for different subsamples are summarized in Table 5.

### 5. Discussion

#### 5.1. Origin of the Offset in the $M_{\text{BH}}-M_{I,\text{bul}}$ Relation

We find that AGNs in our sample have a lower zero point compared to the inactive galaxies. Additionally, the magnitude of the offset in the zero point (0.4 – 0.8 dex) is anti-correlated with the Eddington ratio. This finding can be interpreted in three ways. For AGNs with a high Eddington ratio, either the bulges are over-luminous compared to those in inactive galaxies, the BHs are less massive than those in inactive galaxies at a given bulge luminosity, or BH masses are somehow underestimated. In contrast, ellipticals and classical bulges in our sample follow the Kormendy relation similar to that in inactive galaxies, thereby revealing that there is no excess in the bulge luminosity. Therefore, the offset in the $M_{\text{BH}}-M_{I,\text{bul}}$ relation is unlikely to occur due to the over-luminous bulge.

As a BH is actively growing during the AGN phase, it can be naturally expected that AGNs can systematically have less massive BHs than inactive galaxies at a given bulge luminosity. Assuming a constant Eddington ratio within the AGN lifetime ($t_{\text{AGN}}$), a BH growth factor ($\Delta M_{\text{BH}}/M_{\text{BH}}$) during the AGN phase can be expressed as

$$\frac{M_{\text{final}}}{M_{\text{int}}} \approx \exp(\lambda - \eta \frac{t_{\text{AGN}}}{t_{\text{Edd}}}),$$

where $M_{\text{final}}$ is the final BH mass after the AGN phase, $M_{\text{int}}$ is the initial BH mass, $\eta$ is the radiative efficiency of the accretion disk and $t_{\text{Edd}}$ is the Eddington time scale ($\approx 0.45$ Gyr; Volonteri & Rees 2005). For simplicity, we assume $\eta \approx 0.1$ and $t_{\text{AGN}} \sim 0.05$ Gyr [Yu & Tremaine 2002; Martini et al. 2004; Kim & Ho 2019]. By adopting the median Eddington ratio of our sample ($\lambda \sim 0.06$), the BH growth factor during the AGN phase ($\sim 1.06$ or 0.03 dex) is almost negligible compared to the offset ($\sim 0.4$ dex) in the $M_{\text{BH}}-M_{I,\text{bul}}$ relation. Even with an extreme assumption ($\eta \approx 0.01$; e.g., Davis & Laor 2011), the BH growth factor is less than 0.3 dex. This reveals that undermassive BHs are unlikely to be the main driver of the offset.

It has long been suggested that the scaling factor in the virial mass estimator for BHs can be sensitive to physical properties of AGNs (e.g., Eddington ratio, bolometric luminosity and inclination of BLR; Marconi et al. 2008; Ho & Kim 2014; Mejia-Restrepo et al. 2017). Therefore, the dependence of the zero point offset on the Eddington ratio can be naturally attributed to the different scaling factors instead of a single universal value. To assess this effect more quantitatively, we calculated $\Delta M_{\text{BH}}$ in each object, which is defined as the offset between the BH mass estimated from the virial method and that inferred from the inactive $M_{\text{BH}}-M_{I,\text{bul}}$ relation at a given bulge luminosity in a log-log space. Then we compared $\Delta M_{\text{BH}}$ with the Eddington ratio (Fig. 5). The Spearman correlation coefficient is $-0.49$ (p-value $\sim 0.003$), which implies that the correlation between two variables is significant. To validate the statistical
significance of the correlation, we employed the bootstrapping resampling method. From this experiment, we found a 68% confidence interval of −0.45 to −0.64, again indicating that the correlation is statistically significant. Additionally, ΔMBH appears to converge to 0 when the Eddington ratio is smaller than 0.05, which supports the idea that the zero point offset is due to the dependence of the scaling factor on the Eddington ratio. One may argue that the secondary parameter (e.g., MBH) can be another origin of the systematic offset. To test this hypothesis, we computed the Spearman correlation coefficient (~0.41 with p-value ~0.02) between ΔMBH and MBH. Although the coefficient value is slightly smaller than that of the correlation between ΔMBH and the Eddington ratio, it appears to be moderate. We perform a partial correlation analysis to further investigate whether Eddington ratio or MBH is the primary parameter driving the zero point offset. We find a higher partial correlation coefficient (ρ ~ −0.38) between ΔMBH and Eddington ratio after removing the contribution from BH mass. Note that the coefficient between ΔMBH and BH mass excluding the effect from Eddington ratio is ~0.13. Therefore, we conclude that Eddington ratio is likely to be a main driver of the zero point offset. The last caveat is that low-mass AGNs (MBH ≤ 10^5.5 M☉) with a low Eddington ratio may be excluded with the flux-limited hard X-ray selection. This may be a possible scenario to explain the observed zero point offset, but we cannot address it in this study given the small sample size.

5.2. Comparison with Previous Studies

Previous studies with HST imaging dataset of nearby type 1 AGNs also utilized the BH–host and Kormendy relations to investigate the physical connection between SMBHs and host galaxies of AGNs (e.g., Kim et al. 2008b; Kim & Ho 2019; Zhao et al. 2019, 2021). However, they reached somewhat different conclusions. For example, Kim & Ho (2019) found that AGNs lie systematically below the MBH–Mstellar relation compared to normal galaxies, and they concluded that bulges hosting AGNs are overluminous possibly due to the young stellar population based on the archival data of nearby AGNs (z < 0.35). Those observational results are in broad agreement with our finding in the sense that AGNs are offset from the normal galaxies in the MBH–Mstellar relation. However, their interpretation is somewhat different from ours, possibly because they partly used B- and V-band magnitudes that are more sensitive to young stellar populations compared to I-band used in this study. Additionally, unlike our sample, the sample in Kim & Ho (2019) is somewhat heterogeneous, and the archival imaging data were obtained in various observing configurations (e.g., instrument, filter, and exposure time). Therefore, their result can suffer from hidden biases.

In contrast, Zhao et al. (2021) reported that AGNs with massive hosts follow scaling relations (MBH–Mstellar and Kormendy relation) similar to those of normal galaxies, based on color images of PG quasars (z < 0.5). These results are inconsistent with our finding that ellipticals and classical bulges hosting AGNs deviate from the MBH–Mbulge relation of those in normal galaxies. The massive AGNs in Zhao et al. (2021) are more distant (z ~ 0.4) than those in our sample (z < 0.1), and may be affected by cosmic evolution and/or unknown bias. They also found that only the late-type galaxies with pseudo-bulges of AGNs deviate in the scaling relations, indicating that the brightness of pseudo-bulges hosting AGNs is enhanced due to recent star formation (e.g., Zhuang & Ho 2020; Xie et al. 2021; Zhuang et al. 2021). Interestingly, we also find the same offset in the Kormendy relation only for pseudo-bulges.

6. Conclusion

In this paper, we estimated the photometric properties of the bulges in the host galaxies by performing the careful imaging decomposition on HST images of 35 nearby AGNs, originally selected from hard X-ray data. Along with BH mass estimates from the virial methods, we examined the MBH–Mstellar and Kormendy relations of our sample and compared them with those of inactive galaxies. The main results from these experiments can be summarized as follows.

- The MBH–Mstellar relation of our sample AGNs slightly deviate from that of inactive galaxies in the sense that the BH mass in our sample AGNs is ~ 0.4 dex less than that of inactive galaxies at a given bulge luminosity. The zero point offset in the MBH–Mstellar relation of elliptical and classical bulges in our sample compared to that in inactive galaxies appears to be correlated with the Eddington ratio.

- For ellipticals and classical bulges, our sample follows the Kormendy relation in a similar manner as normal galaxies, indicating there is no evidence for overluminous bulges in our sample. As a result, we conclude that the zero point offset is possibly due to the dependence of the scaling factor on the Eddington ratio.

- Pseudo-bulges in our sample AGNs tend to be overluminous compared to those in normal galaxies, which is inferred from the Kormendy relation. This property of the pseudo-bulges is possibly due to the young stellar populations in the AGN host.

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http://kcor.sai.msu.ru/
Table 1

The Sample.

| Source Name | Alternative Name | Exposure (s) | R.A. (deg.) | Dec. (deg.) | $A_{F814W}$ (mag) | $z$ | $D_{r}$ (Mpc) |
|-------------|------------------|--------------|-------------|-------------|-------------------|----|--------------|
| SWIFT J0123.9−5846 | Fairall 9 | 674 | 20.9408 | −58.8057 | 0.039 | 0.0460 | 210.4 |
| SWIFT J0157.2+4715 | 2MASX J01571097+4715588 | 674 | 29.2956 | 47.2666 | 0.228 | 0.0478 | 218.9 |
| SWIFT J0206.2−0019 | Mrk 1018 | 674 | 31.5666 | −0.2914 | 0.042 | 0.0430 | 196.2 |
| SWIFT J0324.6−0848 | NOG 985 | 674 | 38.6574 | −8.7876 | 0.050 | 0.0430 | 196.4 |
| SWIFT J0333.3+3720 | 2MASX J03331873+3718107 | 674 | 53.3282 | 37.3030 | 0.815 | 0.0547 | 251.8 |
| SWIFT J0429.6−2114 | 2MASX J04293830−2109441 | 674 | 67.4095 | −21.1622 | 0.037 | 0.0700 | 325.8 |
| SWIFT J0510.7+1629 | IRAS 05078+1626 | 674 | 77.6896 | 16.4909 | 0.457 | 0.0173 | 77.7 |
| SWIFT J0516.2−0009 | Ark 120 | 674 | 79.0476 | −0.1498 | 0.194 | 0.0325 | 147.1 |
| SWIFT J0736.9+5846 | Mrk 9 | 674 | 114.2374 | 58.7704 | 0.089 | 0.0398 | 181.5 |
| SWIFT J0743.3−2546 | LEDA 86073 | 674 | 115.8114 | −25.7639 | 1.096 | 0.0238 | 106.5 |
| SWIFT J0747.5+6057 | Mrk 10 | 554 | 116.8714 | 60.9335 | 0.071 | 0.0294 | 131.6 |
| SWIFT J0759.8−3844 | 2MASJ07594181−3843560 | 674 | 119.9242 | −38.7322 | 1.238 | 0.0402 | 183.2 |
| SWIFT J0923.7+2255 | MCG +04−22−042 | 674 | 140.9292 | 22.9090 | 0.067 | 0.0333 | 150.8 |
| SWIFT J0942.2−2344 | CGCG 122−053 | 674 | 145.5200 | 23.6853 | 0.038 | 0.0217 | 97.4 |
| SWIFT J1020.5−0237B | 2MASX J10195855−0234363 | 674 | 154.9941 | −2.5767 | 0.062 | 0.0595 | 274.7 |
| SWIFT J1132.9+1019A | IC 2921 | 674 | 173.2053 | 10.2965 | 0.050 | 0.0440 | 201.0 |
| SWIFT J1139.1+5913 | SBS 1136+594 | 674 | 174.7870 | 59.1990 | 0.023 | 0.0616 | 284.8 |
| SWIFT J1143.7+7942 | UGC 06728 | 674 | 176.3168 | 79.6815 | 0.155 | 0.0606 | 28.1 |
| SWIFT J1148.3+0901 | 2MASX J11475508+0902284 | 674 | 176.9795 | 9.0413 | 0.041 | 0.0693 | 322.2 |
| SWIFT J1316.9−7155 | 2MASX J13165424−7155270 | 674 | 199.2262 | −71.9242 | 0.389 | 0.0703 | 327.2 |
| SWIFT J1349.7+0209 | UM 614 | 674 | 207.4701 | 2.0791 | 0.043 | 0.0331 | 150.0 |
| SWIFT J1416.9−1158 | 2MASX J14165001−1158577 | 674 | 214.2084 | −11.9829 | 0.102 | 0.0992 | 471.1 |
| SWIFT J1421.4+4747 | SBS 1419+480 | 674 | 215.3742 | 47.7902 | 0.027 | 0.0727 | 338.8 |
| SWIFT J1747.7−2253 | 2MASX J17472972−2252448 | 674 | 266.8739 | −22.8791 | 1.555 | 0.0467 | 213.9 |
| SWIFT J1747.8+6837B | Mrk 507 | 674 | 267.1599 | 68.7044 | 0.059 | 0.0551 | 253.9 |
| SWIFT J1747.8+6837B | VII Zw 742 | 674 | 266.7493 | 68.6102 | 0.057 | 0.0630 | 291.5 |
| SWIFT J1844.5−6221 | Fairall 51 | 674 | 281.2249 | −62.3648 | 0.165 | 0.0140 | 62.3 |
| SWIFT J2035.2+2604 | 2MASX J20350566+2603301 | 674 | 308.7735 | 26.0583 | 0.415 | 0.0478 | 218.9 |
| SWIFT J2044.0+2832 | RX J2044.0+2833 | 674 | 311.0188 | 28.5534 | 0.524 | 0.0489 | 224.0 |
| SWIFT J2109.1−0942 | 2MASX J21090996−0940147 | 674 | 317.2915 | −9.6707 | 0.325 | 0.0267 | 120.7 |
| SWIFT J2114.4+8206 | 2MASX J21140128+8204483 | 674 | 318.5049 | 82.0801 | 0.233 | 0.0833 | 391.0 |
| SWIFT J2118.9+3336 | 2MASX J21192912+3332566 | 674 | 319.8714 | 33.5491 | 0.328 | 0.0509 | 233.7 |
| SWIFT J2124.6+5057 | 4C 50.55 | 674 | 321.1643 | 50.9735 | 3.709 | 0.0151 | 67.4 |
| SWIFT J2156.1+4728 | 2MASX J21563399+4728217 | 674 | 323.9750 | 47.4727 | 0.969 | 0.0253 | 114.0 |
| SWIFT J2219.7+2614 | 2MASX J22194971+2613277 | 674 | 334.9573 | 26.2244 | 0.165 | 0.0877 | 413.2 |

Col. (1): Source name. Col. (2): Alternative name. Col. (3): Exposure time. Col. (4): Right Ascension. Col. (5): Declination. Col. (6): Galactic extinction in F814W. Col. (7): Redshift. Col. (8): Luminosity distance.
## Table 2
Physical Properties of the Sample.

| Source Name    | Line | Bulge Type | log $M_{\text{BH}}$ ($M_\odot$) | log $L_{\text{bol}}$ (erg s$^{-1}$) | log $\lambda_E$ |
|----------------|------|------------|---------------------------------|-------------------------------------|-----------------|
| SWIFT J0123.9−5846 | Hα  | PB         | 8.07                            | 45.32                               | −0.85           |
| SWIFT J0157.2+4715 | Hα  | PB         | 7.54                            | 44.84                               | −0.80           |
| SWIFT J0206.2−0019 | Hα  | E          | 8.11                            | 45.01                               | −1.20           |
| SWIFT J0234.6−0848 | Hα  | PB         | 8.13                            | 45.02                               | −1.21           |
| SWIFT J0333.3+3720 | Hα  | E          | 8.25                            | 45.14                               | −1.21           |
| SWIFT J0429.6−2114 | Hα  | E          | 8.83                            | 45.00                               | −1.93           |
| SWIFT J0510.7+1629 | Hα  | E          | 7.76                            | 44.72                               | −1.14           |
| SWIFT J0516.2−0009 | Hα  | CB         | 8.78                            | 45.11                               | −1.77           |
| SWIFT J0736.9−5846 | Hα  | PB         | 7.53                            | 44.40                               | −1.23           |
| SWIFT J0743.3−2546 | Hα  | PB         | 7.09                            | 44.30                               | −0.89           |
| SWIFT J0747.5+6057 | Hα  | PB         | 7.24                            | 44.36                               | −0.98           |
| SWIFT J0759.8−3844 | Hα  | E          | 8.62                            | 45.15                               | −1.57           |
| SWIFT J0923.7+2255 | Hα  | PB         | 7.23                            | 44.87                               | −0.46           |
| SWIFT J0942.2+2344 | Hα  | PB         | 7.04                            | 43.98                               | −1.16           |
| SWIFT J1020.5−0237B | Hα  | PB         | 8.29                            | 44.60                               | −1.79           |
| SWIFT J1132.9+1019A | Hα  | CB         | 7.95                            | 44.72                               | −1.33           |
| SWIFT J1139.1+5913 | Hα  | E          | 8.31                            | 45.14                               | −1.27           |
| SWIFT J1143.7+7942 | Hα  | PB         | 5.71                            | 43.28                               | −0.53           |
| SWIFT J1148.3+0001 | Hα  | PB         | 8.33                            | 45.02                               | −1.41           |
| SWIFT J1316.9−7155 | Hα  | E          | 9.15                            | 45.16                               | −2.09           |
| SWIFT J1349.7+0209 | Hα  | CB         | 7.61                            | 44.51                               | −1.20           |
| SWIFT J1416.9−1158 | Hα  | E          | 9.17                            | 45.53                               | −1.74           |
| SWIFT J1421.4+4747 | Hα  | CB         | 8.65                            | 45.27                               | −1.48           |
| SWIFT J1747.7−2253 | Hα  | E          | 9.09                            | 44.93                               | −2.26           |
| SWIFT J1747.8+6837A | Hα  | PB         | 6.91                            | 44.35                               | −0.66           |
| SWIFT J1747.8+6837B | Hα  | PB         | 6.90                            | 44.59                               | −0.41           |
| SWIFT J1844.5−6221 | Hα  | PB         | 6.90                            | 44.15                               | −0.85           |
| SWIFT J2035.2+2604 | Hα  | CB         | 7.63                            | 44.67                               | −1.06           |
| SWIFT J2044.0+2832 | Hα  | PB         | 7.93                            | 44.93                               | −1.10           |
| SWIFT J2109.1−0942 | Hα  | PB         | 7.22                            | 44.40                               | −0.92           |
| SWIFT J2114.4+8206 | Hα  | E          | 9.13                            | 45.68                               | −1.55           |
| SWIFT J2118.9+3536 | Hα  | E          | 8.22                            | 44.77                               | −1.55           |
| SWIFT J2124.6+5057 | Hα  | E          | 6.80                            | 44.95                               | 0.05            |
| SWIFT J2156.1+4728 | Hα  | CB         | 7.58                            | 44.39                               | −1.29           |
| SWIFT J2210.7+2614 | Hα  | E          | 9.12                            | 45.41                               | −1.81           |

Col. (1): Source name. Col. (2): Line used to estimate BH mass. Col. (3): Bulge type: "E"=elliptical, "CB"=classical bulge, "PB"=pseudo-bulge. Col. (4): BH mass. Col. (5): Bolometric luminosity inferred from the intrinsic X-ray luminosity [Ricci et al. 2017]. Col. (6): Eddington ratio.
## Table 3

Photometric Properties of the Sample.

| Source Name | Nuclear | Bulge | Host |
|-------------|---------|-------|------|
|              | $M_I$ (mag) | $M_I$ (mag) | $n$ | $R_e$ (arcsec) | $(\mu_e)$ (mag arcsec$^{-2}$) | $M_I$ (mag) | $L_{bol}/L_{nuc}$ | $B/T$ |
|              | (1)      | (2)    | (3)  | (4)      | (5)                | (6)      | (7)       | (8) |
| SWIFT J0123.9−5846 | −21.68 | −22.00 ± 0.40 | 0.99 | 0.61 | 15.50 | −23.77 | 1.34 | 0.20 |
| SWIFT J0157.2+4715  | −19.42 | −21.13 ± 0.40 | 1.47 | 0.75 | 16.80 | −22.89 | 4.83 | 0.20 |
| SWIFT J0206.2−0019  | −19.53 | −23.90 ± 0.30 | 4(f) | 8.58 | 19.33 | −23.90 | 55.94 | 1.00 |
| SWIFT J0233.6−0648  | −21.70 | −21.78 ± 0.40 | 1.48 | 1.75 | 18.00 | −23.56 | 1.08 | 0.19 |
| SWIFT J0333.3+3720  | −21.68 | −23.02 ± 0.30 | 4(f) | 7.98 | 20.05 | −23.02 | 3.45 | 1.00 |
| SWIFT J0429.6−2114  | −21.72 | −23.62 ± 0.30 | 4(f) | 9.30 | 19.79 | −23.62 | 5.71 | 1.00 |
| SWIFT J0516.2−0009  | −19.54 | −20.96 ± 0.30 | 4(f) | 3.10 | 20.06 | −20.96 | 3.70 | 1.00 |
| SWIFT J0516.2−0009  | −22.21 | −22.96 ± 0.40 | 4(f) | 2.65 | 17.72 | −23.32 | 1.99 | 0.72 |
| SWIFT J0736.9+5846  | −21.01 | −19.90 ± 0.30 | 0.70 | 0.38 | 16.50 | −22.86 | 0.39 | 0.07 |
| SWIFT J0743.3−2546  | −19.34 | −20.11 ± 0.40 | 2.17 | 0.59 | 17.30 | −22.54 | 2.04 | 0.11 |
| SWIFT J0747.5+6057  | −18.67 | −20.77 ± 0.40 | 1.50 | 0.82 | 17.36 | −23.28 | 6.89 | 0.10 |
| SWIFT J0759.8−3844  | −21.43 | −21.83 ± 0.30 | 4(f) | 1.88 | 18.11 | −21.83 | 1.44 | 1.00 |
| SWIFT J0923.7+2255  | −19.45 | −20.91 ± 0.40 | 1.37 | 0.66 | 16.76 | −22.77 | 3.85 | 0.18 |
| SWIFT J0942.2+2344  | −18.45 | −19.74 ± 0.40 | 0.96 | 0.30 | 16.19 | −21.51 | 3.28 | 0.20 |
| SWIFT J1020.5−0237B | −19.76 | −21.13 ± 0.40 | 1.31 | 0.94 | 17.30 | −23.29 | 3.52 | 0.14 |
| SWIFT J1132.9+1019A | −18.77 | −21.37 ± 0.40 | 2.66 | 0.97 | 17.14 | −22.47 | 10.99 | 0.36 |
| SWIFT J1139.1+5913  | −21.69 | −20.90 ± 0.30 | 4(f) | 2.45 | 19.61 | −20.90 | 0.48 | 0.10 |
| SWIFT J1143.7+7942  | −16.62 | −18.42 ± 0.40 | 1.35 | 0.30 | 17.54 | −20.35 | 5.21 | 0.17 |
| SWIFT J1148.3+0901  | −20.36 | −20.97 ± 0.40 | 1.39 | 0.50 | 16.10 | −22.37 | 1.76 | 0.27 |
| SWIFT J1316.9−7155  | −21.98 | −23.19 ± 0.30 | 4(f) | 4.17 | 18.48 | −23.19 | 3.05 | 1.00 |
| SWIFT J1349.7+0209  | −19.08 | −20.54 ± 0.40 | 4(f) | 0.57 | 16.82 | −21.68 | 3.81 | 0.35 |
| SWIFT J1416.9−1158  | −22.94 | −23.69 ± 0.30 | 4(f) | 7.31 | 19.19 | −23.69 | 2.01 | 1.00 |
| SWIFT J1421.4+4747  | −22.34 | −21.89 ± 0.40 | 2.04 | 1.01 | 16.68 | −22.75 | 0.66 | 0.46 |
| SWIFT J1747.7−2253  | −20.84 | −22.72 ± 0.30 | 4(f) | 5.35 | 19.50 | −22.72 | 5.67 | 1.00 |
| SWIFT J1747.8+6837A | −19.95 | −20.21 ± 0.40 | 1.21 | 0.25 | 15.31 | −22.47 | 1.27 | 0.13 |
| SWIFT J1747.8+6837B | −21.71 | −21.63 ± 0.40 | 2.66 | 2.55 | 18.97 | −23.87 | 0.92 | 0.13 |
| SWIFT J1844.5−6221  | −18.99 | −19.71 ± 0.40 | 1.23 | 0.37 | 16.70 | −21.74 | 1.95 | 0.15 |
| SWIFT J2035.2+2604  | −19.56 | −21.78 ± 0.30 | 3.24 | 2.18 | 18.48 | −22.73 | 7.69 | 0.42 |
| SWIFT J2044.0+2832  | −21.95 | −20.81 ± 0.40 | 0.77 | 0.88 | 17.47 | −22.32 | 0.35 | 0.25 |
| SWIFT J2109.1−0942  | −20.69 | −21.22 ± 0.40 | 1.47 | 0.64 | 16.37 | −22.25 | 1.63 | 0.39 |
| SWIFT J2114.4+8206  | −23.23 | −23.57 ± 0.30 | 4(f) | 10.73 | 20.15 | −23.57 | 1.37 | 1.00 |
| SWIFT J2118.9+3336  | −18.40 | −23.67 ± 0.30 | 4(f) | 10.33 | 19.97 | −23.67 | 127.82 | 1.00 |
| SWIFT J2124.6+5057  | −20.96 | −21.33 ± 0.30 | 4(f) | 0.99 | 17.22 | −21.33 | 1.41 | 1.00 |
| SWIFT J2156.1+4728  | −19.26 | −20.29 ± 0.40 | 2.73 | 1.11 | 18.50 | −21.73 | 2.57 | 0.27 |
| SWIFT J2219.7+2614  | −21.45 | −24.07 ± 0.30 | 4(f) | 14.93 | 20.36 | −24.07 | 11.16 | 1.00 |

Col. (1): Source name. Col. (2): Absolute $I$-band luminosity of nucleus. Col. (3): Absolute $I$-band luminosity of bulge. Col. (4): Sérsic index of bulge; “f” implies that $n$ is fixed to 4. Col. (5): Effective radius of bulge. Col. (6): Mean surface brightness within the effective radius. Col. (7): Absolute $I$-band luminosity of host galaxy. Col. (8): The luminosity ratio of bulge to nucleus. Col. (9): Bulge-to-total light ratio.
Table 4

\( M_{\text{BH}} - M_{I, \text{bul}} \) Relation for Various Subsamples.

| Subsamples          | \( \alpha \) | \( \beta \) | \( \epsilon_0 \) |
|---------------------|--------------|--------------|-------------------|
| Inactive (All)      | \(-0.57\)    | \(-4.17 \pm 0.82\) | \(0.53 \pm 0.06\) |
| AGNs (All)          | \(-0.57\)    | \(-4.40 \pm 0.09\) | \(0.23 \pm 0.10\) |
| AGNs (All; \( \lambda_E \leq 0.06 \)) | \(-0.57\) | \(-4.19 \pm 0.10\) | \(0.11 \pm 0.11\) |
| AGNs (All; \( \lambda_E > 0.06 \)) | \(-0.57\) | \(-4.64 \pm 0.10\) | \(0.12 \pm 0.09\) |
| Inactive (E+CB)     | \(-0.49\)    | \(-2.22 \pm 0.62\) | \(0.31 \pm 0.03\) |
| AGNs (E+CB)         | \(-0.49\)    | \(-2.62 \pm 0.13\) | \(0.28 \pm 0.12\) |
| AGNs (E+CB; \( \lambda_E \leq 0.06 \)) | \(-0.49\) | \(-2.46 \pm 0.11\) | \(0.03 \pm 0.09\) |
| AGNs (E+CB; \( \lambda_E > 0.06 \)) | \(-0.49\) | \(-3.06 \pm 0.23\) | \(0.38 \pm 0.14\) |
| Inactive (PB)       | \(-0.49\)    | \(-2.92 \pm 0.14\) | \(0.62 \pm 0.14\) |
| AGNs (PB)           | \(-0.49\)    | \(-2.74 \pm 0.11\) | \(0.13 \pm 0.11\) |
| AGNs (PB; \( \lambda_E \leq 0.06 \)) | \(-0.49\) | \(-2.20 \pm 0.10\) | \(0.00 \pm 0.00\) |
| AGNs (PB; \( \lambda_E > 0.06 \)) | \(-0.49\) | \(-2.92 \pm 0.10\) | \(0.00 \pm 0.06\) |

Col. (1): Subsample. Col. (2): Slope. Col. (3): Zero point. Col. (4): Intrinsic scatter.

Table 5

Kormendy Relation for Various Subsamples.

| Subsamples          | \( \kappa \) | \( \gamma \) |
|---------------------|--------------|--------------|
| Inactive (E) [G]    | \(2.38 \pm 0.07\) | \(17.16\) |
| Inactive (E+CB)     | \(2.53 \pm 0.06\) | \(17.66\) |
| Inactive (PB)       | \(3.94 \pm 0.29\) | \(18.94\) |
| AGNs (All)          | \(2.56 \pm 0.20\) | \(17.44\) |
| AGNs (E+CB)         | \(2.47 \pm 0.33\) | \(17.51\) |
| AGNs (E+CB; \( \lambda_E \leq 0.06 \)) | \(2.51 \pm 0.40\) | \(17.43\) |
| AGNs (E+CB; \( \lambda_E > 0.06 \)) | \(2.57 \pm 0.91\) | \(17.60\) |
| AGNs (PB)           | \(2.52 \pm 0.61\) | \(17.40\) |
| AGNs (PB; \( \lambda_E \leq 0.06 \)) | \(2.67 \pm 0.71\) | \(17.31\) |
| AGNs (PB; \( \lambda_E > 0.06 \)) | \(2.53 \pm 0.81\) | \(17.44\) |

Col. (1): Subsample; “[G]” denotes that the subsample comes from [Gao et al. 2020]. Col. (2): Slope. Col. (3): Zero point.
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Figure 3. Relations between BH mass ($M_{\text{BH}}$) and absolute $I$-band bulge magnitude ($M_{I,\text{bul}}$) for type 1 AGNs. In all panels, shaded line denotes the relation of inactive galaxies from Kormendy & Ho (2013). (a) Filled circles and the dashed line denote type 1 AGNs and their relation. (b) Open circles (filled triangles) and solid line (dashed line) represent AGNs with low (high) Eddington ratio and their relation, respectively. (c) The sample is divided into two subgroups according to bulge types. Blue shaded (red shaded) line denotes the relation of pseudo-bulges (ellipticals and classical bulges) in inactive galaxies. Red (blue) circles and dashed line denotes AGNs with ellipticals and classical bulges (pseudo-bulges) and their relation, respectively. (d) Red (blue) circles and solid line denote ellipticals and classical bulges (pseudo-bulges) with low Eddington ratio in our sample and their relation, respectively. Red (blue) triangles and dotted line denote ellipticals and classical bulges (pseudo-bulges) with high Eddington ratio in our sample and their relation, respectively.
Figure 4. Relation between effective radius ($R_e$) and mean surface brightness ($\langle \mu_e \rangle$) within $R_e$ for type 1 AGNs. The sample is divided into two subsamples according to bulge types (left) and four subgroups according to bulge types and Eddington ratio (right). For both panels, red (blue) symbols and lines denote ellipticals and classical bulges (pseudo-bulges). Kormendy relations for inactive galaxies adapted from Kim & Ho (2019) are shown by thick shaded lines. Kormendy relation for elliptical galaxies from Gao et al. (2020) is denoted by thick red dashed line. In the left panel, red and blue dashed lines represent the Kormendy relations for AGNs with ellipticals and classical bulges and those with pseudo-bulges, respectively. In the right panel, AGNs with low (high) Eddington ratio and their Kormendy relation are denoted by open circles (filled triangles) and solid (dotted) lines, respectively.

Figure 5. Comparison of Eddington ratio ($\lambda_E$) with BH mass offset ($\Delta \log M_{\text{BH}}$) from the $M_{\text{BH}}$–$M_{\text{I,bul}}$ relation of inactive galaxies. BH mass offset of type 1 AGNs is calculated by subtracting the virial BH mass estimates from that inferred from the $M_{\text{BH}}$–$M_{\text{I,bul}}$ relation of inactive galaxies at a given bulge luminosity. Type 1 AGNs hosted by ellipticals and classical bulges are plotted as filled red circles, while those hosted by pseudo-bulges are plotted as filled blue circles.