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# Supermassive black hole masses of AGNs with elliptical hosts

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**Abstract.** The recently discovered tight correlation between supermassive black hole mass and central velocity dispersion for both inactive and active galaxies suggests a possibility to estimate the black hole mass from the measured central velocity dispersion. However, for most AGNs it is difficult to measure the central velocity dispersions of their host galaxies directly with spectroscopic studies. In this paper we adopt the fundamental plane for ellipticals to estimate the central velocity dispersion and black hole mass for a number of AGNs with morphology parameters of their elliptical host galaxies obtained by the *Hubble Space Telescope* imaging observations. The estimated black hole masses of 63 BL Lac objects, 10 radio galaxies, 10 radio-loud quasars and 9 radio-quiet quasars are mostly in the range of $10^{7.5}$ $M_{\odot}$ to $10^9$ $M_{\odot}$. No significant difference in black hole mass is found for high-frequency peaked BL Lacs and low-frequency peaked BL Lacs, as well as for radio galaxies and radio-loud quasars. The Eddington ratios of radio galaxies are substantially smaller than those of quasars. This suggests that the different observational features of these radio-loud AGNs may be mainly dominated by different accretion rate rather than by the black hole mass, which is in agreement with some evolutionary scenarios recently proposed for radio-loud AGNs. Different to some previous claims, we found that the derived mean black hole mass for radio-loud quasars is only slightly larger than that of radio-quiet quasars. Though the black hole mass distributions between radio-loud and radio-quiet quasars are statistically different, their Eddington ratio distributions are probably from the same population. In addition, we noted that the relation between black hole mass and host galaxy luminosity we obtained using the fundamental plane provides further arguments for a nonlinear scaling law between supermassive black hole mass and galactic bulge mass.

**Key words.** black hole physics – BL Lacertae objects: general – galaxies: active – galaxies: nuclei – quasars: general

## 1. Introduction

The masses of central black holes ($M_{\rm BH}$) in about 40 nearby galaxies have been recently obtained using the stellar and gas dynamic methods by the *Hubble Space Telescope* (HST) (for a recent review see Kormendy & Gebhardt 2001). A tight correlation between black hole mass and bulge velocity dispersion ($\sigma$) has been found for nearby galaxies (Gebhardt et al. 2000a; Ferrarese & Merritt 2000). With the reverberation mapping technique (Netzer & Peterson 1997), the supermassive black hole (SMBH) masses of about 20 Seyfert 1 galaxies (Wandel et al. 1999; Ho 1999) and 20 nearby quasars (Kaspi et al. 2000) were estimated based on a virial assumption about the dynamics of the broad line region of Active Galactic Nuclei (AGNs). Interestingly, the black hole masses derived for a few Seyfert galaxies with measured central velocity dispersions of their host galaxies follow the same $M_{\rm BH}$-$\sigma$ relation as nearby galaxies (Gebhardt et al. 2000b; Ferrarese et al. 2001). This indicates that the $M_{\rm BH}$-$\sigma$ relation is probably universal for both active and inactive galaxies. The small scatters of this relation also imply that it may be more fundamental than the relation between black hole mass and bulge luminosity (Magorrian et al. 1998). The close correlation between black hole mass and bulge properties has important implications for the formation and evolution of SMBHs and galaxies.

On the other hand, the tight $M_{\rm BH}$-$\sigma$ relation suggests an interesting possibility to estimate the central black hole masses for galaxies using the measured values of bulge velocity dispersions. This straightforward method is particularly important for AGNs because the dynamical method cannot be applied for the determination of the black hole mass for most of them. For some AGNs, especially BL Lacertae objects, the reverberation mapping technique cannot be applied because they have no or only

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very weak emission lines in their optical spectra. However, AGNs usually have very bright nuclear emission, which makes it very difficult to measure their stellar velocity dispersions with the spectroscopic method. So far, stellar velocity dispersions have been obtained only for some nearby Seyfert galaxies (Nelson & Whittle 1995; Ferrarese et al. 2001) and recently for a few nearby BL Lac objects (Barth et al. 2002; Falomo et al. 2002). For most AGNs, one has to look for other methods to determine the central velocity dispersions of their host galaxies in order to use the $M_{\rm BH}$-$\sigma$ relation to estimate the SMBH mass.

Imaging studies on the host galaxies of AGNs with HST have clearly revealed that a lot of AGNs, including almost all BL Lac objects, radio galaxies, radio-loud quasars, and some radio-quiet quasars, have massive elliptical hosts (Urry et al. 2000; McLure et al. 1999; Dunlop et al. 2002). It is well known for ellipticals that three observables, the effective radius, the corresponding average surface brightness and the central velocity dispersion, follow a surprisingly tight linear relation (so-called fundamental plane, see Djorgovski & Davis 1987; Dressler et al. 1987; Faber et al. 1989). Some subsequent studies have shown that the elliptical hosts of radio galaxies follow the same fundamental plane as normal ellipticals (Bettoni et al. 2001). Because the fundamental plane is probably universal and exists also for elliptical hosts of AGNs, it is possible to estimate the central velocity dispersions from the morphology parameters of the host galaxies (McLure & Dunlop 2001). This provides another possible way to derive the SMBH masses of AGNs for which high quality images of their host galaxies have been obtained.

In this paper we adopt the fundamental plane to estimate the central velocity dispersions and SMBH masses for some AGNs which have been imaged by HST. In Sect. 2 we introduce the fundamental plane for AGN elliptical hosts. The SMBH masses of these AGNs are derived in Sect. 3. In Sect. 4 the physics nature of these AGNs are briefly discussed based on our results.

## 2. Fundamental plane of elliptical galaxies

The fundamental plane of ellipticals has been extensively studied and well established with the ground based observations (Djorgovski & Davis 1987; Dressler et al. 1987; Faber et al. 1989; Jorgensen et al. 1996). Such a plane has been shown to be close to the plane defining the viral equilibrium if a rigorous homology among galaxies is assumed (Faber et al. 1989). Imaging studies on the host elliptical galaxies of low redshift radio galaxies found a similar fundamental plane as for inactive elliptical galaxies (Bettoni et al. 2001), with radio galaxies representing the brightest end of the population of early type galaxies. This also implies that the global properties of early-type galaxies are not influenced by the gas accretion process around the central black hole. It is therefore quite likely that not only radio galaxies but also other AGNs with elliptical host galaxies follow the similar fundamental plane as normal ellipticals.

Using the observational data of about 300 normal ellipticals and radio galaxies, Bettoni et al. (2001) found that the fundamental plane can be robustly described as

$$\begin{aligned}\log R_{\rm e} \;=\; & (1.27 \pm 0.04) \log \sigma \\ & +(0.326 \pm 0.007) < \mu_{\rm e} >_R -8.56 \pm 0.06, \qquad (1)\end{aligned}$$

where $R_{\rm e}$ is the effective radius in kpc, $\sigma$ is the central velocity dispersion in $\mathrm{km\,s^{-1}}$, and $< \mu_{\rm e} >_R$ is the average surface brightness in $R$-band. If we assume that all AGNs with elliptical hosts follow this fundamental plane, we can estimate their central velocity dispersions based on the morphology parameters, $R_{\rm e}$ and $< \mu_{\rm e} >_R$, which can be derived from high quality imaging studies of their host galaxies.

## 3. Black hole masses of AGNs

In this section we will adopt the fundamental plane and the $M_{\rm BH}$-$\sigma$ relation to estimate the SMBH masses of some BL Lac objects, radio galaxies and quasars that have been imaged by the HST recently. The higher spatial resolution of HST can provide high quality images of the host galaxies of AGNs, which enables us to reliably derive the morphology parameters.

### *3.1. BL Lac objects*

The BL Lac snapshot survey using the HST WFPC2 camera has obtained images for 110 BL Lac objects in a well selected sample (Scarpa et al. 1999). By fitting the surface brightness profiles using the de Vaucouleurs model, Urry et al. (2001) has obtained host galaxy parameters for 72 BL Lac objects. They showed that these detected hosts are very luminous, round galaxies with a median absolute magnitude of $< M_R >= -23.7$ mag and a median effective radius of $< R_{\rm e} >= 8.5$ kpc (we used $H_0 = 50\ \mathrm{km\,s^{-1}\ Mpc^{-1}}$ and $q_0 = 0$ throughout the paper). Among these BL Lacs, 63 objects have measured redshifts. 51 of them are classified as high-frequency peaked BL Lacs (HBL) and 12 of them as low-frequency peaked BL Lacs (LBL). The morphology parameters of their elliptical hosts, including the angular effective radius $r_{\rm e}$, corresponding surface brightness $\mu_{\rm e}$ and absolute $R$ magnitude $M_R$, have been reported in Urry et al. (2001). It has been shown that the $\mu_{\rm e}$–$r_{\rm e}$ relation for the elliptical hosts of these BL Lac objects is almost the same as normal elliptical galaxies. This strongly suggests that the fundamental plane of normal ellipticals exists also for the host galaxies of BL Lac objects. Urry et al. (2001) also mentioned that there are no systematic differences in the host galaxies of HBLs and LBLs.

In Table 1 we listed 63 BL Lac objects, together with their redshifts, $R$-band apparent and absolute magnitudes, effective radius and average surface brightness of their host galaxies. The values for redshifts, $R$-band absolute magnitudes, and effective radii are taken from Urry et al. (2001). The $R$-band apparent magnitudes have been corrected for Galactic extinction, cosmological dimming and

**Table 1.** Sample of BL Lac objects.

| Name | $z$ | $R$ (mag) | $M_R$ (mag) | $r_{\rm e}$ (arcsec) | $R_{\rm e}$ (kpc) | $< \mu_{\rm e} >$ ($R$ mag arcsec$^{-2}$) | log $\sigma$ (km s$^{-1}$) | log $M_{\rm BH}^{\rm MF01}$ ($M_\odot$) | log $M_{\rm BH}^{\rm G00}$ ($M_\odot$) |
|---|---|---|---|---|---|---|---|---|---|
| HBL | | | | | | | | | |
| 0122+0908 | 0.339 | 17.5 | −23.75 | 1.05 | 6.75 | 19.6 | 2.36 | 8.40 | 8.31 |
| 0145+1388 | 0.124 | 16.5 | −22.74 | 1.75 | 5.31 | 19.71 | 2.25 | 7.88 | 7.89 |
| 0158+0018 | 0.229 | 17.43 | −23.05 | 1.9 | 9.34 | 20.82 | 2.15 | 7.44 | 7.54 |
| 0229+2008 | 0.139 | 14.87 | −24.61 | 3.25 | 10.83 | 19.42 | 2.56 | 9.38 | 9.08 |
| 0257+3428 | 0.247 | 16.58 | −24.05 | 1.75 | 9.08 | 19.79 | 2.41 | 8.64 | 8.50 |
| 0317+1838 | 0.19 | 16.39 | −23.71 | 3.25 | 13.89 | 20.95 | 2.26 | 7.93 | 7.93 |
| 0331-3628 | 0.308 | 16.74 | −24.33 | 3.1 | 18.73 | 21.19 | 2.30 | 8.12 | 8.08 |
| 0347-1218 | 0.188 | 16.89 | −23.2 | 1.25 | 5.3 | 19.37 | 2.33 | 8.29 | 8.22 |
| 0350-3718 | 0.165 | 16.47 | −23.35 | 1.7 | 6.51 | 19.62 | 2.34 | 8.32 | 8.24 |
| 0414+0098 | 0.287 | 16.07 | −24.85 | 4.7 | 27.09 | 21.43 | 2.36 | 8.43 | 8.33 |
| 0419+1948 | 0.512 | 18.03 | −24.01 | 0.4 | 3.27 | 18.04 | 2.51 | 9.12 | 8.88 |
| 0502+6758 | 0.314 | 17.22 | −23.88 | 0.6 | 3.67 | 18.1 | 2.53 | 9.23 | 8.96 |
| 0506-0398 | 0.304 | 17.21 | −23.78 | 1.6 | 9.57 | 20.23 | 2.32 | 8.20 | 8.14 |
| 0525+7138 | 0.249 | 16.17 | −24.48 | 1.98 | 10.34 | 19.65 | 2.49 | 9.03 | 8.81 |
| 0548-3228 | 0.069 | 14.31 | −23.71 | 7.05 | 12.81 | 20.54 | 2.33 | 8.29 | 8.22 |
| 0607+7108 | 0.267 | 16.46 | −24.34 | 2.4 | 13.16 | 20.35 | 2.39 | 8.56 | 8.43 |
| 0706+5918 | 0.125 | 15.22 | −24.03 | 3.05 | 9.31 | 19.64 | 2.46 | 8.87 | 8.68 |
| 0737+7448 | 0.315 | 16.79 | −24.32 | 2.1 | 12.88 | 20.39 | 2.38 | 8.48 | 8.37 |
| 0806+5248 | 0.138 | 15.93 | −23.53 | 1.45 | 4.8 | 18.73 | 2.46 | 8.90 | 8.70 |
| 0922+7498 | 0.638 | 17.82 | −24.64 | 0.85 | 7.76 | 19.46 | 2.44 | 8.79 | 8.62 |
| 0927+5008 | 0.188 | 16.95 | −23.14 | 2 | 8.48 | 20.45 | 2.22 | 7.74 | 7.78 |
| 0958+2108 | 0.344 | 17.65 | −23.62 | 0.82 | 5.32 | 19.21 | 2.38 | 8.48 | 8.37 |
| 1011+4968 | 0.2 | 16.61 | −23.6 | 1.8 | 8 | 19.89 | 2.34 | 8.32 | 8.25 |
| 1028+5118 | 0.361 | 17.31 | −24.07 | 1.8 | 12.05 | 20.58 | 2.30 | 8.14 | 8.10 |
| 1104+3848 | 0.031 | 13.1 | −23.21 | 3.95 | 3.4 | 18.08 | 2.51 | 9.13 | 8.88 |
| 1133+1618 | 0.46 | 18.08 | −23.76 | 1.55 | 11.97 | 21.03 | 2.19 | 7.59 | 7.67 |
| 1136+7048 | 0.045 | 14.22 | −22.9 | 3.1 | 3.8 | 18.68 | 2.40 | 8.59 | 8.46 |
| 1207+3948 | 0.615 | 17.98 | −24.4 | 1.2 | 10.76 | 20.37 | 2.32 | 8.22 | 8.16 |
| 1212+0788 | 0.136 | 15.5 | −23.93 | 3.4 | 11.13 | 20.16 | 2.39 | 8.53 | 8.41 |
| 1215+3038 | 0.13 | 15.52 | −23.8 | 8.35 | 26.34 | 22.13 | 2.17 | 7.53 | 7.62 |
| 1218+3048 | 0.182 | 16.46 | −23.56 | 2.6 | 10.75 | 20.53 | 2.28 | 8.02 | 8.01 |
| 1221+2458 | 0.218 | 17.89 | −22.49 | 1.25 | 5.93 | 20.37 | 2.12 | 7.25 | 7.39 |
| 1229+6438 | 0.164 | 15.74 | −24.07 | 2 | 7.62 | 19.24 | 2.49 | 9.03 | 8.80 |
| 1248-2968 | 0.37 | 17.28 | −24.14 | 1.1 | 7.47 | 19.48 | 2.42 | 8.71 | 8.55 |
| 1255+2448 | 0.141 | 16.18 | −23.32 | 2.5 | 8.43 | 20.17 | 2.29 | 8.07 | 8.04 |
| 1407+5958 | 0.495 | 17.2 | −24.78 | 1.75 | 14.06 | 20.41 | 2.40 | 8.60 | 8.47 |
| 1426+4288 | 0.129 | 15.64 | −23.68 | 2.25 | 7.05 | 19.39 | 2.43 | 8.72 | 8.56 |
| 1440+1228 | 0.162 | 16.11 | −23.68 | 3.9 | 14.71 | 21.06 | 2.25 | 7.88 | 7.89 |
| 1458+2248 | 0.235 | 16.84 | −23.69 | 3.2 | 16.03 | 21.36 | 2.20 | 7.66 | 7.7 |
| 1514-2418 | 0.049 | 13.76 | −23.54 | 3.7 | 4.91 | 18.59 | 2.51 | 9.10 | 8.86 |
| 1534+0148 | 0.312 | 16.89 | −24.21 | 2 | 12.19 | 20.39 | 2.36 | 8.39 | 8.30 |
| 1704+6048 | 0.28 | 17.69 | −23.2 | 0.85 | 4.82 | 19.34 | 2.31 | 8.17 | 8.12 |
| 1728+5028 | 0.055 | 15.15 | −22.38 | 3.15 | 4.65 | 19.64 | 2.22 | 7.75 | 7.79 |
| 1757+7038 | 0.407 | 17.97 | −23.63 | 0.85 | 6.12 | 19.61 | 2.32 | 8.23 | 8.17 |
| 1853+6718 | 0.212 | 17.17 | −23.16 | 1.5 | 6.96 | 20.05 | 2.25 | 7.90 | 7.91 |
| 1959+6508 | 0.048 | 14.13 | −23.12 | 5.1 | 6.64 | 19.66 | 2.34 | 8.30 | 8.22 |
| 2005-4898 | 0.071 | 14.22 | −23.86 | 5.65 | 10.53 | 19.98 | 2.41 | 8.66 | 8.51 |
| 2143+0708 | 0.237 | 16.87 | −23.68 | 2.1 | 10.58 | 20.47 | 2.29 | 8.06 | 8.04 |
| 2326+1748 | 0.213 | 16.67 | −23.67 | 1.8 | 8.39 | 19.94 | 2.34 | 8.33 | 8.25 |
| 2344+5148 | 0.044 | 12.89 | −24.19 | 5.93 | 7.12 | 18.75 | 2.59 | 9.52 | 9.19 |
| 2356-3098 | 0.165 | 16.6 | −23.22 | 1.85 | 7.08 | 19.93 | 2.29 | 8.07 | 8.05 |
| LBL | | | | | | | | | |
| 0521-3658 | 0.055 | 14.23 | −23.3 | 2.8 | 4.14 | 18.46 | 2.48 | 8.98 | 8.77 |
| 0828+4938 | 0.548 | 18.03 | −24.14 | 0.65 | 5.51 | 19.09 | 2.42 | 8.69 | 8.53 |

**Table 1.** continued.

| Name | $z$ | $R$ (mag) | $M_R$ (mag) | $r_{\rm e}$ (arcsec) | $R_{\rm e}$ (kpc) | $<\mu_{\rm e}>$ ($R$ mag arcsec$^{-2}$) | log $\sigma$ (km s$^{-1}$) | log $M_{\rm BH}^{\rm MF01}$ ($M_\odot$) | log $M_{\rm BH}^{\rm G00}$ ($M_\odot$) |
|---|---|---|---|---|---|---|---|---|---|
| 0829+0468 | 0.18 | 16.18 | −23.82 | 4.3 | 17.63 | 21.34 | 2.24 | 7.83 | 7.86 |
| 1418+5468 | 0.152 | 15.56 | −24.09 | 3.65 | 13.08 | 20.37 | 2.39 | 8.53 | 8.41 |
| 1538+1498 | 0.605 | 17.7 | −24.64 | 2.5 | 22.25 | 21.69 | 2.23 | 7.79 | 7.82 |
| 1749+0968 | 0.32 | 17.55 | −23.6 | 3 | 18.59 | 21.93 | 2.11 | 7.21 | 7.36 |
| 1807+6988 | 0.051 | 13.43 | −23.95 | 2.1 | 2.89 | 17.04 | 2.72 | 10.14 | 9.68 |
| 1823+5688 | 0.664 | 17.46 | −25.07 | 0.6 | 5.57 | 18.35 | 2.61 | 9.60 | 9.26 |
| 2007+7778 | 0.342 | 17.38 | −23.89 | 3.3 | 21.35 | 21.97 | 2.14 | 7.39 | 7.50 |
| 2200+4208 | 0.069 | 14.41 | −23.61 | 4.8 | 8.72 | 19.81 | 2.39 | 8.56 | 8.43 |
| 2201+0448 | 0.027 | 13.44 | −22.57 | 6.78 | 5.12 | 19.59 | 2.26 | 7.96 | 7.95 |
| 2254+0748 | 0.19 | 15.69 | −24.41 | 4.9 | 20.94 | 21.14 | 2.35 | 8.36 | 8.27 |

$K$-corrections. The average surface brightness was derived from the formula:

$$<\mu_{\rm e}>_R \; = R + 5\log r_{\rm e} + 2.5\log(2\pi) \qquad (2)$$

where the effective radius $r_{\rm e}$ is in unit of arcseconds. We can then estimate the central velocity dispersions for the hosts of BL Lac objects using the fundamental plane (Eq. (1)). The SMBH masses of these objects can be derived by the $M_{\rm BH}$-$\sigma$ relation. Such a relation has been given as

$$M_{\rm BH} = 1.3\times10^8\ M_\odot(\sigma/200\ {\rm km\,s^{-1}})^{4.72} \qquad (3)$$

by Merritt & Ferrarese (2001, hereafter MF01) and as

$$M_{\rm BH} = 1.2\times10^8\,M_\odot(\sigma/200\,{\rm km\,s^{-1}})^{3.75} \qquad (4)$$

by Gebhardt et al. (2000a, hearafter G00). Note that the derived central velocity dispersion using Eq. (1) is in an aperture of diameter of 1.19 $h^{-1}$ kpc ($h = 0.5$ in this paper), while the luminosity-weighted average velocity dispersion in G00 relation is in the half-light radius ($r_{\rm e}$) and the "central" velocity dispersion in MF01 relation in an aperture of radius $r_{\rm e}/8$. There is a systematic difference among these velocity dispersions. However, as demonstrated in G00, MF01 and Barth et al. (2002), such a difference is remarkably less significant when $r \leq r_{\rm e}$. In fact, if we follow the aperture correction method suggested by Jorgensen et al. (1995), we can estimate the difference of these velocity dispersions to be as small as several percent. Therefore, we ignore such a difference in our present work. In Table 1 we give the derived central velocity dispersions and black hole masses using the above relations for 63 BL Lacs.

Figure 1 shows the relation of derived central velocity dispersions and black hole masses with $R$-band absolute magnitudes of the host galaxies of BL Lac objects. Figure 2 shows the histograms of the derived black hole masses (according to the G00 relation) for HBLs and LBLs. It is clear that there is no significant difference in the central velocity dispersions and the black hole masses between HBLs and LBLs. The average black hole masses of both HBLs and LBLs are around $2\times10^8\ M_\odot$. Most BL Lacs have black hole masses in the range of $10^{7.5}\ M_\odot$ to $10^{9.5}\ M_\odot$. A $t$-test gives a significance of 81% that the distributions of SMBH masses of HBLs and LBLs are from the population with the same true variance. Considering the substantial uncertainties in deriving the $R$-band absolute magnitude and central velocity dispersions of host galaxies, we adopt the ordinary least square (OLR) bisector method (Isobe et al. 1990) to fit the relations shown in Fig. 1, which gives: $\log\sigma = -4.49\pm1.30-(0.29\pm0.05)M_R$, $\log M_{\rm BH}^{\rm MF01} = -15.83\pm2.08-(1.01\pm0.08)M_R$, and $\log M_{\rm BH}^{\rm G00} = -12.18\pm1.95-(0.86\pm0.08)M_R$. We noted that the $M_{\rm BH}$-bulge luminosity relation we obtained here is consistent with that found previously for normal galaxies and AGNs (Laor 2001; Wu & Han 2001).

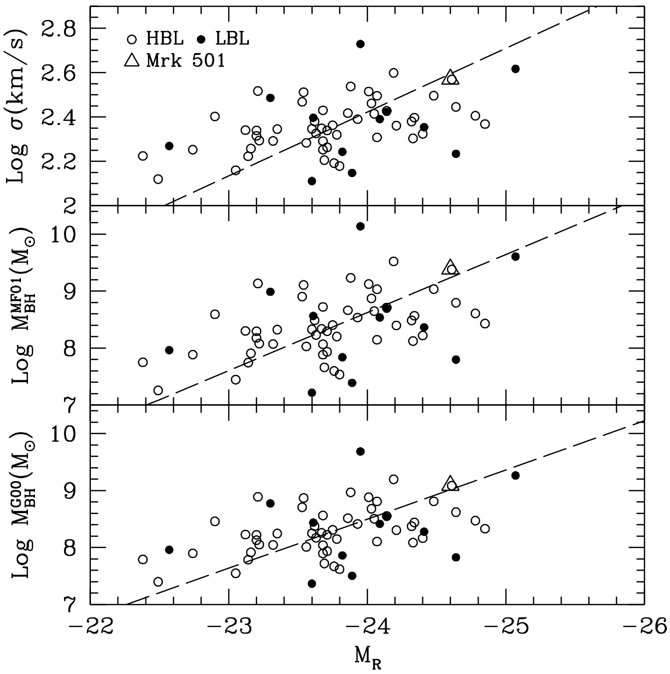

**Fig. 1.** The derived central velocity dispersion, black hole mass (using both MF01 and G00 relations) for BL Lac objects against the $R$-band absolute magnitude of the host galaxies. The open and solid circles correspond to HBLs and LBLs. The dashed line shows the OLS bisector fit to each relation. The open triangle represents the data for Mrk 501.

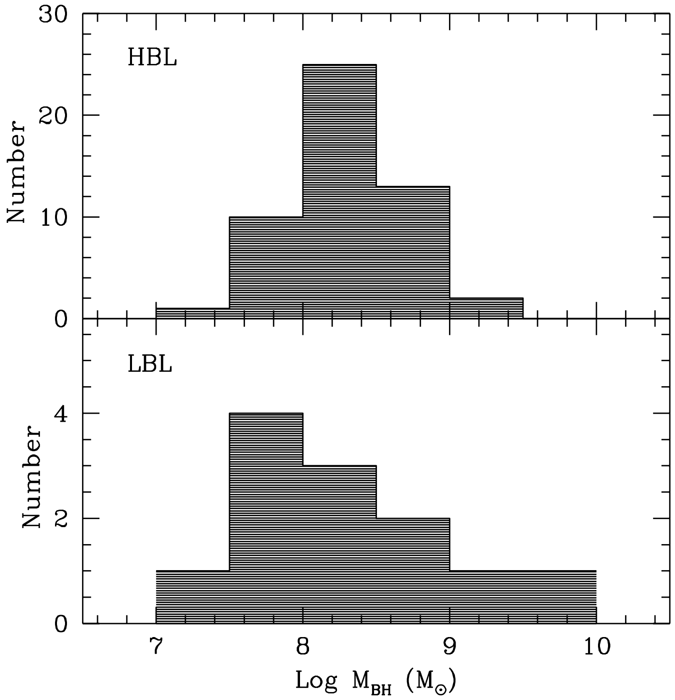

**Fig. 2.** Histogram of the derived black hole mass distribution of HBLs and LBLs using the G00 relation.

Recently Barth et al. (2002) measured the calcium triplet lines in the spectra of a nearby bright BL Lac object Mrk 501 taken with the Palomar Hale 200-inch telescope and derived the stellar velocity dispersion of the host galaxy as $372 \pm 18$ km s$^{-1}$. The $R$-band absolute magnitude of the host galaxy has been estimated to be $-24.6$ (Nilsson et al. 1999). From Fig. 1 we can see the observational data of Mrk 501 are well in agreement with the relation that we found for other BL Lac objects. Therefore we think it is quite possible that Mrk 501 hosts a supermassive black hole with mass of about $(1{\sim}3)\times 10^9\ M_\odot$. We note that this is much larger than the maximum primary black hole mass ($10^8\ M_\odot$) required for the binary black hole model of Mrk 501 (Rieger & Mannheim 2000) and the mass ($\sim 10^7\ M_\odot$) estimated from the $\gamma$-ray variability timescale (Fan et al. 1999).

We note that there are significant uncertainties in our derived velocity dispersions and SMBH masses, which are caused by the systematic errors of fundamental plane relation (Eq. (1)), the measurement uncertainties of $<\mu_{\rm e}>_R$ and $R_{\rm e}$, and the scatters of the $M_{\rm BH}$-$\sigma$ relation. Considering the typical uncertainties of $<\mu_{\rm e}>_R$ (about 0.5 $R$ mag arcsec$^{-2}$) and $R_{\rm e}$ (about 1 kpc), Eq. (1) gives an uncertainty $\Delta\sigma/\sigma$ as large as of about 50%. This leads to an uncertainty $\Delta M_{\rm BH}/M_{\rm BH}$ of about 2. Such a significant uncertainty of the derived SMBH masses should be kept in mind when these values are adopted in any correlation studies.

### *3.2. Radio galaxies, radio-loud and radio-quiet quasars*

A deep HST imaging study of the host galaxies of a sample of 10 radio galaxies (RGs), 10 radio-loud quasars (RLQs) and 13 radio-quiet quasars (RQQs) has been performed recently (McLure et al. 1999; Dunlop et al. 2002). It has been found that the hosts of both radio-loud AGNs and bright radio-quiet AGNs are virtually all massive ellipticals. The basic properties of these host galaxies are indistinguishable from those of normal ellipticals. Therefore, it is quite possible that the host galaxies of these low redshift AGNs also follow the same fundamental plane as normal ellipticals. Using the same approach as we did for BL Lac objects, we can also derive the central velocity dispersions and black hole masses for this sample of AGNs based on the morphology parameters of their host galaxies.

Table 2 listed the name, redshift, $R$-band apparent magnitude and absolute magnitude, effective radius and average surface brightness of 10 RGs, 10 RLQs and 9 RQQs with elliptical hosts (Dunlop et al. 2002). The $R$-band apparent magnitudes of the host galaxies have been corrected for the Galactic extinctions (taken from NED[1]), cosmological dimming and K-corrections (assuming spectra index of $\alpha = 1.5$, Dunlop et al. 2002). The angular size of effective radius was derived using Eq. (9.94) in Peterson (1997) from $R_{\rm e}$ listed in Dunlop et al. (2002) (where they adopted $q_0 = 0.5$):

$$r_{\rm e}('') = \frac{0.0688 h_0 q_0^2 (1+z)^2}{z q_0 + (q_0 - 1)(-1 + \sqrt{2 q_0 z + 1})} R_{\rm e}({\rm kpc}). \qquad (5)$$

The $R$-band absolute magnitudes of the host galaxies were also calibrated to the case of $q_0 = 0$. The average surface brightness was calculated using Eq. (2) for each objects. With these parameters, the central velocity dispersions of the host galaxies of 29 AGNs can be estimated using Eq. (1), and their SMBH masses can be derived using Eqs. (3) and (4). The results are listed in Table 2.

Figure 3 shows the relation of derived central velocity dispersions and black hole masses with $R$-band absolute magnitudes of the host galaxies for 10 RGs, 10 RLQs and 9 RQQs. Figure 4 shows the histograms of the derived black hole masses (according to the G00 relation) for these AGNs. It is clear that there are no significant differences in the central velocity dispersions and SMBH masses among RGs, RLQs and RQQs. The average SMBH masses of RGs, RLQs and RQQs are $10^{8.13}\ M_\odot$, $10^{8.22}\ M_\odot$ and $10^{7.90}\ M_\odot$ respectively. Most of these AGNs have black hole masses in the range of $10^{7.5}\ M_\odot$ to $10^9\ M_\odot$. Our results indicate that there is no difference in SMBH masses of BL Lacs, RGs and RLQs. A $t$-test shows a possibility of 44% that the distributions of SMBH masses of RGs and RLQs are from the same population. Different from some previous claims that RLQs have more massive SMBHs than RQQs (Laor 2000), our result shows that there is only a weak difference in our derived SMBH masses for RQQs and RLQs in this sample. The mean SMBH mass

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[1] `http://nedwww.ipac.caltech.edu`

**Table 2.** Sample of radio galaxies, radio-loud and radio quiet quasars.

| Name | $z$ | $R$ (mag) | $M_R$ (mag) | $r_{\rm e}$ (arcsec) | $R_{\rm e}$ (kpc) | $<\mu_{\rm e}>$ ($R$ mag arcsec$^{-2}$) | log $\sigma$ (km s$^{-1}$) | log $M_{\rm BH}^{\rm MF01}$ ($M_{\odot}$) | log $M_{\rm BH}^{\rm G00}$ ($M_{\odot}$) |
|---|---|---|---|---|---|---|---|---|---|
| RG | | | | | | | | | |
| 0230-027 | 0.239 | 16.84 | −23.67 | 1.61 | 7.7 | 19.88 | 2.33 | 8.27 | 8.20 |
| 0307+169 | 0.256 | 16.24 | −24.09 | 1.88 | 9.4 | 19.61 | 2.47 | 8.91 | 8.71 |
| 0345+337 | 0.244 | 16.85 | −23.17 | 2.71 | 13.1 | 21.01 | 2.22 | 7.75 | 7.79 |
| 0917+459 | 0.174 | 15.63 | −24.29 | 5.73 | 21.9 | 21.42 | 2.29 | 8.10 | 8.06 |
| 0958+291 | 0.185 | 16.59 | −23.45 | 2.12 | 8.5 | 20.22 | 2.28 | 8.01 | 8.00 |
| 1215-033 | 0.184 | 16.55 | −22.94 | 2.13 | 8.5 | 20.19 | 2.28 | 8.05 | 8.03 |
| 1215+013 | 0.118 | 16.14 | −23.35 | 1.66 | 4.7 | 19.25 | 2.329 | 8.24 | 8.18 |
| 1330+022 | 0.215 | 16.5 | −23.81 | 3.53 | 15.7 | 21.24 | 2.22 | 7.77 | 7.80 |
| 1342-016 | 0.167 | 15.06 | −24.67 | 6.29 | 23.3 | 21.05 | 2.41 | 8.64 | 8.49 |
| 2141+279 | 0.215 | 15.93 | −24.20 | 5.58 | 24.8 | 21.66 | 2.27 | 8.00 | 7.99 |
| RLQ | | | | | | | | | |
| 0137+012 | 0.258 | 16.49 | −24.17 | 2.83 | 14.2 | 20.75 | 2.32 | 8.21 | 8.15 |
| 0736+017 | 0.191 | 16.11 | −23.68 | 3.25 | 13.3 | 20.67 | 2.31 | 8.19 | 8.14 |
| 1004+130 | 0.24 | 16.21 | −24.22 | 1.71 | 8.2 | 19.38 | 2.48 | 8.98 | 8.76 |
| 1020-103 | 0.197 | 16.59 | −23.46 | 1.70 | 7.1 | 19.74 | 2.34 | 8.31 | 8.24 |
| 1217+023 | 0.24 | 16.66 | −23.83 | 2.32 | 11.1 | 20.48 | 2.30 | 8.13 | 8.09 |
| 2135-147 | 0.2 | 16.57 | −23.47 | 2.74 | 11.6 | 20.76 | 2.25 | 7.87 | 7.88 |
| 2141+175 | 0.213 | 16.47 | −23.54 | 1.85 | 8.2 | 19.81 | 2.37 | 8.46 | 8.35 |
| 2247+140 | 0.237 | 16.51 | −23.92 | 2.84 | 13.5 | 20.78 | 2.29 | 8.09 | 8.06 |
| 2349-014 | 0.173 | 15.39 | −24.41 | 5.05 | 19.2 | 20.91 | 2.38 | 8.50 | 8.39 |
| 2355-082 | 0.21 | 16.48 | −23.73 | 2.38 | 10.4 | 20.35 | 2.31 | 8.18 | 8.13 |
| RQQ | | | | | | | | | |
| 0054+144 | 0.171 | 16.05 | −23.70 | 2.76 | 10.4 | 20.25 | 2.34 | 8.31 | 8.23 |
| 0204+292 | 0.109 | 15.45 | −23.36 | 3.33 | 8.8 | 20.05 | 2.33 | 8.27 | 8.21 |
| 0244+194 | 0.176 | 16.8 | −22.36 | 2.41 | 9.3 | 20.71 | 2.18 | 7.57 | 7.65 |
| 0923+201 | 0.19 | 16.61 | −23.35 | 2.01 | 8.2 | 20.13 | 2.29 | 8.07 | 8.04 |
| 0953+414 | 0.239 | 17.58 | −22.98 | 1.59 | 7.6 | 20.59 | 2.14 | 7.39 | 7.50 |
| 1012+008 | 0.185 | 16.05 | −23.87 | 7.18 | 28.7 | 22.32 | 2.15 | 7.43 | 7.54 |
| 1549+203 | 0.25 | 18.15 | −22.38 | 1.01 | 5 | 20.19 | 2.10 | 7.20 | 7.35 |
| 1635+119 | 0.146 | 16.28 | −23.13 | 2.27 | 7.6 | 20.06 | 2.28 | 8.03 | 8.01 |
| 2215-037 | 0.241 | 16.64 | −23.64 | 1.39 | 6.7 | 19.36 | 2.42 | 8.68 | 8.53 |

of 9 RQQs is smaller by only a factor of two than that of 10 RLQs. However, a $t$-test gives a possibility of only 4.5% that the two distributions are from the same population. Although it may indicate some statistical differences between RLQs and RQQs (see also Dunlop et al. 2002), a more definitive conclusion about such a difference can be reached only with with larger and more complete samples of quasars. The OLR bisector fits of the relations shown in Fig. 3 give: $\log\sigma = -1.92 \pm 0.71 - (0.18 \pm 0.03)M_R$, $\log M_{\rm BH}^{\rm MF01} = -10.39 \pm 2.35 - (0.78 \pm 0.10)M_R$, and $\log M_{\rm BH}^{\rm G00} = -6.93 \pm 2.02 - (0.64 \pm 0.08)M_R$. These relations are slightly flatter than those we obtained for 63 BL Lac objects. This may be caused by the smaller sample of 29 AGNs or several offset LBLs shown in Fig. 1.

We noted that the SMBH masses of 10 RLQs and 7 RQQs in our AGN sample have been estimated in McLure & Dunlop (2001) based on the H$\beta$ emission line width measurements and an empirical relation between broad line region size and optical luminosity (Kaspi et al. 2000). After re-calculating the SMBH masses, assuming the characteristic velocity in the broad line region of AGN can be estimated from the observed $FWHM$s of H$\beta$ lines by $V_{\rm BLR} = \frac{\sqrt{3}}{2} FWHM_{\rm H\beta}$ (Wandel et al. 1999), in Fig. 5 we plotted the comparison of the SMBH masses derived by using the fundamental plane with those obtained by H$\beta$ line study. The agreement is not bad but on average the SMBH masses estimated based on H$\beta$ line study are larger than those obtained by us by a factor of two. If the relation between $V_{\rm BLR}$ and $FWHM_{\rm H\beta}$ was assumed to be $V_{\rm BLR} = 1.5 \times FWHM_{\rm H\beta}$ as taken by McLure & Dunlop (2001), the difference between the SMBH masses obtained by H$\beta$ line study will be larger than our estimations by approximately a factor of 5. It is unclear whether such differences are due to our assumption of the fundamental plane for AGN host galaxies or the overestimations of the broad line region sizes of AGNs according to the empirical relation between the broad line region size and the optical luminosity (Kaspi et al. 2000). We note that the latter relation is much more scattered than the previous one. Another advantage of our method is that it is model independent, while the method based on H$\beta$ line study sensitively depends on the assumptions of the dynamics and geometry of broad line regions of AGNs (Krolik 2001). Considering that both methods may have uncertainties of

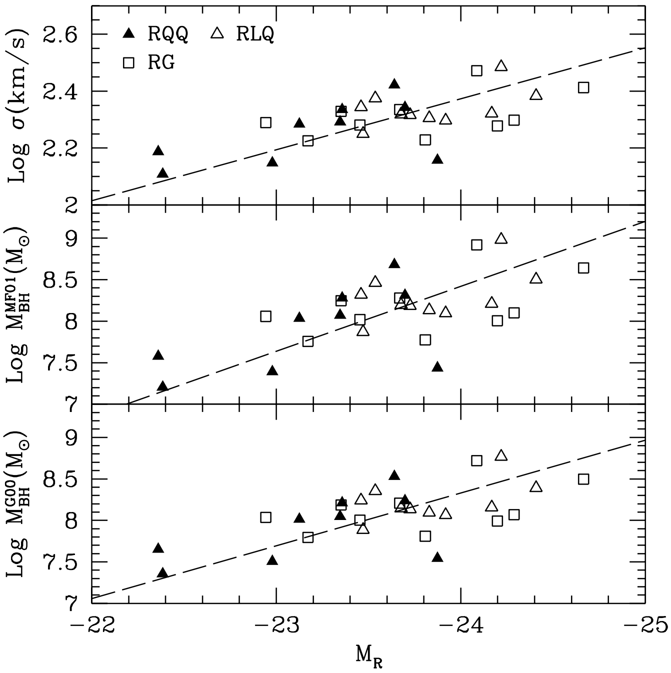

**Fig. 3.** The derived central velocity dispersion, black hole mass (using both MF01 and G00 relations) for AGNs against the $R$-band absolute magnitude of the host galaxies. The solid and open triangles represent radio-quiet and radio-loud quasars. The open squares represent radio galaxies. The dashed line shows the OLS bisector fit to each relation.

as larger as a factor of three, the difference in SMBH estimations shown in Fig. 5 is not unexpected.

Using the derived SMBH masses, we can estimate the Eddington ratio (defined as the ratio of bolometric luminosity and Eddington luminosity) of the source in our sample of RGs, RLQs and RQQs. We adopted the assumptions of $L_{\rm bol} \simeq 10\lambda L_{5100\,\mathring{\rm A}}$ (Kaspi et al. 2000) and $f_\nu \propto \nu^{-0.2}$ (Dunlop et al. 2002) to convert the $R$-band luminosity to the bolometric luminosity for the nuclear component of AGNs. Figure 6 shows the distributions of Eddington ratios of 9 RGs, 10 RLQs and 9 RQQs. It is clear that the Eddington ratios of RGs are systematically smaller than those of RLQs and RQQs by two orders, while there is less significant difference in Eddington ratios for RLQs and RQQs. Our result is qualitatively consistent with that obtained by Ho (2002) who recently suggested that the strongly active AGNs have larger Eddington ratios. Figure 6 shows that both RLQs and RQQs have a bolometric luminosity comparable to the Eddington luminosity. A $t$-test also shows a significance of 56% that the Eddington ratios of RLQs and RQQs are from the same population. Therefore, our results indicate that the SMBH masses of RLQs may be slightly larger than those of RQQs; their Eddington ratios may not be significantly different. However, we must noted that these results were obtained with a small sample of radio-loud and radio-quiet quasars. More definitive conclusions can be reached only with larger and more complete samples.

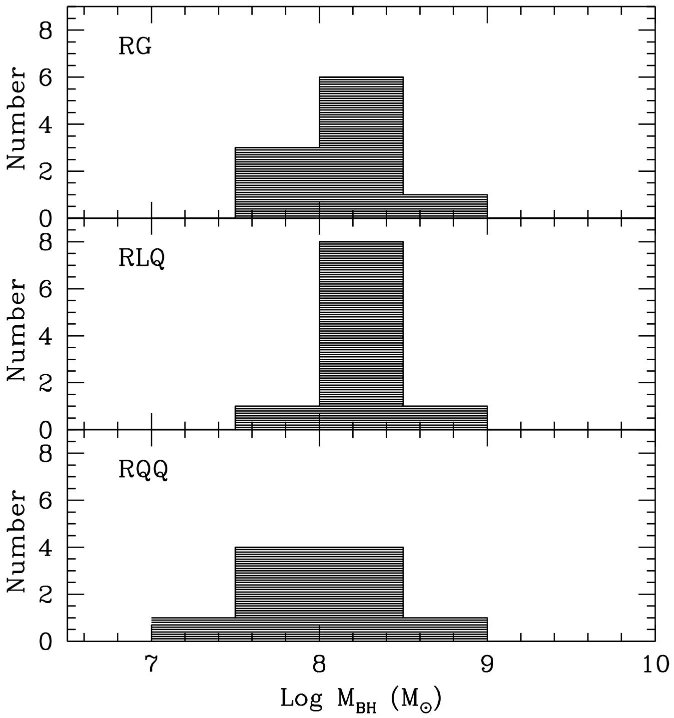

**Fig. 4.** Histogram of the derived black hole mass distribution of radio galaxies, radio-loud and radio-quiet quasars using the G00 relation.

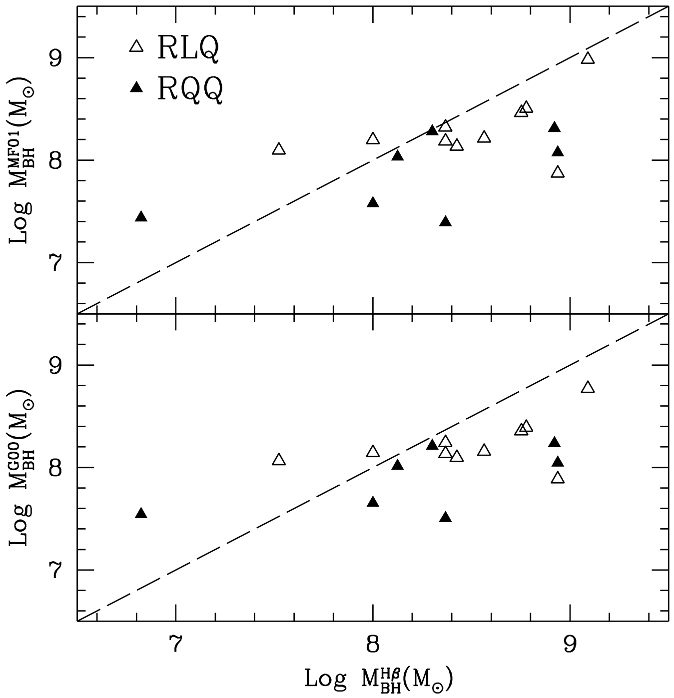

**Fig. 5.** Comparison of the estimated SMBH masses of quasars by MF01 and G00 relations with those derived from the H$\beta$ line study. The dashed line shows the one-to-one correspondence.

## 4. Discussions

The SMBH masses of AGNs are important to understand the nature of AGN activities, however, there are only very limited methods which can be used to derive the

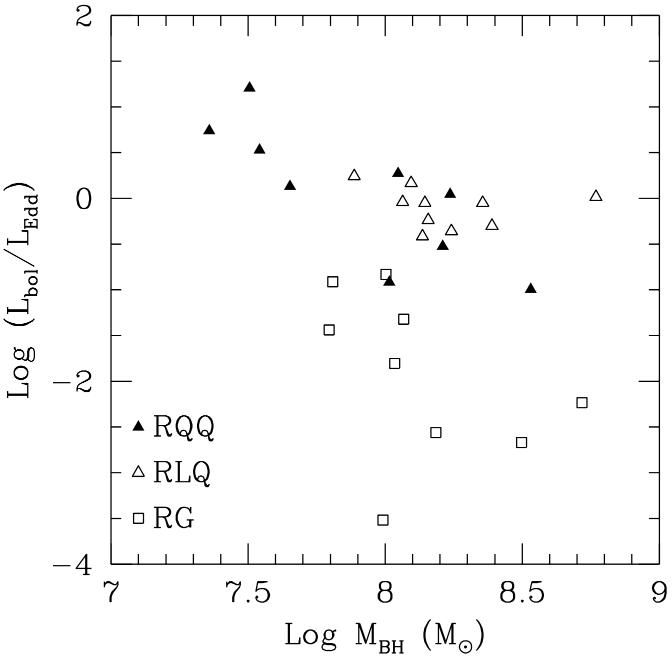

**Fig. 6.** Comparisons of Eddington ratios of radio-loud quasars, radio-quiet quasars and radio galaxies.

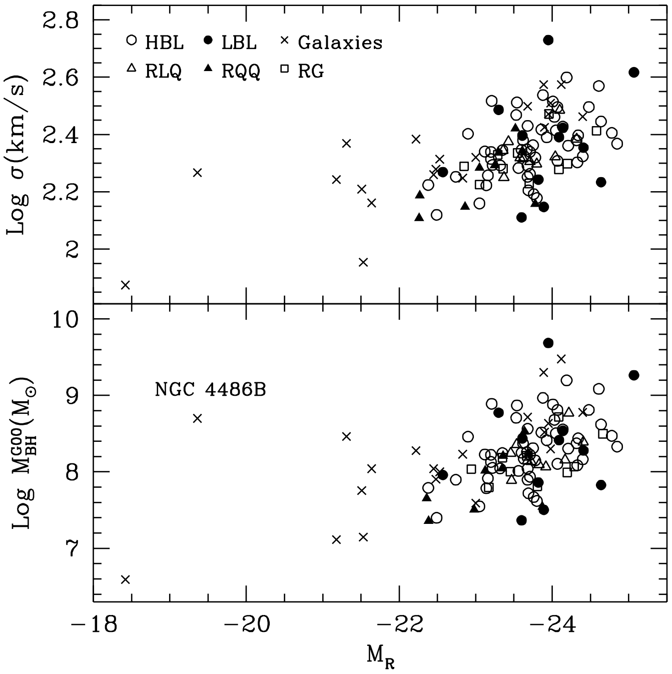

**Fig. 7.** Comparison of the relations of central velocity dispersion, black hole mass estimated by the G00 relation with the *R*-band absolute magnitude for AGN hosts and nearby galaxies.

mass of them (Ho 1999). Many observational studies have shown that a lot of AGNs, especially radio-loud AGNs, have massive elliptical hosts. The basic properties of these host galaxies are indistinguishable from normal ellipticals. By assuming that the elliptical hosts of AGNs follow the same fundamental plane as normal ellipticals and adopting the $M_{\rm BH}$-$\sigma$ relation recently discovered for both inactive and active galaxies, we estimated the SMBH masses for 63 BL Lac objects and 29 other AGNs that have been imaged by HST recently. Our results, though with substantial uncertainties, show that the SMBH masses of these AGNs are mostly in the range of $10^{7.5}$ $M_\odot$ to $10^{9.5}$ $M_\odot$. There are no significant differences in SMBH masses for different AGNs with elliptical hosts. This seems to be a natural consequence if we believe that the tight correlations between the SMBH masses and the galaxy properties also exist for the host galaxies of AGNs. In Fig. 7, we compare our results obtained for AGNs with the measured central velocity dispersions and black hole masses of 20 nearby elliptical galaxies compiled by Kormendy & Gebhardt (2001). Except for the outlier NGC 4486B whose outer region may have been stripped away in the tidal interactions with a more massive companion galaxy (Faber 1973), the relations of our derived central velocity dispersions and SMBH masses with the *R*-band absolute magnitudes are consistent with the trends for normal ellipticals. In fact, the derived SMBH masses of AGNs have a significant overlap with those of massive normal ellipticlas. Moreover, we note that the consistency of our derived $\sigma$-$M_R$ relation with the recent measurement of the stellar velocity dispersion of Mrk 501 (Barth et al. 2002) also supports the assertion that using the fundamental plane to derive the central velocity dispersions of AGN elliptical hosts is possible and practical.

Our results show that both HBLs and LBLs have similar SMBH masses in the range from $10^7$ $M_\odot$ to $10^{9.5}$ $M_\odot$. The SMBH masses of BL Lac objects are similar to those in radio galaxies and radio-loud quasars. This indicates that the different observational appearances among HBLs, LBLs and radio-loud AGNs cannot be dominated by the different SMBH masses. Several evolutionary scenarios have been recently suggested for radio-loud AGNs. Ghisellini et al. (1998) proposed an evolutionary sequence HBL → LBL → flat-spectrum radio quasars (FSRQ) according to the increasing level of external radiation to the soft radiation field in the emitting region. D'Elia & Cavaliere (2001) and Cavaliere & D'Elia (2002) suggested that the gradual depletion of the central environment may lead to the evolution from FSRQ → LBL → HBL. Similarly, Böttcher & Dermer (2002) recently argued that the decline of accretion power can also lead to such an evolutionary sequence. As indicated by Böttcher & Dermer (2002), the key parameter of these scenarios is accretion rate rather than the SMBH mass. The depletion of accretion power can lead to the decrease of the accretion rate, which may result in the transition of different accretion modes. Theoretical investigations have pointed out that accretion near the Eddington limit may produce optically thick accretion disks extending all the way to the innermost stable orbit, while accretion at very lower accretion rate may lead to advection dominated accretion mode (see Narayan et al. 1998 for a review). In fact, Fabian & Rees (1995) has proposed that the nearby galaxies can be modeled with the advection-dominated accretion flow. The radio properties of some low-luminosity AGNs may be also related to the advection-dominated accretion mode (Ulvestad & Ho 2001). Recently Ghisellini & Celotti (2001) also proposed that the separation of FR I and FR II radio galaxies may be closely related to the critical accretion rates. In addition, the state transition of Galactic black hole X-ray transients has been explained according to the different accretion modes at the different accretion rates (Esin et al. 1998). Recently Fender & Kuulkers (2001) also found that the formation and luminosity of jets in Galactic X-ray transients are closely related to the accretion rates. From all these points we suspect that the main reason for the evolutionary sequence of radio-loud AGNs may be accretion rate rather than the SMBH mass. Our estimations of the SMBH masses and Eddington ratios of different AGNs are also consistent with this suspicion. In addition, our results show that there may still be a difference in SMBH masses of radio-loud and radio-quiet quasars, but such a difference is not significant as previously claimed. The Eddington ratios of these two subclasses of quasars seem to be from the same population. These points are very important for our understanding of the physics of quasars and obviously need to be confirmed with larger samples.

We note that the relations between SMBH mass and the elliptical host luminosity derived by us for AGNs are a little different from those obtained by some previous studies. McLure & Dunlop (2002) derived such a relation for 92 active and inactive galaxies as $\log M_{\rm BH} \propto -0.50 M_R$. They argued that it is consistent with a linear scaling between the black hole and bulge mass. Wandel (2002) reached a similar conclusion for a sample of 35 quiescent galaxies and 47 broad line AGNs. However, Laor (2001) and Wu & Han (2001) obtained steeper slopes of the $M_{\rm BH}$–bulge luminosity relation for different samples of AGNs and argued that the scaling of the black hole and bulge mass is nonlinear. Here we provide an additional argument for this nonlinear relation. In our present study, the slope of the relation between SMBH mass and the elliptical host luminosity is estimated from $-0.64$ to $-1.02$ for different samples. This is identical to a nonlinear relation between the black hole and bulge mass $M_{\rm BH} \propto M_{\rm bulge}^{(1.27\sim1.95)}$ if the mass-to-light ratio of the host galaxy is taken to be $M/L \propto L^{0.31}$ (Jorgensen et al. 1996). In fact, we can obtain this conclusion directly from some existing relations. From the fundamental plane Eq. (1), the $M_{\rm BH}$–$\sigma$ relation Eq. (3) or (4), and the formula for average brightness (Eq. (2)), we can derive a relation between the SMBH mass and $R$-band absolute magnitude of the host galaxy as: $\log M_{\rm BH} \propto (0.96 \sim 1.21) M_R$. This clearly indicates a nonlinear relation: $M_{\rm BH} \propto M_{\rm bulge}^{(1.83\sim2.31)}$. Such a result is well in agreement with that in Wu & Han (2001) who obtained $M_{\rm BH} \propto M_{\rm bulge}^{(1.74\pm0.14)}$. However, we noted the large uncertainties in our derived SMBH masses and host galaxy luminosities may have significant effects on the correlation between SMBH and galactic bulge masses. Although the non-linear scaling between them has been also implied in some theoretical models (e.g. Adams et al. 2001; Wang et al. 2000), more detailed theoretical investigations, as well as more high quality imaging observations on larger samples of active and inactive galaxies, are obviously needed to confirm it.

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