THE BLACK HOLE FUNDAMENTAL PLANE: REVISITED WITH A LARGER SAMPLE OF RADIO AND X-RAY-EMITTING BROAD-LINE AGNs

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ABSTRACT

We use a recently released SDSS catalog of X-ray–emitting AGNs in conjunction with the FIRST radio survey to investigate the black hole (BH) fundamental plane relationship between the 1.4 GHz radio luminosity ($L_{\text{r}}$), 0.1–2.4 keV X-ray luminosity ($L_{\text{X}}$), and black hole mass ($M$), namely, \( \log L_{\text{r}} = \xi_{\text{RX}} \log L_{\text{X}} + \xi_{\text{RM}} \log M + \text{constant} \). For this purpose, we compile a large sample of 725 broad-line AGNs, which consists of 498 radio-loud sources and 227 radio-quiet sources. We confirm that radio-loud objects have a steeper slope ($\xi_{\text{RX}}$) with respect to radio-quiet objects and that the dependence of the BH fundamental plane on the BH mass ($\xi_{\text{RM}}$) is weak. We also find tight correlation with a similar slope between the soft X-ray luminosity and broad emission-line luminosity for both radio-loud and radio-quiet AGNs, which implies that their soft X-ray emission is unbeamed and probably related to the accretion process. With the current larger sample, we find that there is no clear evidence of evolution for radio-quiet AGNs, while for radio-loud ones there is a weak trend in which $\xi_{\text{RM}}$ decreases as the redshift increases. This may be understood in part as due to the observed evolution of the radio spectral index as a function of redshift. Finally, we discuss the relativistic beaming effect and other uncertainties related to the BH fundamental plane. We conclude that, although it does introduce scatter into the fundamental plane relation, Doppler boosting alone is not enough to explain the observed steeper value of $\xi_{\text{RX}}$ in the radio-loud subsample with respect to the radio-quiet ones.

Subject headings: accretion, accretion disks — black hole physics — galaxies: active — galaxies: nuclei — radio continuum: galaxies — X-rays: galaxies

Online material: color figures, machine-readable table

1. INTRODUCTION

Astrophysical black holes do not emit light directly, but they can be probed by their gravitational influence on neighboring matter, which produces observable signatures of black hole activity. The key mechanism for a black hole to become active is the accretion process (Frank et al. 2002), which is usually accompanied by a relativistic jet. Accretion disks and jets can produce photons from radio to X-ray band. The radio emission is usually believed to originate from the synchrotron radiation of the jet (Begelman et al. 1984), while the optical/UV emission mostly comes from the multicolor blackbody radiation emitted from the accretion disk (Shakura & Sunyaev 1973), and the X-ray radiation is usually associated with the innermost region of the accretion disk, where the temperature is the highest. In some cases, the contribution of inverse Compton scattering from high-energy electrons in a disk corona is also needed to account for the observed power-law spectrum in the X-ray band (Haardt & Maraschi 1993). If jet production is directly related to the accretion process, we would expect a natural correlation between radio and X-ray luminosities (Merloni et al. 2003; Heinz & Sunyaev 2003; Falcke et al. 2004).

The radio to X-ray correlation has long been studied in both Galactic black hole (GBH) candidates and active galactic nuclei (AGNs). Gallo et al. (2003) found a strong correlation between the radio and X-ray emission ($L_{\text{r}} \propto L_{\text{X}}^{0.7}$) using the simultaneous X-ray and radio observational data of stellar-mass black hole X-ray binaries (XRBs) during the low/hard state. In addition, they suggested that when XRBs enter the hard to soft transition state, the jet is suppressed and the radio emission decreases. Recently, some studies have shown that the substantial scatter exists in such a relationship of GBHs (Gallo 2006; Xue & Cui 2007; Xue et al. 2008). In the case of AGNs, Brinkmann et al. (1997) obtained a remarkable correlation between 2 keV X-ray luminosity and 5 GHz radio luminosity for 324 radio-loud AGNs. Canosa et al. (1999) found a strong correlation between soft X-ray and 5 GHz radio luminosities for 40 low-power radio galaxies. Brinkmann et al. (2000) studied a sample derived from the cross-correlation of the ROSAT All-Sky Survey (RASS) catalog and the Very Large Array (VLA) Faint Images of the Radio Sky at Twenty cm (FIRST 20 cm) catalog. They found that for 843 AGNs, the X-ray and radio luminosities are correlated over two decades in radio luminosity, spanning radio-loud and radio-quiet regimes, but that radio-quiet quasars seem to follow a different correlation from radio-loud ones. Recently, Panessa et al. (2007) investigated the radio/X-ray luminosity correlation for low-luminosity AGNs, including local Seyfert galaxies and low-luminosity radio galaxies (LLRGs). They found that X-ray and radio luminosities are significantly correlated over 8 orders of magnitude, with Seyfert galaxies and LLRGs showing the similar slope, which seems different from the previous results.

Theoretical explanations for the observed radio to X-ray relation have been discussed in a number of previous works. Fender et al. (2003) found that, at relatively lower accretion rate ($M < 7 \times 10^{-5} M_{\odot}/\text{yr}$), black hole X-ray binaries would enter a “jet-dominated” state. At this stage, the majority of the liberated accretion power is transferred into the jet and does not dissipate as X-ray emission in the accretion flow. This was also suggested by Falcke et al. (2004), who demonstrated that, below a critical value of the accretion rate [$\lesssim 1\%$–10\% $M_{\odot}/\text{yr}$], the spectral energy distribution (SED) of a black hole accreting source is dominated by the nonthermal radiation from the jet, while for sources with higher accretion rates ($M \leq M_{\text{Edd}}$), the radiation is dominated by the accretion flow. Using a coupled disk-jet model, Yuan & Cui (2005) showed that, in GBHs when the X-ray luminosity is smaller than a certain value ($<10^{-5}$ to $10^{-6} L_{\text{Edd}}$), the
jet will dominate the radiation and the radio to X-ray correlation becomes $L_r \propto L_X^{3/2}$. When the X-ray luminosity exceeds that critical value, the accretion flow would produce most of the X-ray emission and the radio-to-X-ray correlation then becomes $L_r \propto L_X^{1/2}$. Therefore, the accretion rate decides the detailed physical model of the accretion disk, which then leads to different observed radio to X-ray correlation slopes (Körding et al. 2006). Although it is still not clear whether such a critical accretion rate is of the same order of magnitude for both GBHs and AGNs, the similarity of accretion-jet physics in these two systems seems to imply that similar results may also be found in AGNs.

In a comprehensive study, Merloni et al. (2003) examined a sample combining Galactic black hole systems and supermassive black hole systems by investigating their compact emission in X-ray (2–10 keV) and radio (5 GHz) bands. They found that the radio luminosity ($L_r$) is strongly correlated with both the black hole mass ($M$) and the X-ray luminosity ($L_X$) (the so-called fundamental plane of black hole activity). The relation is $\log L_r = (0.60 \pm 0.11) \log L_X + (0.78 \pm 0.09) \log M + (7.33 \pm 0.05)$. Subsequently, Wang et al. (2006) selected a uniform sample of broad-line AGNs which was cross-identified from RASS, the Sloan Digital Sky Survey (SDSS), and the FIRST 20 cm radio survey to test the black hole fundamental plane relation. Their final sample consisted of 115 broad emission-line AGNs, including 39 radio-quiet AGNs and 76 radio-loud ones. They found in the relationship has a very weak dependence on the black hole mass. Moreover, radio-quiet and radio-loud objects have different radio-to-X-ray slopes, which is 0.85 for radio-quiet objects and 1.39 for radio-loud sources. This differs from the result of Merloni et al. (2003), where the relationship seems to be universal for different types of black hole sources. However, the limited statistics of the sample in Wang et al. (2006) motivated us to increase the number of sources in order to confirm the results on stronger statistical bases. With a larger sample, we are also able to study the possible evolution of the black hole fundamental plane relation as we have enough sources in each redshift bins.

We organize the paper as follows. In § 2 we present our sample selection criteria and the main properties of our sample. In § 3 we show the derived fundamental plane relation and investigate the possible evolution of such a relation. In § 4 we briefly discuss and summarize our results.

2. THE RADIO AND X-RAY–EMITTING BROAD-LINE AGN SAMPLE

2.1. Sample Selection

Our sample is selected based on the cross-identification of the newly published X-ray–emitting SDSS AGN catalog (Anderson et al. 2007) and the catalog of the FIRST 20 cm radio survey (White et al. 1997). Anderson et al. (2007) used X-ray data from RASS and both optical imaging and spectroscopic data from SDSS. It is worth emphasizing that the RASS and SDSS are extremely well matched to each other via a variety of coincidences (similar survey depth, sensitivity, and sky coverage, etc.; Anderson et al. 2003). The RASS/SDSS data from 5740 deg² of sky spectroscopically covered in SDSS Data Release 5 provide an expanded catalog of 7000 confirmed quasars and other AGNs that are probable RASS identifications (Anderson et al. 2007).

One of the main benefits of this sample is that the SDSS surveyed area is also covered by the FIRST 20 cm radio survey. We cross-correlate the broad-line AGN catalog of Anderson et al. (2007) with the FIRST radio-detected sources to build a RASS-SDSS-FIRST cross-identified sample of 868 broad-line AGNs. All of these 868 sources have been observed and detected at 1.4GHz (FIRST 20 cm survey) and in 0.1–2.4 keV energy band (RASS). The optical spectra from the SDSS data archive can be used to estimate the central black hole mass. Here we exclude the high-redshift sources ($z > 2.171$) in our sample due to the lack of the Hβ and Mg ii λ2798 emission lines in their SDSS optical spectra. Black hole masses of the remaining 725 sources are estimated. The radio-loudness ($R$) is calculated with the rest-frame $B$-band (4400 Å) and 5 GHz flux density according to the definition $R = f_{\text{5GHz}}/f_{\text{B}}$ (Kellermann et al. 1989), and the 5GHz flux density is derived from the 1.4 GHz flux density assuming a spectral index of 0.5 (Kellermann et al. 1989). Radio-loud and radio-quiet sources are separated by $R = 10$. Please see § 2.2 of Wang et al. (2006) for the details of data reduction and black hole mass estimation (Kaspi et al. 2000, 2005; McLure & Jarvis 2002; Wu et al. 2004).

Our final sample comprises 725 entries, of which 498 are radio-loud and 227 are radio-quiet. In addition, we discover several radio-loud narrow-line Seyfert 1 galaxies (NLS1’s) in our study. A detailed discussion of these radio-loud NLS1’s is presented in the Appendix. Throughout this paper, we use a cosmology² with $H_0 = 70$ km s⁻¹ Mpc⁻¹, $\Omega_L = 0.7$, and $\Omega_M = 0.3$.

2.2. Sample Properties

We describe here the main properties of our selected AGN sample. Table 1 gives the total 725 sources with the SDSS optical name, redshift, broadband (0.1–2.4 keV) soft X-ray luminosity, rest-frame 1.4 GHz radio luminosity, radio-loudness, black hole mass, black hole mass, and radio-loudness (0.1–2.4 keV). X-ray luminosity, black hole mass (in units of $M_\odot$), 1.4 GHz radio luminosity, and ratio of X-ray to Eddington luminosity ($L_{\text{Edd}}$)³ of our sample. The radio-loudness

| Name                      | $z$   | $\log(L_X/\text{ergs s}^{-1})$ | $\log(L_r/\text{ergs s}^{-1})$ | $\log R$ | $\log(M/M_\odot)$ | $L_{\text{broad-line}}$ | Flag |
|---------------------------|-------|-------------------------------|-------------------------------|----------|-------------------|--------------------------|------|
| SDSS J000608.04-010700.7  | 0.949 | 45.60                         | 41.13                         | 1.345    | 8.71              | 43.47                    | 0    |
| SDSS J00710.01+005329.1    | 0.316 | 44.95                         | 39.79                         | 0.549    | 9.07              | 42.90                    | 1    |
| SDSS J004319.73+005115.4   | 0.308 | 44.64                         | 39.61                         | 0.506    | 9.42              | 42.90                    | 1    |

Note.—Table 1 is published in its entirety in the electronic edition of the Astrophysical Journal. A portion is shown here for guidance regarding its form and content.

² A 1 means that $L_{\text{broad-line}}$ is used for $L_{\text{broad-line}}$; 0 means that $L_{\text{Mg II}}$ is used for $L_{\text{broad-line}}$.

³ The broad emission-line luminosity. It is represented by the Hβ broad component luminosity or the Mg ii emission-line luminosity (when Hβ is unavailable).

1 See Vizier Online Data Catalog, 8071 (R. H. Becker et al., 2003).
distribution does not show a clear dichotomy between radio-loud and radio-quiet AGNs. This is not surprising for samples of FIRST-detected quasars. The radio-loudness dichotomy was found mostly for optically selected samples and is usually absent for samples of radio-detected sources (Brinkmann et al. 2000; White et al. 2000; Lacy et al. 2001).

Our sample is a part of the broad-line AGN catalog provided by Anderson et al. (2007), which includes typical broad-line quasars, Seyfert 1 galaxies, low-redshift Seyfert 1.5–1.9 galaxies, and some rare galaxies such as NLS1’s. Compared with Wang et al. (2006), the distribution ranges of different physical parameters in our sample are relatively larger. The significant range in the luminosity at each redshift bin avoids the strong dependence of luminosity on redshift in a flux-limited sample (Avni & Tananbaum 1982). In particular, more convincing results can be obtained with the larger sample.

However, we must notice the selection biases in our sample. First of all, AGNs with radio flux fainter than the FIRST detection limit cannot be detected by FIRST. Therefore, our sample does not include radio-quiet AGNs with $\log (\text{Radio Loudness}) < -0.23$. In addition, based on the redshift distribution shown in Figure 1, it is clear that most AGNs at high redshifts in our sample are radio-loud. Therefore, any conclusion based on the total sample is biased toward luminous radio-loud AGNs. We also perform a Kolmogorov-Smirnov (K-S) test to evaluate the distribution similarity of physical parameters shown in Figure 1 between radio-quiet and radio-loud subsamples (such as $L_r$, $L_X$, and $L_X/L_{\text{Edd}}$). We find that the probabilities of similarity are all less than 0.05, meaning that the distribution of these physical quantities in the two subsamples are essentially different, with a relatively larger mean value of each parameter for radio-loud AGNs.

In Figure 2 we plot radio vs. X-ray luminosity (left) and the Eddington-luminosity–scaled radio vs. scaled X-ray luminosity (right). Objects in different black hole mass bins are presented with different symbols and colors to highlight a possible segregation in the plot. Clearly, there is no trend of sources in different
black hole mass bins being parallel to each other, which is consistent with the result in Wang et al. (2006). Again, a tight correlation between the radio and X-ray luminosities is clear, with radio luminosity spanning more than 6 orders of magnitude.

Figures 3 and 2 are identical except that in Figure 3, different colors and symbols are used to denote different radio-loudness bins as opposed to black hole mass bins. AGNs in different radio-loudness bins seem to distribute in parallel sequences. The result also confirms the conclusion of Wang et al. (2006).

3. CORRELATION ANALYSIS

In this section we derive the black hole fundamental plane relation based on the current large sample. We also adopt several statistical methods to test its significance. Finally, we examine the possible evolution of this relation at different redshifts.

3.1. The Fundamental Plane Relation

In three-dimensional space \((\log L_r, \log L_X, \log M)\), black hole systems are preferentially distributed on a fundamental plane (Merloni et al. 2003). Based on our sample of AGNs, we fit the data in the form

\[
\log \left( \frac{L_r}{10^{40} \text{ ergs s}^{-1}} \right) = \xi_{RX} \log \left( \frac{L_X}{10^{44} \text{ ergs s}^{-1}} \right) + \xi_{RM} \log \left( \frac{M}{10^8 M_\odot} \right) + \text{constant.} \tag{1}
\]

We also fit the relation between Eddington-luminosity-scaled radio and X-ray luminosities for the radio-quiet subsample only. The fitting formula is

\[
\log \left( \frac{L_r}{L_{Edd}} \right) = \xi_{ERX} \log \left( \frac{L_X}{L_{Edd}} \right) + \text{constant.} \tag{2}
\]

We apply the ordinary least-squares (OLS) multivariate regression method (Isobe et al. 1990) to the total, radio-loud, and radio-quiet subsamples, respectively. The OLS bisector fitting result for equation (1) with errors at the 1 \(\sigma\) confidence level and the dispersion (\(\sigma_r\))^5 are given in Table 2. We also list results of previous works for comparison. Our result is generally consistent with Wang et al. (2006), but now with smaller uncertainty for each coefficient due to the larger sample. The conclusions are similar: first, the coefficient \(\xi_{RX}\) tends to be larger as the radio-loudness increases; second, the black hole mass seems to be unimportant in the correlation between radio and soft X-ray luminosities. We should note that the black hole fundamental plane coefficients calculated by Merloni et al. (2003) are based on a radio-loud and radio-quiet combined sample, with a predominance of radio-quiet sources. Our result for the radio-quiet subsample is similar to that of Merloni et al. (2003), but the dependence on the black hole mass is weaker in our case.

\(^5\) We define the dispersion as the square root of the variance of the differences between the observed radio luminosity and that calculated from the fitting relation.

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![Figure 2](image1.png)  
Fig. 2.—Rest-frame 1.4 GHz radio luminosity \((L_r)\) vs. the 0.1–2.4 keV X-ray luminosity, with different symbols representing different logarithmic bins of the black hole mass (in units of \(M_\odot\)). In the left panel we plot the logarithm of the luminosity directly, while in the right panel we scale the radio and X-ray luminosity with \(L_{Edd}\). [See the electronic edition of the Journal for a color version of this figure.]

![Figure 3](image2.png)  
Fig. 3.—Same as Fig. 2, but for different radio-loudness bins. We plot the radio vs. X-ray luminosity in the left panel, and the Eddington-luminosity-scaled radio vs. X-ray luminosity in the right panel. [See the electronic edition of the Journal for a color version of this figure.]
The fitting result for equation (2) with errors at the 1 σ confidence level is
\[
\log \left( \frac{L_r}{L_{\text{Edd}}} \right) = (0.96 \pm 0.04) \log \left( \frac{L_X}{L_{\text{Edd}}} \right) + (-4.82 \pm 0.08).
\]

(3)

The dependence of \( \frac{L_r}{L_X} \) on the black hole mass is shown in Figure 4. The overall correlation is weak, except that a positive correlation is observed for sources (mostly radio-quiet ones) with black hole masses smaller than \( 10^7 \) \( M_\odot \). Figure 5 shows the edge-on black hole fundamental plane relation for radio-quiet sources, with radio-loud AGNs overplotted for comparison. We also plot \( \frac{L_r}{L_{\text{Edd}}} \) vs. \( \frac{L_X}{L_{\text{Edd}}} \) in Figure 6, with different symbols representing sources in different radio-loudness bins. Parallel sequences can be seen clearly from these two figures.

3.2. Statistical Tests for the Fundamental Plane Relation

3.2.1. Partial Correlation Tests

As Bregman (2005) pointed out, the correlation between X-ray and radio luminosities may be dominated by the distance effect. Following Wang et al. (2006) we performed the partial Kendall \( \tau \) correlation test to examine this effect (Akritas & Siebert 1996). In Table 3, columns (1)–(3) list the variable names of \( X \), \( Y \), and \( Z \), respectively, where the partial correlation of \( X \) and \( Y \) is calculated with the influence of \( Z \) variable excluded. Column (4) gives the subsample type. Column (5) lists the number of sources in each subsample. Columns (6)–(8) show results of the partial correlation test, the square root of the calculation variance, and the probability of the null hypothesis. The null hypothesis is rejected with a probability less than the significance level (i.e., \( \sim 0.05 \)). From Table 3 we can see that the partial correlation between \( L_r \) and \( L_X \) is strong even after excluding the distance effect, because the \( P \) value is less than \( 10^{-10} \).

3.2.2. The Scrambling Test

Besides the partial correlation test performed above, we adopt another method introduced by Bregman (2005) to evaluate the degree of influence that any distance effect has on our sample (i.e., Merloni et al. 2006). We calculate the Pearson correlation coefficient (\( \rho \)) between \( \log(L_r/10^{40} \text{ ergs s}^{-1}) \) and \( \xi_{\text{RX}} \), \( \log(L_X/10^{44} \text{ ergs s}^{-1}) \), and \( \xi_{\text{RM}} \) \( \log(M_{\text{BH}}/10^8 \Msun) \) by randomly assigning radio fluxes to objects in our sample. This procedure is performed \( 10^6 \) times in order to construct the Monte Carlo test. The result is shown in Figure 7. The correlation coefficients are adopted from Table 2. For comparison, we overplot the Pearson correlation coefficient of the original sample with a vertical line in each panel of Figure 7.

For radio-quiet objects, our \( 10^6 \) realizations of randomized data sets produce only one case, in which the Pearson correlation coefficient exceeds the value of the real data sets. For radio-loud sources, not even one shows a stronger correlation than the real value. This means that, for the radio-quiet subsample, the...

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**TABLE 2**

| Subsample               | Number | \( \xi_{\text{RX}} \)   | \( \xi_{\text{RM}} \)   | Constant | \( \sigma \) |
|------------------------|--------|-------------------------|-------------------------|----------|-------------|
| Total                  | 725    | 1.47 ± 0.06             | 0.04 ± 0.07             | -0.33 ± 0.06 | 0.83        |
| Radio-quiet            | 227    | 0.73 ± 0.10             | 0.31 ± 0.12             | -0.68 ± 0.07 | 0.42        |
| Radio-loud             | 498    | 1.50 ± 0.08             | -0.20 ± 0.10            | 0.05 ± 0.10 | 0.75        |
| Merloni et al. (2003)  | ...    | 0.60 ± 0.11             | 0.78 ± 0.11             | 7.33 ± 4.07 | 0.88        |
| Total*                 | 115    | 1.33 ± 0.15             | 0.30 ± 0.18             | -0.40 ± 0.14 | 0.89        |
| Radio-quiet*           | 39     | 0.85 ± 0.10             | 0.12 ± 0.13             | -0.77 ± 0.07 | 0.38        |
| Radio-loud*            | 76     | 1.39 ± 0.17             | 0.17 ± 0.21             | -0.17 ± 0.21 | 0.77        |

* Results derived by Wang et al. (2006).
The similar slope of radio-loud and radio-quiet sources in the \( L_X \) vs. \( L_{H/3} \) plot seems to indicate that the soft X-ray emission traces well the ionizing luminosity and is probably isotropic and closely related to the accretion process of the central black hole for both radio-quiet and radio-loud sources. For radio-loud broad-line AGNs, the jet contribution to the soft X-ray emission is probably unimportant. The beaming effect due to the relativistic jet seems also weak in the soft X-ray band. Otherwise, we should expect the large scatter in the \( L_X \) vs. \( L_{H/3} \) relation for radio-loud sources in our sample.

The high-redshift sources here usually have the measurement of the Mg \( \upmu \) 2798 broad emission line instead of the H\( \beta \) broad emission line in the observed wavelength. In Figure 9 we show the X-ray luminosity versus the Mg \( \upmu \) emission-line luminosity in our sample (left) and the radio luminosity versus the Mg \( \upmu \) emission-line luminosity (right). The result is consistent with what derived from Figure 8 for low-redshift objects.

### 3.4. Evolution of the Black Hole Fundamental Plane

With the currently available large sample, we are able to investigate the evolution of the black hole fundamental plane relation by dividing the sample into different redshift bins. The result is listed in Table 4 and plotted in Figure 10. For radio-quiet objects, the coefficients \( \xi_{\text{RM}} \) and \( \xi_{\text{X}} \) are almost constant in different redshift bins. For radio-loud sources, \( \xi_{\text{X}} \) is almost constant with redshift, while \( \xi_{\text{RM}} \) seems to decrease from positive to negative values as the redshift increases, with the exception of the last redshift bin, where \( \xi_{\text{RM}} \) is positive again, although it shows the largest error bars.

Now we can compare the evolution result obtained by us with some theoretical predictions. From Heinz & Sunyaev (2003), the radio flux produced via the synchrotron radiation from relativistic jet follows the scaling relation

\[
F_r \propto M^{2p+13-(2+p)\alpha_8/(8+2p)} \eta^{(2p+13)/(p+4)},
\]

where \( \alpha_r \) and \( \rho \) represent the radio spectral index (\( f_r \propto \nu^{-\alpha_r} \)) and the electron energy distribution index (\( N \propto E^{-\rho} \)), respectively. \( M \) is the central black hole mass. The variable \( \eta \) is the dimensionless accretion rate (\( \eta = M/M_{\text{Edd}} \)). This relation is valid for radio-loud AGNs, whose radio emission is believed to be produced via the synchrotron radiation of the relativistic jet.

The dimensionless accretion rate (\( \eta \)) is roughly proportional to the ratio between broad emission-line and Eddington luminosities (\( \eta = L_{\text{broad}}/L_{\text{Edd}} \)). Wandel et al. (1999). In the subsection above, we have shown that the soft X-ray luminosity is linearly scaled

### TABLE 3

| \( X \) | \( Y \) | \( Z \) | Type | Number | \( \tau \) | \( \sigma \) | \( P_{null} \) |
|---|---|---|---|---|---|---|---|
| \( \log L_X \) | \( \log L_{\nu} \) | \( \log D \) | Radio-loud | 498 | 0.321 | 0.0264 | <1.00E-10 |
| \( \log L_X \) | \( \log L_{\nu} \) | \( \log D \) | Radio-quiet | 227 | 0.270 | 0.0424 | 1.91E-10 |
| \( \log L_X \) | \( \log L_{\nu} \) | \( \log D \) | Total | 725 | 0.308 | 0.0220 | <1.00E-10 |
| \( \log L_X \) | \( \log L_{\nu} \) | \( \log M \) | Radio-loud | 498 | 0.567 | 0.0201 | <1.00E-10 |
| \( \log L_X \) | \( \log L_{\nu} \) | \( \log M \) | Radio-quiet | 227 | 0.578 | 0.0366 | <1.00E-10 |
| \( \log L_X \) | \( \log L_{\nu} \) | \( \log M \) | Total | 725 | 0.598 | 0.0188 | <1.00E-10 |
| \( \log (L_X/L_{\text{Edd}}) \) | \( \log (L_{\nu}/L_{\text{Edd}}) \) | \( \log D \) | Radio-loud | 498 | 0.472 | 0.0249 | <1.00E-10 |
| \( \log (L_X/L_{\text{Edd}}) \) | \( \log (L_{\nu}/L_{\text{Edd}}) \) | \( \log D \) | Radio-quiet | 227 | 0.517 | 0.0340 | <1.00E-10 |
| \( \log (L_X/L_{\text{Edd}}) \) | \( \log (L_{\nu}/L_{\text{Edd}}) \) | \( \log D \) | Total | 725 | 0.572 | 0.0204 | <1.00E-10 |
| \( \log (L_X/L_{\text{Edd}}) \) | \( \log (L_{\nu}/L_{\text{Edd}}) \) | \( \log M \) | Radio-loud | 498 | 0.572 | 0.0204 | <1.00E-10 |
| \( \log (L_X/L_{\text{Edd}}) \) | \( \log (L_{\nu}/L_{\text{Edd}}) \) | \( \log M \) | Radio-quiet | 227 | 0.555 | 0.0325 | <1.00E-10 |
| \( \log (L_X/L_{\text{Edd}}) \) | \( \log (L_{\nu}/L_{\text{Edd}}) \) | \( \log M \) | Total | 725 | 0.550 | 0.0160 | <1.00E-10 |
with the broad emission-line luminosity for both radio-loud and radio-quiet subsamples. Therefore, we can use $L_X/L_{\text{Edd}}$ to represent the dimensionless accretion rate ($\dot{m}$). After replacing $\dot{m}$ with $L_X/L_{\text{Edd}}$ and considering the relation between the Eddington luminosity and the black hole mass ($L_{\text{Edd}} \propto M_{\text{BH}}$), equation (4) can be turned into

$$L_r \propto M^{-\alpha_r} L_X^{(p+13)/2(p+4)}.$$  \hfill (5)

Therefore, the coefficients $\xi_{\text{RM}}$ and $\xi_{\text{RX}}$ of the radio-loud subsample can be determined by $\alpha_r$ and $p$.

In our radio-loud AGN subsample, there are 114 sources that were also detected by the Green Bank 4.85 GHz northern sky survey (GB6) (Gregory et al. 1996). Thus, we are able to estimate the real radio spectral index $\alpha_r$ ($f_r \propto \nu^{-\alpha_r}$) of this small subsample with the observed flux densities at 1.4 and 4.8 GHz. We plot the radio spectral index versus the redshift for sources in this subsample in Figure 11. There is a weak trend in which the spectral index increases with the increasing of the redshift. The mean values of $\alpha_r$ in each redshift bins are $-0.28$, $-0.12$, $-0.31$, $-0.27$, $-0.06$, $-0.11$, and $0.04$ (from low redshift to high redshift). We note that this is probably due to a selection effect in observations, as we may miss high-redshift AGNs with the negative spectral index.

Using the average radio spectral indices in different redshift bins, we calculate the theoretical value of the coefficients $\xi_{\text{RM}}$ and $\xi_{\text{RX}}$ based on equation (5). The general trend of $\xi_{\text{RM}}$ is to decrease from $0.28$ ($\alpha_r = -0.28$) to $-0.04$ ($\alpha_r = 0.04$), while $\xi_{\text{RX}}$ slightly increases from $1.23$ to $1.44$. This can be seen clearly in Figure 12. Therefore, the evolution of $\xi_{\text{RM}}$ and $\xi_{\text{RX}}$ of the radio-loud subsample with the redshift is consistent with the theoretical prediction.

On the other hand, it is also possible that the soft X-ray emission of broad-line AGNs is produced by the synchrotron process in a hot corona around accretion disks. Heinz (2004) calculated the theoretical correlation between the radio luminosity, X-ray luminosity and black hole mass when the jet radiation dominates. If the physical parameters (i.e., magnetic field strength, electron energy distribution index, etc.) of the hot corona and the jet are similar, we can use the equations given by Heinz (2004) to roughly estimate the coefficients $\xi_{\text{RM}}$ and $\xi_{\text{RX}}$ in different redshift bins. We find that with this model, $\xi_{\text{RM}}$ decreases from $0.047$ ($\alpha_r = -0.28$) to $0.007$ ($\alpha_r = 0.04$), and $\xi_{\text{RX}}$ increases from $1.23$ to $1.44$. Therefore, even if the soft X-ray emission mechanism is synchrotron radiation, the observed evolution of the black hole fundamental plane coefficients can still be explained. We cannot exclude such a possibility because the origin of the soft X-ray emission is still uncertain.

The radio spectral indices of these 114 radio-loud AGNs obtained from observations allow us to directly calculate their rest-frame 1.4 GHz radio fluxes without assuming the canonical value of $\alpha_r$ as $0.5$. The black hole fundamental plane relation is fitted based on this small subsample with measured $\alpha_r$. The derived $\xi_{\text{RX}}$...
and $\xi_{RM}$ coefficients are $1.34 \pm 0.16$ and $-0.31 \pm 0.21$, respectively. These values are consistent within errors with what we obtained from the radio-loud subsample if we set $\alpha_r = 0.5$ ($\xi_{RX} = 1.50 \pm 0.08$ and $\xi_{RM} = -0.20 \pm 0.10$). This indicates that our results for radio-loud AGNs are quite robust.

4. DISCUSSION AND CONCLUSION

4.1. Comparison with Previous Works

The $\xi_{RM}$ coefficient we derived is rather small, meaning that the dependence of the fundamental plane relation on the black hole mass is weak, which is different from the result obtained by Merloni et al. (2003). However, there are some differences between our sample and that of Merloni et al. (2003). We only include the broad-line AGNs, while their sample includes both GBHs and SMBHs. In our sample, the X-ray and radio emission are measured in $0.1-2.4$ keV and $1.4$ GHz, respectively, while Merloni et al. (2003) used the data of $2-10$ keV X-ray emission and $5$ GHz radio core emission. It is still unclear whether the soft ($0.1-2.4$ keV) and hard X-ray ($2-10$ keV) emission have the similar origin for broad-line AGNs. A sample with both available data in the soft and hard X-ray bands will help us address this problem. This is beyond the scope of our present study and will be done in the near future.

Another point worthy of mention is that the black hole mass data in Merloni et al. (2003) were mainly obtained from the literature. This could introduce scatter due to the different mass measurement techniques. In our present study the black hole masses of AGNs were estimated from the broad emission-line and continuum properties using the same method, which does not introduce any additional bias. In addition, the black hole masses in our sample span a relatively smaller range than that in Merloni et al. (2003), since we only include broad-line AGNs.

4.2. Relativistic Beaming and Other Uncertainties

Because the radio emission is produced by the relativistic jet, Doppler boosting of the synchrotron radiation (namely, the relativistic beaming) would affect the observed radio flux significantly. Here we try to address the question of whether the observed larger fundamental plane coefficient $\xi_{RX}$ (or the larger radio luminosity) of radio-loud sources is due to the Doppler boosting effect.

If the radio emission of both radio-loud and radio-quiet quasars is from jets, the larger radio luminosity observed in radio-loud sources can be considered to have much stronger Doppler-boosting effect than radio-quiet AGNs. In other words, we can assume that the radio emission of radio-quiet AGNs is unbeamed. In § 3.3, we showed that the soft X-ray emission of broad-line AGNs is probably isotropic and unbeamed for both radio-loud and radio-quiet sources. Therefore, for a radio-loud quasar, its intrinsic radio luminosity ($L_{r, \text{jet}}$) (unbeamed) may be estimated with its observed X-ray luminosity through the $L_{r, X}$ correlation derived from radio-quiet sources. We will use the ratio between the observed radio luminosity ($L_r$) and the intrinsic radio luminosity ($L_{r, \text{jet}}$) to represent the boosting factor of radio-loud sources. The equation describing the Doppler boosting effect was given by Heinz & Merloni (2004):

$$L_r = L_{r, \text{jet}} \left[ \frac{1}{1 + \beta \cos \theta} \right]^{\frac{1}{\alpha_r}} + \frac{1}{1 - \beta \cos \theta} \right]^{\frac{1}{\alpha_r}}$$

In Figure 13 we show the distribution of the boosting factor ($L_r/L_{r, \text{jet}}$) of the radio-loud subsample (left) and the boosting factor as a function of the inclination angle $\theta$ (right) when a different Lorentz factor ($\Gamma$) is given. It is apparent in Figure 13 that only with smaller $\theta$ (<5°) and larger $\Gamma$ (>10) can we produce boosting factors as high as 1000. Such conditions can only be met in BL Lac objects and are not likely to be the case for normal broad-line AGNs studied in this work. With the typical Lorentz factor of $\Gamma \sim 5$ for broad-line AGNs (Orr & Browne 1982) and a nonnegligible inclination angle ($\theta \gtrsim 10^\circ$; Maraschi & Rovetti 1994), the boosting value is estimated to be less than 30. As can
be seen in Figure 13, it is about half of radio-loud sources whose boosting factors are larger than the predicted maximum boosting value. Therefore, although the Doppler-boosting effect indeed has a significant influence on the radio emission of radio-loud AGNs, this effect alone is not enough to explain the observed larger radio luminosity of radio-loud broad-line AGNs. This is consistent with the result given by Heinz & Merloni (2004) for the case of unbeamed X-ray emission.

The nonsimultaneous observations in the radio, X-ray, and optical bands for sources in our sample may lead to other uncertainties. Both the ROSAT and FIRST surveys were conducted in the 1990s (Becker et al. 1995; Voges et al. 1999; Britzen et al. 2007). SDSS-I observations started in 1998 and ended in 2005 (York et al. 2000). So the data in different bands were obtained within 10 years or so. Unless the luminosities of most objects in our sample varied significantly in these years, our result may not be affected too much due to this effect. In addition, several (~2–3) factors change of the luminosities of some individual objects have little influence on the statistically significant results derived here for a large sample. However, as broad-line AGNs often show X-ray variabilities in timescales from hours to decades, the nonsimultaneous observations could be an issue if the X-ray fluxes of AGNs vary significantly. Therefore, simultaneous observations in different bands for a sample of broad-line AGNs are still needed to confirm our results, although they are difficult to conduct for a large sample.

4.3. Emission Mechanisms

The existence of the AGN radio-loud and radio-quiet dichotomy is still an unsolved issue. There are indications that the radio
emission of radio-quiet AGNs is likely produced by a weak (subrelativistic) jet near the black hole (Blundell & Beasley 1998; Leipski et al. 2006), while radio-loud quasars are usually associated with large-scale jets of higher radio power (Rawlings & Saunders 1991; Miller et al. 1993). Here we fit the black hole fundamental plane relation for a broad-line AGN sample and find that the coefficients are quite different between radio-loud and radio-quiet quasars, especially the coefficient $\xi_{RX}$, which is steeper for radio-loud objects. We also find that the larger radio luminosities of radio-loud AGNs cannot be produced by the Doppler boosting effect alone. Therefore, the radio emission mechanism may be quite different for radio-loud and radio-quiet AGNs. This kind of difference can be caused by many uncertain physical parameters, including the detailed disk/jet magnetic field strength and configuration, the electron energy distribution, and the black hole spin, etc. (Heinz & Sunyaev 2003; Sikora et al. 2007). More detailed observational and theoretical studies are still required.

For the soft X-ray emission, we have shown that the correlation slopes between the soft X-ray luminosity and the broad emission-line luminosity are all around 1 for both radio-loud and radio-quiet AGNs. Therefore, the soft X-ray emission is probably produced via the accretion process near the central black hole, and it is unbeamed and isotropic for both radio-loud and radio-quiet sources. Otherwise, larger scatters should exist in the $L_X$ vs. $L_{H\alpha}/L_{Mg\text{II}}$ relation. However, there are many uncertain factors related to the origin of the soft X-ray emissions of AGNs (the accretion flow, hot corona, and warm absorber, etc.). A detailed study of the soft X-ray spectra for a larger sample of broad-line AGNs may give us clues to understand the origin of the soft X-ray emissions.

4.4. Conclusion

We revisited the fundamental plane relation of the black hole activity based on a large broad-line AGN sample selected on the basis of the cross-identification of the RASS, SDSS, and FIRST catalogs. The results of our work confirm the main result of Wang et al. (2006), namely, the black hole fundamental plane relation of the radio-quiet subsample is different from that of the radio-loud subsample; the coefficient $\xi_{RX}$ becomes larger as the radio-loudness increases; the black hole mass seems unimportant in the black hole fundamental plane relation. We also found that the soft X-ray emission is most likely produced via the accretion process of the central black hole for both radio-quiet and radio-loud sources. In particular, for radio-loud sources, the jet contribution to the soft X-ray emission seems unimportant and the Doppler boosting of the relativistic jet is also weak in the soft X-ray band. Moreover, by dividing the radio-loud and radio-quiet samples into different redshift bins, we studied the evolution of the fundamental plane relation. For radio-quiet sources, there seems to be no clear evolution, while for radio-loud objects, the correlation coefficient $\xi_{RM}$ tends to decrease as the redshift increases. We found that the evolution of the radio spectral index can help us at least partly understand such an evolution. Finally, we briefly discussed the beaming effect and some other uncertainties associated with the fundamental plane relation derived here. We found that Doppler boosting effect indeed has significant influence on the radio emission of radio-loud AGNs, but this effect alone is not enough to explain the observed radio luminosity of the radio-loud sources.

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APPENDIX

RADIO-LOUD NARROW-LINE SEYFERT 1 GALAXIES IN OUR SAMPLE

Narrow-line Seyfert 1 galaxies (NLS1’s) are a subclass of the AGN population. Their optical broad permitted emission lines are usually narrower (FWHM$_{12}$ < 2000 km s$^{-1}$) than that in normal broad-line Seyfert 1 galaxies (BLS1’s) (Osterbrock & Pogge 1985). The NLS1’s also show weak [O iii] $\lambda$5007/H$_{\text{total}}$ emission and strong Fe ii emissions (Boroson & Green 1992). Recently, Komossa et al. (2006) argued that the classical criterion (FWHM$_{12}$ < 2000 km s$^{-1}$) is not well defined or may even be completely arbitrary. They suggested that $R_{4750} > 0.5$ may be a physically more meaningful criterion to distinguish NLS1’s from ordinary BLS1’s.

The study of the physical mechanism of NLS1’s is still ongoing. There is growing evidence that most NLS1’s are objects with low black hole masses and high accretion rates, close to or even above the Eddington accretion rate (Colin & Kawaguchi 2004).

Radio-loud NLS1’s are rare objects in the NLS1 population (Komossa et al. 2006). In order to understand their radio properties, it is important to expand the number of radio-loud NLS1’s. Anderson et al. (2007) roughly examined the optical broad permitted emission line of AGNs in their catalog. They marked those objects that have FWHM$_{12}$ < 2000 km s$^{-1}$ as “NLS1?” in the comment columns of their tables. Seventy-four of these objects have optical spectra from SDSS and are detected in the FIRST radio survey and thus are included in our analysis in this paper. We calculated the radio-loudness values for these objects, and found that five of them are radio-loud. We list the properties of these five sources in Table 5.

In a newly published work Yuan et al. (2008) present a comprehensive study of a sample of 23 radio-loud NLS1 galaxies. Among those 23 sources, two radio-loud NLS1’s are also discovered in our present work, which are SDSS J144318.56$+$472556.7 and SDSS J114654.28$+$323652.3. Two these independent studies confirm the nature of radio-loud NLS1’s of these two objects.

The optical Fe ii strength, $R_{4750}$, is the ratio of the Fe ii complex between the rest wavelength $\lambda$4434 $\lambda$ and $\lambda$4684 to the total H$\beta$ flux, including the narrow component (Boroson & Green 1992).

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TABLE 5

Radio-Loud Narrow-Line Seyfert 1 Galaxies

| Name                   | z  | FWHM$_{12}$/1 km s$^{-1}$ | log(M$_{BH}$/M$_{\odot}$) | log R | $R_{4750}$ |
|------------------------|----|--------------------------|---------------------------|-------|------------|
| SDSS J144318.56$+$472556.7$^*$ | 0.703 | 1810.1                   | 7.14                      | 2.91  | 5.50       |
| SDSS J114654.28$+$323652.3         | 0.465 | 2374.3                   | 7.43                      | 1.98  | 1.59       |
| SDSS J073320.84$+$390505.2          | 0.664 | 2867.8                   | 7.86                      | 2.80  | 3.27       |
| SDSS J154510.96$+$345246.9          | 0.516 | 3269.7                   | 8.13                      | 1.34  | 0.74       |
| SDSS J123304.05$-$003134.1$^*$     | 0.471 | 3297.7                   | 7.81                      | 2.32  | 2.18       |

$^*$ H$\beta$ emission line is fitted with just one Gaussian.

*H/β* emission line is fitted with just one Gaussian.