Chin. J. Astron. Astrophys. Vol. 3 (2003), No. 3, 212–224
(*http://www.chjaa.org* or *http://chjaa.bao.ac.cn*)

Chinese Journal of
Astronomy and
Astrophysics

On the Correlation between Radio Properties and Black Hole Mass of Quasars *

Xue-Guang Zhang, Ting-Gui Wang and You-Jun Lu

Center for Astrophysics, and Department of Astronomy and Applied Physics,
University of Science and Technology of China, Hefei 230026; zxg@mail.ustc.edu.cn

Received 2003 January 15; accepted 2003 April 7

Abstract The question whether the radio properties of quasars are related to the mass of the central black hole or the accretion rate is important for our understanding of the formation of relativistic jets, but no consensus has been reached from statistical analyses. Using two large quasar samples, one radio-selected, one optical-selected, we re-examined these relations and find that previous differences between radio- and optical- selected samples can be ascribed, at least partly, to the effect of the narrow line component. All previous claimed correlations are much weaker, if exist at all.

Key words: galaxies: active — galaxies: nuclei — quasars — black hole

1 INTRODUCTION

There is now strong evidence that supermassive black-holes are ubiquitous in active or nearby inactive galaxies (e.g., van der Marel 1999; Kormendy & Gebhardt 2001; Kormendy & Richstone 1995; Ho 1999). Kinematic studies of nuclear gas disks (Harms et al. 1994) and dynamical studies of stars in galactic centers, using high spatial resolution data (Gebhardt et al. 2002), have yielded estimates of the central black hole (BH) mass for several tens of normal galaxies. These experiments have led to the discovery of several strong correlations between the black hole mass and the properties of the galaxies (Gebhardt et al. 2000; Ferrarese & Merritt 2000; Tremaine et al. 2002). However, these techniques are most useful for inactive galaxies and are much less powerful for AGNs. The reason is that the radiation due to nuclear activity swamps the light from the host galaxies, and that it is difficult to resolve spatially the kinematics due to their relative large distance. Nonetheless, the BH masses in AGNs can be estimated via the virial theorem, $M \propto R \times V^2$, assuming the broad line region (BLR) kinematics is largely keplerian. Keplerian motion of the BLR gas is supported by the intensive studies of NGC 5548 (Wanders et al. 1997), NGC 7469 (Peterson & Wandel 1999) and 3C390.3 (Peterson & Wandel

* Supported by the National Natural Science Foundation of China.

2000). Therefore, the broad line width can be used as a measure of the characteristic velocity. BLR sizes can be estimated through the reverberation mapping technique (for details of this technique see Peterson 1993). The consistency between the two methods is demonstrated by the consistency between the BH masses estimated from the reverberation mapping technique and spatially resolved kinematics (Gebhardt et al. 2000; Ferrarese et al. 2001).

Using the reverberation mapping technique, BLR sizes are currently known for several tens of objects. Kaspi et al. (2000) found a useful empirical relation between the BLR size and the nuclear luminosity, $R \propto L^{0.7}_{5100\text{Å}}$ for those objects in which the BLR size is measured by the reverberation mapping technique. This empirical relation also holds for other broad line AGNs, and black hole masses can be estimated for those objects with measurements of the broad line width and continuum luminosity. However, we should carefully deal with the correlation. Wang & Zhang (2003) found that very low luminosity AGNs do not follow such a relation. Fortunately, the objects checked in our sample are all luminous AGNs.

Using the BH masses estimated with the above techniques, several authors investigated the relation between the radio properties and the BH mass or the accretion rate, and they obtained very different results. Franceschini et al. (1998) found that the radio luminosity $L_{5\text{GHz}}$ has a steep dependence with the BH mass M_{BH}, $L_{5\text{GHz}} \propto M_{\text{BH}}^{2.6\pm0.29}$ for a sample of nearby galaxies. Nelson (2000) also demonstrated that the radio power has a strong correlation with the BH mass M_{BH} for radio quiet AGNs. Laor (2000) showed that in the BQS sample, all radio quiet QSOs have BH masses $M_{\text{BH}} < 3 \times 10^8\, M_\odot$ while nearly all radio loud quasars have BH masses $M_{\text{BH}} > 10^9\, M_\odot$, and there is little overlap among radio quiet and radio loud QSOs. Ho (2002) examined a large sample of low luminosity AGNs, Seyfert galaxies and QSOs and found that the radio loudness (RL) depends strongly on the dimensionless accretion rate $\dot{m}$. He suggested the upper envelope or loose relation $L_{\text{rad}} \propto M_{\text{BH}}^{2.5}$ (see also Dunlop et al. 2002). Lacy et al. (2001) obtained $L_{\text{rad}} \propto M_{\text{BH}}^{1.9\pm0.2}(L/L_{\text{Edd}})^{1.0}$ for radio quiet or loud QSOs using the First Bright Quasar Sample (FBQS).

However, Gu, Cao & Jiang (2001, hereafter Gu01) found that RL decreases with the BH mass for a sample of radio quasars, and that a significant fraction of their sources has small BH masses with $M_{\text{BH}} < 10^8 M_\odot$. Oshlack, Webster & Whiting (2002, hereafter OWW) obtained a similar result for a flat spectrum radio quasar sample and concluded that there is no upper envelope in $L_{\text{rad}} - M_{\text{BH}}$ for radio loud QSOs. In addition, these authors found an inverse correlation between radio loudness and the black hole mass. The latter authors also argued that the optical selected quasar sample tends to miss optically less luminous radio-loud sources, i.e., objects with small BH masses.

We noticed that the narrow line component has not been subtracted for some objects in the Gu01 sample and for all in the OWW sample. Although BH masses can be estimated by the reverberation mapping technique and some empirical relation between the size of BLR and continuum luminosity, the approach only works well for the broad lines. The inclusion of the narrow component will underestimate the broad line width, resulting in smaller BH masses. A significant fraction of low BH mass objects found in Gu01 and OWW may be due to this.

In this paper, we re-examine the correlation between radio properties and the black hole mass or accretion rate for a larger radio loud sample and a larger radio quiet sample, and properly take care of the effects of the narrow line component. The paper is organized as follows: in the next section, we describe the data sample. In Section 3, we present our results. Finally, a brief conclusion is given in Section 4. The cosmological parameters $H_0 = 75$ km s^{-1}Mpc^{-1} and $q_0 = 0.5$ are adopted.

2 DATA AND METHODS

We combine the samples used by Gu01 and OWW (refer to the definition of the samples) as the radio-selected sample, except that the line widths for PKS 2143–156 and 0237–233 quoted by the above authors are likely to be wrong. For PKS 2143–156, Jackson & Browne (1991) obtained a full width at half maximum (FWHM) of Hβ of 4690 km s^{-1} whereas OWW had 836 km s^{-1}. PKS 0237–233 had a width of 3 000 km s^{-1} in Baker et al. (1994) but Gu01 quoted 931 km s^{-1}. We adopt the values of Jackson & Browne (1991) and Baker et al. (1994). In addition, we re-examined the optical spectrum of PKS 1128–047 obtained by Francis (2001), and noticed that Hα is blended with the strong [NII]λ6548, 6583Å in the low resolution and low S/N ratio spectrum. The peak intensity of [NII]λ6583Å is higher than that of Hα. The Hα+[NII] blending can be well fitted with three narrow lines and do not require a broad component of Hα. Strong [SII]λ6718, 6731Å and [OII]λ 3727Å also support this deblending approach. Therefore, it seems that the OWW measurement of Hα width for this object is questionable, and we ignore it in the further analysis.

As mentioned in the Introduction, the reverberation mapping technique has only been applied to the BLR, and any empirical relation derived based on this technique is only valid for the broad line component. However, the narrow line component was not subtracted for 44 objects in Gu01 and all objects in OWW. In active galaxies, there are two distinct emission line regions, a broad line region (BLR) which emits only the permitted and semi-forbidden lines, while a much larger narrow line region (NLR), which contributes both permitted and forbidden lines. As a result, a permitted line usually consists of both a broad and a narrow component, while a forbidden line has only a narrow component. OWW fitted the emission line profile (including both the narrow component from the narrow line region and the broad component from the broad line region) with either a single Lorentz or Gaussian profile. Since the width of the broad line component is much larger than that of a narrow component, a weak broad component mimics the broad wings of a Lorentzian component. Therefore, it is not a surprise that a line with a strong narrow component can be described by a Lorentzian function in case of low spectral resolution and/or low S/N data such as used by OWW. It was found that the broad line spectrum is similar to the zero order in different AGNs, and so is the narrow line spectrum. However, the broad and narrow line spectra are very different. As a result, the line ratio of [OIII]λ5007/Hβ can be used as a rough indicator of the relative contributions of the broad and narrow components in an AGN.

In order to examine the effect of narrow line component on the line width measurement, hence the BH mass estimation, we compile the [OIII]λ5007 and Hβ equivalent widths from the literature for the objects in Gu01 and OWW. We collected the EWs of [OIII]λ5007 and Hβ for 62 of 85 quasars in the Gu01 sample, and for 30 of 39 quasars in OWW sample.

For checking whether radio and optical selected samples are different, we take the low redshift quasars from Large Bright Quasar Survey (LBQS) for comparison. We restrict to low redshifts so that Hβ or/and MgII lines are detected in the optical band. Radio observations have been carried out at 8.4 GHz for a substantial fraction of LBQS, including most low redshift objects (Hooper et al. 1996; Visnovsky et al. 1992; Hooper et al. 1995). The line parameters were measured by Forster et al. (2001) and the narrow line component was subtracted. Restriction to objects with both pointed radio observations and measurement of at least one of MgII or Hβ width resulted in a sample of 160 quasars, in which 14 are radio loud according to the formal definition of RL > 10, where RL denotes the flux ratio f_ν(5GHz)/f$_\nu$(5100Å).

For consistency when we compare the radio and optical selected samples, we converted all 5 GHz data to 8.4 GHz with an average radio spectral index $\alpha = -0.5$ ($s_\nu \propto \nu^{-\alpha}$). Given the closeness of the two frequencies, this should not introduce large uncertainties in the radio loudness or radio power.

BH masses are estimated using either the Hβ line width and the empirical relation between the BLR size and the optical luminosity (Kaspi et al. 2000; Wandel 1999), or using the MgII line width and the empirical relation between the BLR size and the mono-chromate luminosity at 3000Å (McLure & Jarvis 2002). The basic underlying assumptions are: (1) the BLR is virialized; (2) the empirical relation between the BLR size and the optical luminosity holds; and (3) we take $V = k \times \mathrm{FWHM}$ with $k = 1.5$, which represents a reasonable choice for radio loud quasars, as suggested by Mculure & Dunlop (2001). The empirical size-luminosity relation is derived based on the sample of mainly radio quiet objects, and it is likely that only the disk luminosity is related to the broad line excitation. However, particularly for the flat radio sources of radio loud quasars, the continuum emission consists of both a disk component and a beamed jet component. The inclusion of the jet component will cause the reduction of the line EW by a factor of

$$\frac{\mathrm{EW}_{\mathrm{disk+jet}}}{\mathrm{EW}_{\mathrm{disk}}} = \frac{L_{\mathrm{disk}}}{L_{\mathrm{disk+jet}}}, \qquad (1)$$

where L_{disk}, $L_{\mathrm{jet+disk}}$ are continuum luminosities of the disk and of the disk plus jet at the wavelength of the emission line, and $\mathrm{EW}_{\mathrm{disk}}$ and $\mathrm{EW}_{\mathrm{disk+jet}}$, are the line EWs when there is only the disk continuum, and when both the disk and the jet continua are present. We use Eq. 1 to correct for the jet contribution. The modification to take account of the velocity anisotropy is also straightforward with the inclination and model of anisotropy, e.g., one needs only to rewrite k as $k = 0.5/\sin\theta$ for a disk-like BLR (Wills & Browne 1996), and a slightly complicated expression, for a flat BLR with both an isotropic and a disk-like velocity components (McLure & Dunlop 2001). However, both the velocity distribution and the inclination are difficult to obtain. We do not try to correct this for individual object, but we correct the systematic difference between the flat and steep spectrum by assuming that the intrinsic width of the two are statistically the same and the difference is due to the inclination effect (see below).

Following Ho (2002), the parameter λ is defined as $\lambda = L_{\mathrm{bol}}/L_{\mathrm{Edd}}$, where the Eddington luminosity is $L_{\mathrm{Edd}} = 1.3 \times (M_{\mathrm{BH}}/M_\odot)10^{38}$ erg s^{-1}, and the bolometric luminosity is estimated using the average SED for quasars by setting $L_{\mathrm{bol}} \approx 9\lambda L_\lambda(5100\text{Å})$ (Kaspi et al. 2000), the continuum luminosity having been corrected for the jet contribution using Eq. 1. In the case of a constant radiative efficiency, this parameter provides an estimate of the accretion rate.

3 RESULTS

Table 1 lists the emission line properties and BH masses for 57 objects without the narrow line subtraction. Figure 1a shows that the [OIII]λ5007/Hβ ratio is correlated with the Hβ line width for the 57 objects in which line decomposition was not carried out. A Spearman rank correlation analysis gives a correlation coefficient (r_s) of –0.78, which corresponds to a chance probability of $P_r < 10^{-10}$. However, no correlation is found for the 42 objects in Gu01 for which the narrow line component has been subtracted (see Fig. 1).

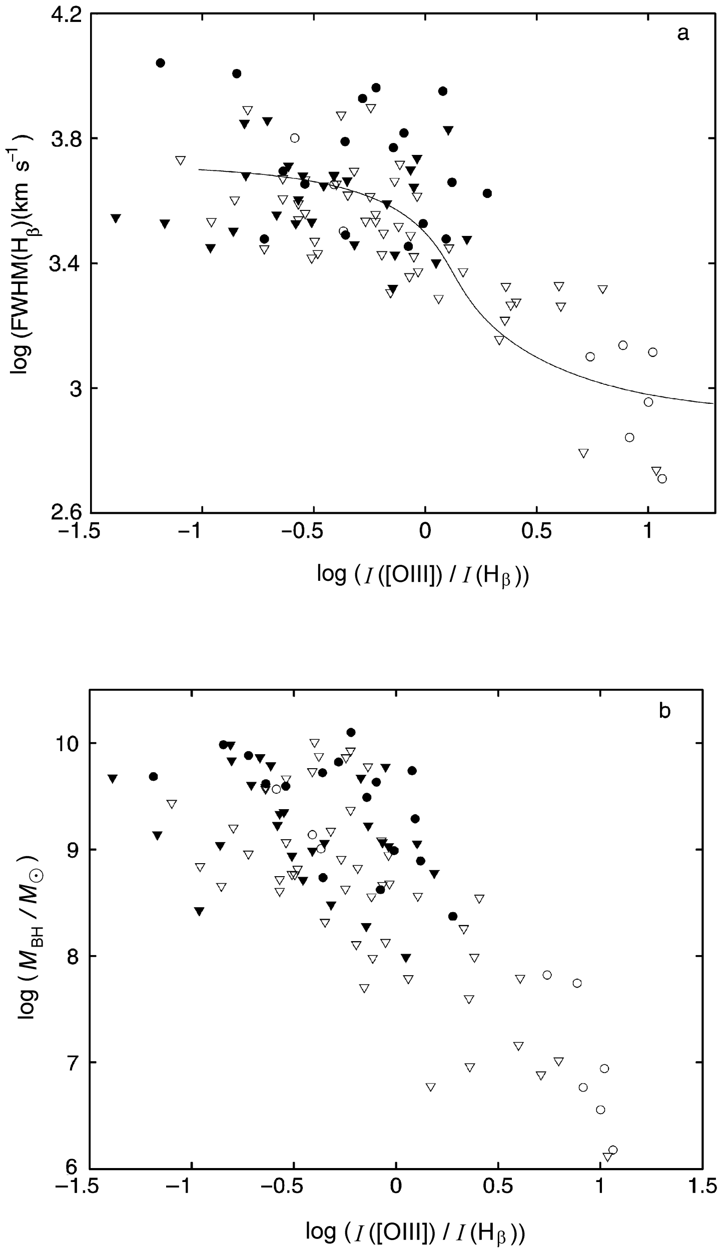

Fig. 1 Effect of narrow line contamination on the line width and on the BH mass estimate in the Gu01 and OWW samples. Panel (a) plots O[III]λ5007/Hβ versus FWHM, and panel (b), O[III]λ5007/Hβ versus $M_{\rm BH}$ estimated by OWW and Gu01. Circles (triangles) represent steep (flat) spectrum quasars, and filled (open) symbols for objects in which narrow line has (has not) been subtracted. The solid line on the top panel refers to the toy model of two component emission line (see text).

Table 1 Properties of Emission Lines and the BH Masses

1	2	3	4	5	6	7	1	2	3	4	5	6	7
steep-spectrum quarsars of Gu01													
0210+860	0.186	10.04	37.6	3	6.851		0437+785	0.454	0.39	110.2	7	9.138	9.138
0723+679	0.846	0.43	70	3	9.114	9.006	0809+483	0.871	5.50	15.8	3	8.382	
1634+628	0.988	7.71	206.3	3	7.743		1849+670	0.657	0.26	102.5	4	9.566	9.566
1945+725	0.303	11.56	15.9	4	6.735		2218+395	0.655	8.25	8.7	5	7.506	
2342+821	0.735	10.49	13.1	3	7.558								
flat-spectrum quarsars of Gu01													
0024+348	0.333	10.88	2.5	5	6.762		0110+495	0.395	0.29	75	2	8.676	8.920
0133+476	0.859	0.33	9.2	3	9.064	8.670	0135–247	0.831	0.40	79	1	9.602	9.861
0444+634	0.781	0.54	47.6	5	8.658	8.763	0454–810	0.444	0.566	30.1	6	8.516	8.482
0514–459	0.194	0.70	7.9	7	7.998	7.557	0906+430	0.668	4.06	3.2	3	8.361	
0954+556	0.901	2.15	8.2	3	8.541		1034–293	0.312	0.92	9.7	6	9.178	8.780
1045–188	0.595	5.13	5.8	7	7.272		1202–262	0.789	0.42	130	1	9.400	9.400
1244–255	0.633	0.73	64	1	9.437	9.634	1642+690	0.751	2.42	9.2	3	8.237	
1726+455	0.714	0.32	28	2	8.673	8.617	1856+737	0.46	0.39	118	2	9.256	9.256
2155–152	0.672	2.28	5.2	6	8.021		2255–282	0.926	0.60	59	1	9.609	9.780
flat-spectrum quarsars of OWW													
0221+067	0.51	2.30	6.9	8	7.294		0327–241	0.888	0.14	25.1	8	8.598	8.986
0454+066	0.405	3.98	5.3	8	7.576		0502+079	0.954	0.45	3.3	8	8.877	8.649
0912+029	0.427	0.64	74.8	8	7.719	8.438	0925–203	0.348	0.31	56.4	8	8.462	9.096
1016–311	0.794	0.60	101.9	8	8.892	8.892	1020–103	0.196	0.57	90.4	8	9.418	10.196
1034–293	0.312	0.27	12.9	8	8.752	8.939	1036–154	0.525	0.77	36.9	8	7.805	8.311
1101–325	0.355	0.65	42.7	8	8.606	9.155	1107–187	0.497	1.48	8.3	8	7.057	
1136–135	0.557	0.85	82.9	8	8.663	9.414	1200–051	0.381	0.93	49.7	8	8.413	9.008
1226+023	0.158	0.23	50.5	8	9.297	9.897	1237–101	0.751	0.08	34.1	8	9.286	9.767
1254–333	0.190	0.16	70.8	8	8.831	9.534	1302–102	0.286	0.11	28.2	8	8.749	9.173
1352–104	0.332	1.28	82.1	8	8.146		1359–281	0.803	2.56	150.7	8	8.068	
1510–089	0.362	0.19	70.8	8	8.587	9.290	1546+027	0.415	0.27	79.8	8	8.310	9.050
1706+006	0.449	6.26	44.5	8	6.784		1725+044	0.296	0.89	51.9	8	7.849	8.458
1954–388	0.626	0.76	16.0	8	8.636	8.887	2004–447	0.240	1.15	57.5	8	7.479	
2120+099	0.932	0.86	124.7	8	8.188	8.188	2128–123	0.499	0.29	67.9	8	9.305	9.996
2143–156	0.698	0.23	79.4	8	9.177	9.915	2329–415	0.671	0.48	67.0	8	8.929	9.615

Notes: Column (1) is the source name, col. (2) is the redshift of the source, col. (3) is the intensity ratio O[III]λ5007/Hβ, col. (4) is the EW of Hβ, in units of Å, col. (5) is the references of the line intensity and EW, col. (6) and col. (7) list the BH masses before and after considering the subtraction of the jet contribution and other corrections discussed above, in the form of $\log(M_{\rm BH}/M_\odot)$. The BH masses of quasars from the OWW sample listed in col. (5) are collected from OWW using $k=\sqrt{3}/2$ to calculate the keplerian velocity; when corrected, we use $k=3/2$. References: 1: Baker et al. (1999); 2: Henstock et al. (1997); 3: Lawrence et al. (1996); 4: Stickel & Kühr (1993a); 5: Stickel & Kühr (1993b); 6: Stickel et al. (1989); 7: Stickel et al. (1993); 8: Francis (2001).

This suggests that the line width estimate in Gu01 and OWW are significantly affected by the narrow component for the strong [OIII]λ5007 objects. To see if this trend is consistent with the contamination of narrow line component, we consider a simple two component model for Hβ line profile: a broad Gaussian component plus a narrow Gaussian component. In this model, the line profile can be written as:

$$I(v) = I_{\rm n} \exp(-4{\rm ln}2\ v^2/{\rm FWHM}_{\rm n}^2) + I_{\rm b} \exp(-4{\rm ln}2\ v^2/{\rm FWHM}_{\rm b}^2), \tag{2}$$

where $\rm FWHM_n$ and $\rm FWHM_b$ are the FWHM of narrow and broad component, respectively, and $I_{\rm n}$ and $I_{\rm b}$ are the intensities of broad and narrow line components up to a constant. From Eq. 2, it is straightforward to relate the FWHM of the total line to other quantities:

$$tf\ {\rm e}^{-x^2{\rm ln}2} - (1-f){\rm e}^{-\frac{x^2{\rm ln}2}{t^2}} = \frac{1}{2}(tf+1-f), \tag{3}$$

where $f = I_{\rm n}/I_{\rm tot}$, $x = {\rm FWHM_{tot}}/{\rm FWHM_n}$ and $t = {\rm FWHM_b}/{\rm FWHM_n}$. The observed correlation between the FWHM of Hβ and the [OIII]λ5007/Hβ ratio is consistent with this toy model if we choose the parameters, $\rm FWHM_b \sim (5-8)\times 10^3$ km s^{-1}, $\rm FWHM_n \sim (300-700)$ km s^{-1}, and [OIII]λ5007/H$\beta_{\rm n} = 11$ (Fig. 1a). The last value is consistent with the mean observed [OIII]λ5007/Hβ ratio for the narrow line spectrum of Seyfert galaxies. The narrow component can significantly alter the total line width for [OIII]λ5007/H$\beta > 1$ as seen in the figure. For [OIII]λ5007/H$\beta < 1.0$, the line width is not severely affected by the narrow component. For a few objects in this sample, the [OIII]λ5007/Hβ ratio is larger than 10, and the line is dominated by the narrow component.

To see the impact of the narrow line component on the BH mass estimate, Figure 1b shows the BH mass estimated by Gu01 and OWW versus the [OIII]λ5007/Hβ ratio for the above 57 objects. The correlation is obvious with the Spearman rank correlation coefficient $r_s = -0.72$, corresponding to a probability $< 10^{-10}$ of the null hypothesis being true. Therefore, it is necessary to correct for this effect before any further correlation analysis of BH mass with other quantities. There are several choices of doing this. A good approach is to subtract the narrow component by fitting some two-component model to the observed spectra. However, we are not able to obtain all these spectra. For intermediate [OIII]λ5007/Hβ ratios, it is possible to estimate roughly the width of the broad line from the measured width of Hβ and the width of [OIII]λ5007 by assuming Gaussian profiles for both components and a typical [OIII]λ5007/H$\beta_{\rm n} = 11$ for the narrow component (see Eq. 2). For objects with large [OIII]λ5007/Hβ, such an approach is not reliable because of the dominance of the narrow component. In addition, the intrinsic [OIII]λ5007/Hβ_n for the narrow line component is uncertain and may vary from object to object, so we do not adopt this approach. In the later analysis, we will consider objects with [OIII]λ5007/Hβ ratio smaller than 1.0 or with the narrow component subtracted as "credible". If only "credible" data are considered, then almost all the radio loud objects in Gu01 and OWW have BH masses larger than $10^8\,M_\odot$.

Before proceeding further, it is necessary to correct the systematic inclination effect on the line width for the flat spectrum radio quasars. There is evidence that the BLR is disk-like in radio loud quasars (Wills & Browne 1996; Zhang & Wu 2002). Rokaki et al. (2003) also have found that there is a good correlation between the orientation θ and the parameter FWHM(Hα) for superluminal quasars and also argued that the BLR is disk-like. However, we cannot find the disk orientation for all the quasars in our sample, we can only correct the effect on average. Since flat spectrum radio source are seen face-on, they show smaller line width on average. By considering only the "credible" objects, the average FWHMs of Hβ are 4007 and 5884 km s^{-1} for flat and steep spectrum objects, respectively. Assuming the flat and steep spectrum has statistically indistinguishable intrinsic line width, we correct the line width of a flat spectrum source by a factor 1.47, or a factor 2 in the BH mass.

It is also necessary to correct for the jet contribution to the continuum in the BH mass estimated from Eq. 1. We adopt the $\rm EW_{disk}$ of Hβ line as 100Å (Boroson & Green 1992), and correct the continuum by a factor of $EW_{obs}/100Å$ for those with EW_{obs} less than 100Å. It should be noted that this correction is small on average for either flat or steep spectrum radio loud quasars in this sample since the average EW of these radio quasars is about 70Å and 76Å, respectively, and the BH mass depends on $L_{5100Å}$ as $L^{0.7}_{5100Å}$. We also re-calculate the radio loudness using this correction to the optical flux. Now RL is an indicator of the radio emission of the jet to the disk emission. We note that there may be an additional correcting factor due to the obscuring of the continuum in objects with large [OIII]λ5007/Hβ ratio if the weakness of the broad line component is due to absorption. OWW mentioned that quasars in their sample may be partially obscured (see also Francis 2001), but they did not correct the absorption before calculating the BH mass. This correction will raise the BH mass and lower the radio loudness.

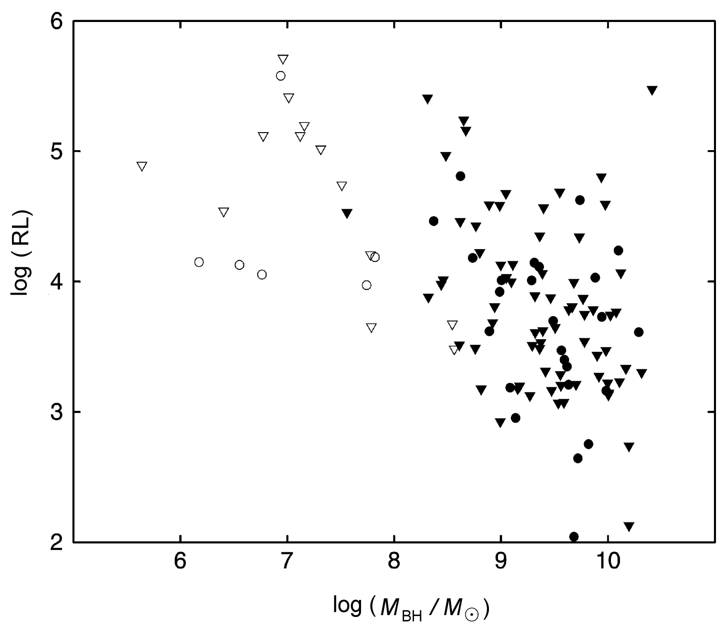

Fig. 2 BH mass M_{BH} against radio loudness RL for radio loud quasars. Flat spectrum sources are marked with triangles, steep spectrum objects with circles, filled symbols for objects with [OIII]λ5007/Hβ $<$ 1.0 or with subtracted narrow component, open symbols for those with [OIII]λ5007/Hβ $>$ 1.0 and with the narrow component not subtracted.

Figure 2 plots the black hole mass against the radio loudness for radio loud quasars. When only "credible" data are considered, the claimed anti-correlation by Gu01 and OWW is only significant at a level of 93% with the Spearman-rank correlation coefficient −0.19 for the combined sample, −0.15 for flat spectrum objects, and −0.32 for steep spectrum objects. Though the number of the steep spectrum sources is small, there is no difference between the steep and flat radio quasars on this diagram. The significant anti-correlation between radio loudness and black hole mass claimed by Gu01 and OWW is thus likely due to contamination of the narrow line component (see Fig. 2). Relativistic boosting may have a severe effect on the estimation of intrinsic radio loudness, but the correction of this effect is difficult. Jarvis & McLure (2002) adopted an average correction factor of 100 for the flat spectrum source, by assuming average

Lorentz factor of 10 for jets and no emission from the extended isotropic component. However, the luminosity of the isotropic component is likely to be much larger (by orders of magnitude) than the unbeamed power of the jet (e.g. Urry et al. 1991). As a result, the actual correction should be much smaller than what they adopted. The overall similar radio power of steep and flat radio quasars is consistent with this picture.

There is a moderately strong correlation between BH mass and radio power for the OWW and Gu01 combined data sample ($r_s = 0.41$, $P_r < 10^{-4}$) for objects with "credible" data only (see Fig. 3). The flat and steep spectrum sources appear indistinguishable on the diagram. This result is consistent with the result of Dunlop et al. (2002) who analyzed the correlation between BH mass and radio power, but is different from the result of OWW.

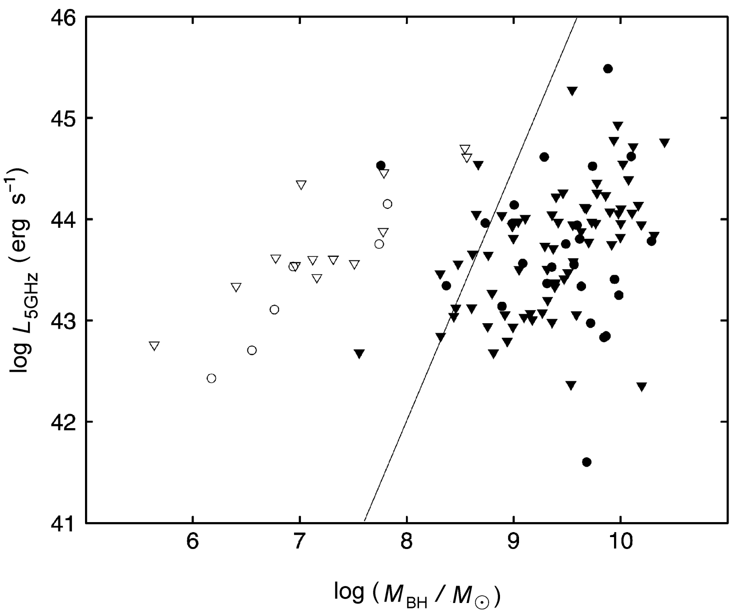

Fig. 3 BH mass versus the radio power at 5 GHz for radio loud quasars. The symbols are as in Fig. 2. The solid line presents the upper and lower envelope for radio loud quasars, $L_{\rm rad} \propto M_{\rm BH}^{2.5}$, given by Dunlop et al. (2002). This figure shows that most objects above this limit are severely affected by the narrow component.

The relationship between BH mass and radio luminosity for quasars in the LBQS sample is shown in Fig. 4. For comparison, the radio selected objects from Gu01 and OWW are also shown. Apparently, the selected quasars on average have larger BH mass with respect to the LBQS quasars. The majority (70%) of the selected quasars in the sample have BH masses larger than $10^9\,M_{\odot}$, while only 8% of quasars in the LBQS do. However, for the LBQS sample only, there is no apparent difference in the BH mass distributions for radio loud and radio quiet objects, in contrast to the BQS sample. This suggests that the radio-BH mass relation is sample-dependent, thus may be due to selection effect. In the combined radio loud and radio quiet sample, there is a weak correlation between radio power and BH mass. This reveals that any correlation between BH mass and radio power is much scattered, if exist at all.

For a sample of radio galaxies and radio loud and quiet quasars, observed with HST WFPC, Dunlop & Mclure (2002) found that the maximum radio power varied with BH mass as $P_{\rm rad}^{\rm max} \propto$

$M_{\rm BH}^{2.0-2.5}$. OWW found some of their quasars go above this upper limit, but, for most of these sources, the Hβ line width is severely affected by the narrow line component. Those with "credible" data obey this relation. However, half of the radio loud objects in the LBQS are located above this upper limit, this is not quite well understood.

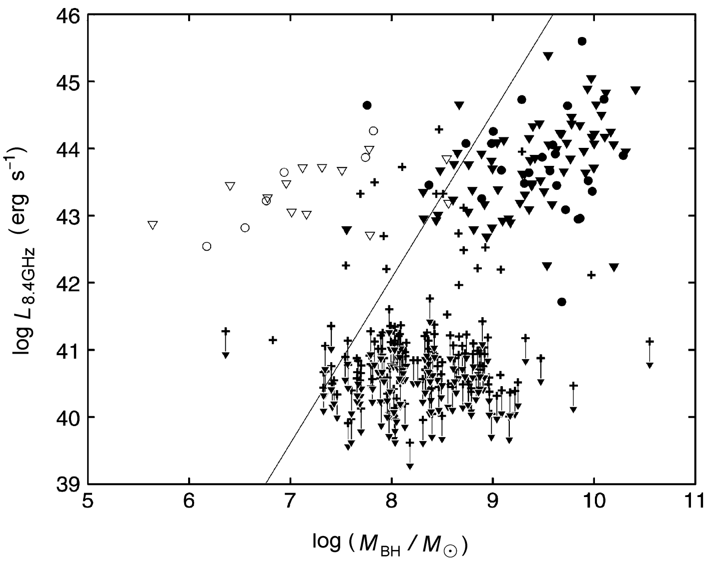

Fig. 4 Plot of $M_{\rm BH}$ versus radio luminosity at 8.4 GHz for quasars in LBQS. The solid line is the upper envelope of the relation $L_{\rm rad} \propto M_{\rm BH}^{2.5}$ (Dunlop et al. 2002). Plus symbols for the LBQS data, the other symbols are the same as in Fig. 2.

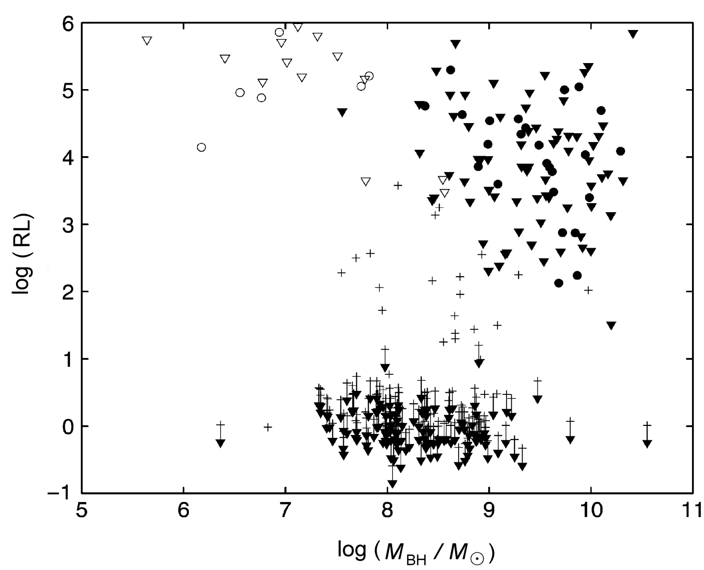

Fig. 5 Radio loudness RL versus the BH mass $M_{\rm BH}$. The symbols are as in Fig. 4.

As shown in Fig. 5, there is no significant correlation between radio loudness and BH mass for either radio loud or radio quiet samples. The Spearman correlation coefficients are 0.21 and –0.21 for the radio loud and radio quiet samples, respectively. Unlike the BQS sample, the BH masses for radio loud and radio quiet quasars are indistinguishable in the LBQS sample, though the number of radio loud objects is still small.

Ho (2002) found a tight correlation between radio loudness and accretion rate for a sample of AGNs that includes very low luminosity AGNs, Seyfert galaxies and QSOs. We plot the radio loudness RL against the parameter λ in Fig. 6. Though our sample has a similar range of RL as Ho's, the range of λ is much narrower. The radio loud quasars are located far above the relation found by Ho (2002), while the radio quiet quasars, somewhat below this line. In fact, the radio loud and radio quiet quasars have a similar range of λ, and no correlation is found between the RL and λ for the radio loud sample. It should be pointed out that Ho's sample does not contain powerful radio sources, and most radio loud objects have very low accretion rates (out of the range of Fig. 6). The radio loud objects on average have a smaller parameter λ than the radio quiet objects. The median λ is 0.037 for the radio loud sample, and 0.091 for the radio quiet sample.

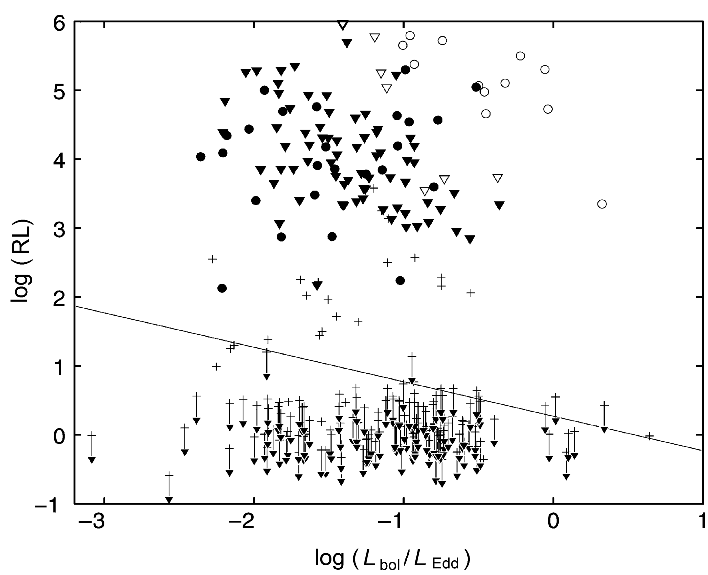

Fig. 6 $L_{\rm bol}/L_{\rm Edd}$ versus the radio loudness RL. The thick solid line marks the relation found by Ho (2002). The symbols are the same as in Fig. 4. This figure shows that radio loud quasars have a similar range of $L_{\rm bol}/L_{\rm Edd}$ as radio quiet quasars.

4 CONCLUSIONS

We re-examined the relation of radio properties with such fundamental parameters as the black hole mass and accretion rate for samples of radio and optically selected quasars, and take into account the effects of the narrow line component and the continuum of the jet component. The results show that the anti-correlation between radio loudness and BH mass for radio-selected quasars previously claimed by several authors is likely to be spurious and due to the inclusion of the narrow line component. In addition, all previously claimed correlations of radio loudness or radio power with black hole mass or accretion rate are weak or non-existent for either the radio-selected quasar sample or the optically selected LBQS sample. These results suggest that the radio emission is not simply related to the black hole mass or accretion rate, as proposed recently by several authors (e.g. Urry 2003).

Acknowledgements This work is partly supported by the National Natural Science Foundation of China (NSF-19925313 and NSF-10233030). This research has made use of the NASA/IPAC Extragalactic Database (NED), which is operated by the Jet Propulsion Laboratory, California Institute of Technology, under contract with the National Aeronautics and Space Administration.

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