On the masses of black-holes in radio-loud quasars

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19 March 2002

ABSTRACT
The central black-hole masses of a sample of radio-loud quasars are estimated by using the data of $H_β$ line-width and the optical continuum luminosity. The vast majority of the quasars in this sample have black-hole masses larger than $10^8 M_☉$, while a few quasars may contain relatively smaller black-holes. We found a significant anti-correlation between the radio-loudness and the central black-hole mass. It might imply that the jet formation is governed by the black-hole mass.

Key words: galaxies: active - galaxies: nuclei - quasars: general

1 INTRODUCTION
The radiant energy is believed to be released through accretion onto supermassive black-holes in the currently most favoured model of powering quasars. The black-hole mass is a crucial quantity in this model. There are some different approaches adopted to estimate the central black-hole mass, such as, gas kinematics near a black hole, accretion disc spectra fitting, variability in optical or X-ray wavebands (see Ho & Kormendy 2000 for a review and references therein). Due to the technical difficulties in the studies of the nuclear gas kinematics and the stellar dynamics in quasars (Nelson 2000), the central black-hole masses are derived only for a few quasars until recently.

On the assumption of the broad emission lines being produced in clouds which is gravitationally bound and orbiting with Keplerian velocities (Dibai 1981), the central black-hole mass can be derived by using the broad line width and the distance of the Broad Line Region (BLR) from the centre. The central black-hole mass is then given by $M_{bh} = R_{BLR} V^2 G^{-1}$, where $R_{BLR}$ is the radius of the BLR and $V$ is the velocity of the clouds in the BLR. This approach is strongly supported by the Keplerian dynamics of the BLR in a well explored source NGC5548 (Peterson & Wandel 1999; 2000).

The reverberation-mapping method (Peterson 1993; Netzer & Peterson 1997) is applied to measure the radius of the BLR from the time delay between the line and continuum variations. The masses of the black-holes in several tens Seyfert galaxies and quasars have been derived in this way (Wandel et al. 1999; Kaspi 2000). Generally speaking, the distances of the clouds from the black-hole measured by the reverberation-mapping method are very reliable, but it can be used only for a few long-term monitoring objects. Recently, a tight correlation is found between the radius of the BLR $R_{BLR}$ and the optical continuum luminosity $L$ (Wandel et al. 1999; Kaspi et al. 1996). Kaspi et al. (2000) suggested a $R_{BLR}$-$L$ relation: $R_{BLR} \propto L^{0.7}$, for a sample of Seyfert 1 galaxies and quasars, in which the radius of the BLR are measured with the reverberation-mapping method. So, the $R_{BLR}$ can be derived from this empirical relation, and one can therefore estimate the central black hole mass of the quasar using observed broad-line width and optical luminosity.

Franceschini, Vercellone & Fabian (1998) found a surprisingly tight correlation between black-hole mass and radio power in a small sample of nearby mostly non-active galaxies. This relation is confirmed by Mclure et al.(1999). They measured the properties of the host galaxies for a sample of Active Galactic Nuclei (AGNs) including both radio-loud and radio-quiet sources. The black-hole masses are estimated using the $M_{bh} - M_{bulge}$ relation suggested by Magorrian et al.(1998). They found that the black-holes are systematically heavier in radio-loud sources than that in their counterparts. Mclure & Dunlop (2000) found the median black-hole mass of radio-loud quasars is a factor of three larger than that of radio-quiet quasars in their sample. It is suggested that a radio-loud quasar may require a black-hole mass $> 6 \times 10^8 M_☉$ for some unknown reasons. Recently, Laor (2000a) found the similar results for a sample of 87 PG quasars. He found that most quasars (after excluding four radio intermediate quasars) with $M_{bh} > 10^9 M_☉$ are radio-loud and essentially all quasars with $M_{bh} < 3 \times 10^8 M_☉$ are radio-quiet.

In this work, we focus on radio-loud quasars. The central black hole masses are estimated for a sample of radio-loud quasars. The sample are described in Sect. 2. Section 3 contains the results. The last section is devoted to discussion. The cosmological parameters $H_0 = 75$ km s$^{-1}$ Mpc$^{-1}$ and $q_0 = 0.5$ have been adopted in this work.
2 THE SAMPLE

We consider the sample of a combination of all quasars in 1 Jy, S4 and S5 catalogues. Optical counterparts have been found for 97% of the radio sources in 1 Jy catalogue (Stickel, Meisenheimer & Kühr 1994). The S4 survey has a FWHM density $S_{\text{GHz}} \geq 0.5$ Jy (Pauliny-Toth et al. 1978), while the S5 survey contains the sources with $S_{\text{GHz}} \geq 0.25$ Jy (Kühr et al. 1981). For the S4 catalogue, about 90% of the radio sources have known optical counterparts (Stickel & Kühr 1994), and about 75% of the sources have optical counterparts in S5 catalogue (Stickel & Kühr 1996). In this combined sample, there are 358 sources identified as quasars.

We search the literature and collect all sources in this sample with available data of Hβ profiles. This leads to 86 sources including 55 flat-spectrum sources and 31 steep-spectrum sources. We find 78 sources with $M_v < -23.0$ in this sample. When more than one value of the Hβ line width are found in the literature, we take the data in the most recent reference uniformly. In Table 1, the FWHM (full width at half-maximum) of Hβ and corresponding references are listed. It appears that the FWHM of Hβ spreads a wide range from less than 1000 km s$^{-1}$ to more than 10000 km s$^{-1}$.

In this work, we use the relation between $R_{\text{BRLR}}$ and the monochromatic luminosity at 5100 Å found by Kaspi et al. (2000) to derive the radius of the BLR. We take $V = 1.5 \times H_\beta$ FWHM, suggested by Mclure & Dunlop (2000), to derive the velocity of the clouds. The black-hole mass is then estimated by using $M_{\text{bh}} = R_{\text{BRLR}} V^2 G^{-1}$. The results are given in Table 1.

3 RESULTS

The radio luminosity is K-corrected to the rest frame of the sources. The relation between the radio luminosity and the black-hole mass is present in Fig. 1. It is shown that the vast majority of quasars have black-hole masses larger than $10^8 M_\odot$ and some even $> 10^9 M_\odot$. There is a tendency that the radio luminosity increases with the black-hole mass, which is consistent with that given by Mclure et al. (1999) and Laor (2000a).

The radio loudness $R$ and black-hole mass relation is plotted in Fig. 2. We find a significant anti-correlation between them at 99.98 per cent confidence (Spearman correlation coefficient $\rho$) with a correlation coefficient: -0.4. It should be cautious that such a correlation might be caused by the common dependence of the optical continuum luminosity $L_\lambda(5100\AA)$. We therefore use the partial Spearman rank correlation method (Macklin 1982) to check this correlation. A relatively weaker correlation with a correlation coefficient -0.205 is present independent of $L_\lambda(5100\AA)$. The significance of the partial rank correlation is -1.886, which is equivalent to the deviation from a unit variance normal distribution if there is no correlation present. This anti-correlation still holds though it becomes relatively weaker while subtracting the affection of the $L_\lambda(5100\AA)$.

We use $L_{\text{bol}} \approx 9 \alpha L_\lambda(5100\AA)$ (Kaspi et al., 2000) to estimate the bolometric luminosity roughly. Figure 3. shows the distribution of sources in $M_{\text{bh}}-L_{\text{bol}}$ space. The relation between radio loudness $R$ and $L_{\text{bol}}/L_{\text{Edd}}$ is plotted in Fig. 4. No significant correlation is found between them.
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Table 1 – continued Data of the sample.

| Source     | Type | Redshift | Hβ FWHM (km s⁻¹) | Reference       | Mass (M☉) |
|------------|------|----------|------------------|-----------------|-----------|
| 1721+343   | FS   | 0.206    | 2880             | C97             | 8.516     |
| 1725+044   | FS   | 0.293    | 2090             | C97             | 8.545     |
| 1726+455   | FS   | 0.714    | 2953             | H97             | 8.695     |
| 1828+487   | SS   | 0.691    | 7050             | C97             | 10.33     |
| 1849+670   | SS   | 0.657    | 6317             | SK93a           | 9.212     |
| 1856+737   | FS   | 0.460    | 4777             | C97             | 9.386     |
| 1928+738   | FS   | 0.302    | 3360             | C97             | 9.347     |
| 1945+725   | SS   | 0.303    | 8460             | SK93a           | 6.957     |
| 2043+749   | SS   | 0.104    | 11000            | C97             | 10.10     |
| 2111+801   | FS   | 0.524    | 7050             | SK93a           | 9.090     |
| 2128−123   | SS   | 0.691    | 9159             | L96             | 10.33     |
| 2135−147   | SS   | 0.200    | 8460             | C97             | 9.386     |
| 2201+315   | FS   | 0.298    | 3380             | C97             | 9.347     |
| 2216−038   | FS   | 0.901    | 3300             | N95             | 9.718     |
| 2218+395   | SS   | 0.655    | 694              | SK93b           | 7.618     |
| 2247+140   | FS   | 0.237    | 2520             | C97             | 8.524     |
| 2251+158   | FS   | 0.859    | 2800             | N95             | 9.644     |
| 2255−282   | FS   | 0.926    | 3600             | B99             | 9.641     |
| 2311+469   | SS   | 0.741    | 5884             | SK93b           | 9.780     |
| 2342+821   | SS   | 0.735    | 1302             | L96             | 7.783     |
| 2344+092   | FS   | 0.673    | 3900             | B96             | 9.788     |
| 2345−167   | FS   | 0.576    | 4999             | JB91            | 9.198     |

References: AW91: Appenzeller & Wagner (1991). B94: Baker et al. (1994). B99: Baker et al. (1999). B96: Brotherton (1996). C97: Corbin (1997). GW94: Gelderman & Whittle (1994). H78: Hunstead et al. (1978). H97: Henstock et al. (1997). JB91: Jackson & Browne (1991). L96: Lawrence et al. (1996). M96: Marziani et al. (1996). N95: Netzer et al. (1995). S89: Stickel et al. (1989). SK93a: Stickel & Kühr (1993a). SK93b: Stickel & Kühr (1993b). S93: Stickel et al. (1993). W86: Wilkes (1986). WB86: Wills & Browne (1986). ZO90: Zheng & O’Brien (1990).

Figure 1. The radio luminosity νLν≤5G and black-hole mass relation for the sample. The open circles represent flat-spectrum sources. The filled circles represent steep-spectrum sources. The open squares represent the sources with M_V > -23.

Figure 2. The radio loudness parameter R and black-hole mass relation for the sample. The dotted line represent R = 1000 (Symbols as in Fig. 1.).

Figure 3. The L_{bol} and black-hole mass relation. The four lines indicate the location of objects radiating with a luminosity equal to L_{Edd}(Solid), 0.1L_{Edd}(dashed), 0.01L_{Edd}(dotted) and 0.001L_{Edd}(dot-dashed). Symbols are the same as Fig. 1.

4 DISCUSSION

There are 7 sources in our present sample having black-hole masses less than 10^8 M☉. It is unlike the previous conclusion that all radio-loud quasars (or galaxies) contain black-holes heavier than ~ 10^9 M☉ (Mclure et al. 1999; Mclure & Dunlop 2000; Laor 2000a). It should be noted that 5 of these 7 sources have the Hβ FWHM less than 1000 km s⁻¹. We note that 3 of these 7 sources are less luminous than M_V = -23.0. It is obviously that the narrow Hβ line leads to a small back-hole for these 7 sources. It is strongly desired to be observed perhaps with HST on these sources to see if the host galaxies of them are elliptical or not.

The widths of broad Hβ lines in the sources of our sample range from a minimum of FWHM ≈ 500 km s⁻¹ (only...
slightly broader than the narrow lines) to $\geq 10^4 \text{ km s}^{-1}$. The typical value are around 5000 km s$^{-1}$. The FWHM of narrow emission lines are usually in the range from 200 km s$^{-1}$ to 900 km s$^{-1}$, and most of them are around 350 – 400 km s$^{-1}$ (Peterson 1997). We find that the FWHM of H$_\beta$ line of these seven sources approximate to that of the typical narrow line sources (e.g. O[III]). So, we cannot rule out the possibility that the H$_\beta$ line in these sources may be the narrow component emitted from the narrow line regions. If this is the case, the present procedure of black-hole mass estimate may be problematic for these sources. So, the physical origin of these narrow H$_\beta$ lines is crucial in estimate of black-hole masses for these sources.

Recently, McLure & Dunlop (2000) considered a disc-like BLR. The disc orientation to the observer has been taken into account to estimate the central black-hole mass. They found that the estimated virial black-hole masses are quite reliable compared with that obtained from the $M_{bh} - \sigma$ relation of Gebhardt et al. (2000) and Merritt & Ferrarese (2000). For this disc-like BLR model, the real velocity of the clouds would be larger than the velocity derived directly from the observed line width if the disc is face-on. It implies that the masses of the black-hole in flat-spectrum sources might be under-estimated. The ratio $R_c$ of the core to extended radio luminosity in the rest frame of the sources can be used as an indicator of the jet orientation. We tentatively correct the orientation effect of the disc-like BLR by multiplying H$_\beta$ FWHM by a factor of $R_c^{0.1}$ (Lacy et al. 2001).

The value of the $R_c$ for most sources in our sample can be found in Cao & Jiang (2001). For those sources without measured $R_c$, we assume $R_c = 0.1$ for steep-spectrum sources and $R_c = 10$ for flat-spectrum sources, respectively (Lacy et al. 2001). We can then re-estimate the black-hole masses for the sources in our sample. The black-hole masses are plotted against the radio luminosity and the radio-loudness in Fig. 5 and Fig. 6, respectively.

Both Figs. 1 and 5 show a tendency that the radio loudness increases with the black-hole mass. It still exists if we exclude seven sources with black-hole masses $M_{bh} < 10^8 M_\odot$. It is consistent with the results given by McLure et al. (1999) and Laor (2000a). We find that the correlation has been improved in Fig. 5, where the orientation effect on the velocity of clouds is tentatively corrected. In some theoretical jet formation models, the power is generated through accretion and then extracted from the disc/black-hole rotational energy and converted into the kinetic power of the jet (Blandford & Znajek 1977; Blandford & Payne 1982). Roughly speaking, the jet formation is predominantly set by the black-hole (Laor 2000b), though the details are still unknown. It is easy to understand that the more massive black-holes always channel much of the accretion gas into powerful relativistic jets, then the larger radio luminosity appears.

The radio loudness parameter $R \equiv f_\nu(5\text{GHz})/f_\nu(4400\text{Å})$ is a good indicator of the ratio of jet power to accretion power, at least for steep-spectrum quasars. The anti-correlation between ra-
dio loudness $R$ and the black-hole mass implies that the jet formation is related with the black-hole mass. For flat-spectrum quasars, the radio emission is strongly beamed to us, and the optical emission may also be contaminated by the synchrotron emission from the jet. We then limit our analysis on steep-spectrum quasars in our sample and find a similar anti-correlation as the whole sample. The bolometric luminosity is estimated from the optical luminosity in this work. So, the masses of black-holes in flat-spectrum quasars may be over-estimated, i.e., masses given in Table 1 are the upper limits for flat-spectrum quasars if the optical continuum emission contains emission from the jets. We note that all sources with radio loudness $R < 1000$ have black-hole masses larger than $10^9 M_\odot$, which is consistent with Laor's (2000a) result.

In Fig. 3, we find that the vast majority of the objects appear to be radiating between 0.01 and 0.1 Eddington luminosity. We note that there is no correlation between radio loudness $R$ and luminosity $L_{bol}/L_{Edd}$. It may implies that the jet formation is not related to the type of accretion disc in the source.

ACKNOWLEDGMENTS

We thank the anonymous referee for the helpful comments. The support from NSFC, the NKBRSF (No. G1999075403), and Pandeng Project is gratefully acknowledged. 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 Aeronautic and Space Administration.

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