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On the black-hole mass – radio luminosity relation for flat-spectrum radio-loud quasars

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ABSTRACT

A new analysis of the connection between black-hole mass and radio luminosity in radio-selected flat-spectrum quasars (FSQ) is presented. In contrast to recent claims in the literature, we find no evidence that the black-hole masses of radio-selected FSQ are systematically lower that those of luminous optically-selected radio-loud quasars. The black-hole masses of the FSQ are estimated via the virial black-hole mass estimator which utilizes the line-width of the Hβ emission line as a tracer of the central gravitational potential. By correcting for the inevitable effects of inclination, incurred due to the FSQ being viewed close to the line of sight, we find that the black-hole masses of the FSQ with intrinsically powerful radio jets are confined, virtually exclusively, to $M_{bh} > 10^8$ M$_\odot$. This is in good agreement with previous studies of optically selected FSQ and steep-spectrum radio-loud quasars.

Finally, following the application of a realistic Doppler boosting correction, we find that the FSQ occupy a wide range in intrinsic radio luminosity, and that many sources would be more accurately classified as radio-intermediate or radio-quiet quasars. This range in radio luminosity suggests that the FSQ are fully consistent with an upper boundary on radio power of the form $L_{5\mathrm{GHz}} \propto M_{bh}^{2.5}$.

Key words: galaxies:active - galaxies:nuclei - quasars:general - radio continuum:galaxies - quasars:emission lines

1 INTRODUCTION

It is now widely believed that the energy emitted by active galactic nuclei (AGN) is a consequence of mass accretion onto a central supermassive black hole. It is possible that the mass of the central black hole may be a crucial fundamental parameter in understanding the physics of AGN.

In particular, one question which has recently received a great deal of attention in the literature is whether or not the mass of an AGN's black hole is strongly related to it's radio luminosity. This question is of importance, because if it is established that radio-loud and radio-quiet quasars have different black-hole mass distributions, it may help explain why quasars of comparable optical luminosities can differ in their radio luminosity by many orders of magnitude. On the contrary, if radio-loud and radio-quiet quasars are found to have essentially identical black-hole mass distributions, then the search for the origin of radio loudness must move to some other physical parameter such as black-hole spin.

Recent studies of the black-hole mass – radio luminosity relation ($M_{bh} - L_{\mathrm{rad}}$) relation have produced apparently contradictory results. Franceschini, Vercellone & Fabian (1998) found that high frequency (5 GHz) radio luminosity correlated strongly with the mass of the central black hole in a sample of nearby inactive galaxies from the work of Kormendy & Richstone (1995). This surprisingly tight correlation had the form $L_{5\mathrm{GHz}} \propto M_{bh}^{2.5}$, which they proposed was indicative of advection dominated accretion being the primary mechanism in controlling the radio output of objects with a low accretion rate.

Using the spectral data of Boroson & Green (1992), Laor (2000) investigated the relation between black-hole mass and radio luminosity in the Palomar-Green quasar sample using the virial black-hole mass estimator. The results from this analysis pointed to an apparent bi-modality in black-hole mass, with virtually all of the radio-loud quasars containing black holes with masses $M_{bh} > 10^9$ M$_\odot$, whereas the majority of quasars with black hole masses $M_{bh} < 3 \times 10^8$ M$_\odot$ were radio quiet.

A similar result was arrived at by McLure & Dunlop (2002) using a sample of radio-loud and radio-quiet quasars matched in terms of both redshift and optical luminosity. The results of this study indicated that the median black-hole mass of the radio-loud quasars was a factor of ~ 2 larger than that of their radio-quiet counterparts. However, the substantial over-lap between the black-hole mass distributions of the two quasar samples indicated in ad-

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dition that black-hole mass could not be the sole parameter controlling radio power.

The FIRST Bright Quasar Survey (FBQS; Gregg et al. 1996; White et al. 2000) has also been used to probe the relationship between radio luminosity and black-hole mass. The radio-loud quasars in the FBQS fill the gap between radio-quiet and radio-loud quasars and are thus ideal probes of medium power radio sources. From their study of the FBQS, Lacy et al. (2001) found a continuous variation of radio luminosity with black hole mass, in addition to evidence supporting the view that radio power also depends on the accretion rate relative to the Eddington limit.

However, two studies have recently questioned whether there is any real connection between black-hole mass and radio power. Using a compilation of objects which ranged from nearby quiescent galaxies to low-redshift quasars, Ho (2002) re-examined the relationship between black-hole mass and radio luminosity. In contrast to the studies outlined above, the results of this analysis suggested that there was no clear relationship between radio power and black-hole mass, leading the author to conclude that radio-loud AGN could be powered by black holes with a large range of masses ($10^6 \rightarrow 10^9 \mathrm{M}_\odot$).

At least part of the disagreement about what black-hole mass is required to produce a radio-loud AGN is due to different methods of classifying what constitutes 'radio-loud'. For example, the classification adopted by Ho (2002) is the so-called radio-loudness parameter $\mathcal{R}$, the ratio of radio-to-optical luminosity, under which any object satisfying $\mathcal{R} > 10$ is classified as radio-loud. Although there can be little doubt that objects with black-hole masses of $10^6 \rightarrow 10^8 \mathrm{M}_\odot$ can be radio-loud under this classification, it is worth noting that only one object in the sample of Ho (2002) with an estimated black-hole mass of $< 10^8 \mathrm{M}_\odot$, would also satisfy the alternative radio-loudness criterion of $L_{5\mathrm{GHz}} > 10^{24}$W Hz^{-1}sr^{-1} (Miller et al. 1990).

Following their study of the black-hole masses and host-galaxy properties of low redshift radio-loud and radio-quiet quasars, Dunlop et al. (2002) proposed an alternative view of the $M_{bh} - L_{\mathrm{rad}}$ plane. They argue that the location of both active and non-active galaxies on the $M_{bh} - L_{\mathrm{rad}}$ plane appears to be consistent with the existence of an upper and lower envelope, both of the approximate form $L_{5\mathrm{GHz}} \propto M_{bh}^{2.5}$, but separated by some 5 orders of magnitude in radio power. In this scheme the upper and lower envelopes delineate the maximum and minimum radio luminosity capable of being produced by a black hole of a given mass. Dunlop & McLure (2002) demonstrate that this scenario naturally describes the FBQS data of Lacy et al. (2001), and we note here that it is also consistent with the findings of Ho (2002).

However, the recent study by Oshlack, Webster & Whiting (2002; hereafter OWW02) of the black-hole masses of a sample of flat-spectrum radio-loud quasars from the Parkes Half-Jansky Flat Spectrum sample of Drinkwater et al. (1997), casts doubt on the existence of any upper threshold in the $M_{bh} - L_{\mathrm{rad}}$ plane. OWW02 found that their flat-spectrum quasars, which are securely radio-loud with respect to either classification mentioned above, harbour black-hole masses in the range $10^6 \rightarrow 10^9 M_\odot$, and therefore lie well above the upper $L_{5\mathrm{GHz}} \propto M_{bh}^{2.5}$ boundary proposed by Dunlop et al. (2002). The conclusion reached by OWW02 following this result was that previous studies have actively selected against including powerful radio sources with relatively low black-hole masses, due to their concentration on luminous, optically selected radio-loud quasars.

In this paper we use the OWW02 sample to re-examine the position of these flat-spectrum radio-loud objects on the $M_{bh} - L_{\mathrm{rad}}$ plane when both Doppler boosting effects and the likely geometry of the broad-line region are taken into account. The motivation behind this re-analysis is to determine, once the inevitable complications associated with flat-spectrum quasars are considered, whether this sample of objects does genuinely violate the apparent upper boundary to radio luminosity suggested by previous studies.

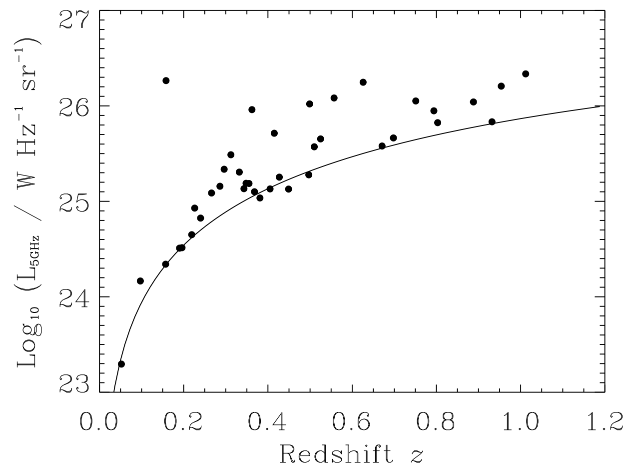

Figure 1. Rest-frame 5 GHz radio luminosity versus redshift for the flat-spectrum sources analysed by OWW02. The solid line represents the flux-density limit of the Parkes half-Jy flat-spectrum sample assuming a spectral index of $\alpha = 0.5$. Some objects appear below this line because the remeasured spectral index using the whole radio spectrum is steeper than $\alpha = 0.5$

The paper is set out as follows, in Section 2 we briefly summarise the main aspects of the virial black-hole mass estimate. In Section 3 we provide a brief description of the OWW02 sample. In Section 4 we discuss the amount of Doppler boosting one might expect in flat-spectrum radio sources, and in Section 5 we consider what effect a BLR with a flattened disk-like geometry will have on the virial black-hole mass estimates. In Section 6 we briefly discuss how the combination of these may affect the $L_{\mathrm{rad}} - M_{bh}$ relation for flat-spectrum quasars.The implications of this work are discussed in Section 7. All cosmological calculations presented in this paper assume $\Omega_{\mathrm{M}} = 0.3$, $\Omega_\Lambda = 0.7$, $H_\circ = 70\ \mathrm{km\,s^{-1}\ Mpc^{-1}}$.

2 MEASURING BLACK HOLE MASSES

In recent years a number of methods have been utilized to estimate the mass of the black holes in both active and non-active galaxies. The two methods which have received most attention are based on the correlations found between black-hole mass and both the luminosity of the host galaxy spheroid component (e.g. Kormendy & Richstone 1995; Magorrian et al. 1998), and the stellar velocity dispersion (Ferrarese & Merritt 2000, Gebhardt et al. 2000).

However, with reference to determining the masses of *active* black-holes, the virial black-hole mass estimator has now become well established. The virial black-hole mass estimate uses the width of the broad Hydrogen Balmer emission lines to estimate the broad line region (BLR) velocity dispersion. The black hole mass may then be calculated under the assumption that the velocity of the BLR clouds is Keplerian:

$$M_{bh} = R_{\mathrm{BLR}} V^2 G^{-1}, \quad (1)$$

where V is the velocity dispersion of the BLR clouds, usually estimated from the full-width half maximum (FWHM) of the Hβ line, and $R_{\rm BLR}$ is the radius of the broad-line region.

The measurement of the radius of the BLR is ideally achieved by reverberation mapping, in which the continuum and line variations of a number of sources are monitored over a number of years. The time lag between the continuum variations and the variations of broad lines will thus give the distance of the line emitting clouds from the ionizing source (e.g. Wandel, Peterson & Malkan 1999; Kaspi et al. 2000).

Unfortunately, reverberation mapping of quasars is extremely time consuming and it remains unrealistic that the black-hole masses of a large sample of quasars can be measured in this way. However, the existing reverberation mapped data does provide an alternative. The radius of the BLR is found to be correlated with the monochromatic AGN continuum luminosity at 5100Å, λL_{5100} (e.g. Kaspi et al. 2000). Therefore, this correlation can be exploited to produce a virial black-hole mass estimate from a single spectrum covering the Hβ emission line.

In this paper we adopt the calibration of the correlation between $R_{\rm BLR}$ and λL_{5100} from McLure & Jarvis (2002), i.e.

$$R_{\rm BLR} = (25.4 \pm 4.4)[\lambda L_{5100}/10^{37}{\rm W}]^{(0.61 \pm 0.10)}, \qquad (2)$$

which, when combined with BLR velocity estimate from the $H\beta$ FWHM, leads to a black-hole mass estimate given by :

$$\frac{M_{bh}}{{\rm M}_\odot} = 4.74 \left(\frac{\lambda L_{5100}}{10^{37}{\rm W}}\right)^{0.61} \left(\frac{{\rm FWHM}(H\beta)}{\rm km\,s^{-1}}\right)^{2}, \qquad (3)$$

which is adopted throughout this paper. We note that using the black-hole mass estimator based on the $R_{\rm BLR} - \lambda L_{5100}$ relation of Kaspi et al. (2000), as adopted by OWW02, results in a typical difference in estimated black-hole mass of $\lesssim$0.1 dex when converted to our chosen cosmology, and therefore has little bearing on the conclusions of this paper.

3 THE FLAT-SPECTRUM SAMPLE

The data used in this analysis are derived from the Parkes Half-Jansky Flat Spectrum sample of Drinkwater et al. (1997), where full details may be found. The crucial selection criteria for this work are a flux limit at 2.7 GHz of $S_{2.7} > 0.5$ Jy and a spectral index between 2.7 GHz and 5 GHz $\alpha_{2.7}^{5.0} < 0.5$, where $S_\nu \propto \nu^{-\alpha}$. The total sample comprises 323 radio sources. A sub-sample of 39 of these sources was compiled by OWW02 for which it was possible to obtain spectra covering the broad Hβ emission line from various sources in the literature (Francis et al. 2001; Wilkes et al. 1983).

We have remeasured all of the radio spectral indices for the 39 sources in this sub-sample using all of the publicly available radio data. Consequently, our rest-frame 5 GHz radio luminosities differ slightly to those of OWW02. It is worth noting at this point that some of the ‘flat-spectrum’ objects in this sample actually have spectral indices steeper than the spectral index cut-off of $\alpha = 0.5$. This may be due to a number of uncertain effects, including variability of the source and any spectral curvature. Fig. 1 shows the radio luminosity redshift plane for the OWW02 sample after converting to our chosen cosmology.

4 DOPPLER BOOSTING OF THE RADIO FLUX IN FLAT-SPECTRUM RADIO SOURCES

Flat-spectrum radio samples unavoidably contain a mix of radio source populations including starbursts (Windhorst et al. 1985),

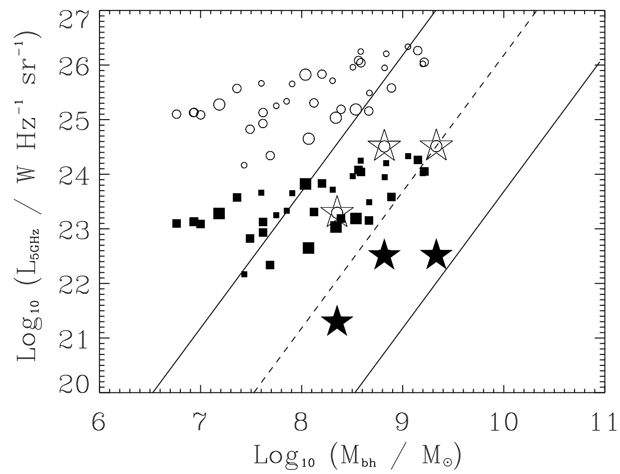

Figure 2. Total radio luminosity at 5 GHz ($L_{\rm 5GHz}$) versus black-hole mass (M_{bh}) for the flat-spectrum quasars from OWW02. The open circles are the original points of OWW02 converted to our cosmology without a correction for Doppler boosting. The filled squares are the same sources but with the flux-density decreased by a factor of ~ 100, in accordance with what we expect the average Doppler boosting factor to be. The size of the symbols are scaled with radio spectral index, the smallest symbols represent $\alpha < 0.0$; medium sized symbols represent $0.0 < \alpha < 0.5$; large symbols represent $\alpha > 0.5$. The stars represent the three sources with $\alpha > 0.5$ discussed in section 6. The lines are relations of the form $L_{5\,\rm GHz} \propto M_{bh}^{2.5}$ offset by 2.5 orders of magnitude from each other and represent the envelopes discussed in Dunlop et al. (2002), converted to our chosen cosmology. As can be seen, the de-boosting of the radio flux density in these sources is sufficient to push the majority of the sources within the region enclosed by the upper and lower lines.

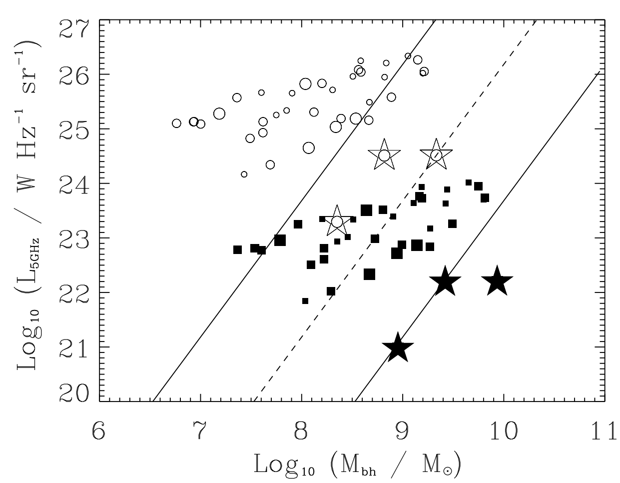

Figure 3. As Fig. 2 but with the filled symbols representing sources now displaced to the right of the plot due to including a mean correction to the FWHM of the broad Balmer lines, in accordance with the disk-BLR model of McLure & Dunlop (2002). As can be seen, all sources may now easily reside within the upper and lower boundaries represented by the solid lines. The outliers to the right of the lower boundary are easily reconciled with the envelope as the correction for the disk-like geometry is probably an overestimate for these sources where the data suggests that they are not beamed directly along out line-of-sight. Thus, these sources would move up and to the left of the plot if this is indeed the case.

Giga-Hertz Peaked Spectrum (GPS) sources and Compact Steep Spectrum (CSS) sources [see e.g. O'Dea (1998) for a review]. However one population is thought to dominate, the Doppler boosted sources (e.g. Scheuer 1987). These are preferentially selected in high-frequency samples because the superposition of many synchrotron self-absorbed spectra along our line-of-sight results in a flat-spectrum at high-radio frequencies.

As the radio emission is propagating along our line-of-sight in these objects, the relativistic velocities associated with powerful radio sources (e.g. Cohen et al. 1971) means that face-on radio sources may undergo relativistic beaming which we see as a boost in the flux.

From a statistical study of low-frequency and high-frequency selected radio sources, Jackson & Wall (1999) have shown that high-frequency selected flat-spectrum sources have an opening angle within 7° of our line-of-sight. We note however that this value is essentially a mean value and that both smaller or larger opening angles are undoubtedly consistent with a Doppler boosting paradigm. The opening angles may also depend on the intrinsic radio power of the source (e.g. Jackson & Wall 1999), thus the level of Doppler boosting in a sample of flat-spectrum sources may have a wide distribution.

However, keeping these caveats in mind, we can estimate the amount of Doppler boosting the average flat-spectrum sources will exhibit, compared with the Doppler boosting of the average quasar, if the maximum opening angle is known for each population. Following the method of Jarvis & Rawlings (2000), we take the maximum opening angle for which we observe a radio source as a quasar to be 53°, as derived from the quasar fraction in low-frequency selected samples (Willott et al. 2000). Consequently, averaging over solid angle, the mean opening angle of steep spectrum radio-loud quasars is $\sim 37^\circ$.

The boosting of the radio flux increases as Γ^2:

$$\Gamma = \gamma^{-1}(1-\beta\cos\theta)^{-1}, \tag{4}$$

where γ is the Lorentz factor, $\beta = v/c$ and θ is the angle between the radio jet and the line of sight. Therefore, adopting the conservative approach of substituting $\theta_{\rm flat} = 7^\circ$ for the flat-spectrum sources (many of the sources will have $\theta < 7^\circ$) and $\theta_{\rm steep} = 37^\circ$ for the steep spectrum quasar population, we find that the Doppler boosting factor is $\Gamma^2_{\rm flat}/\Gamma^2_{\rm steep} \gtrsim 100$. Hence, the intrinsic radio luminosity of the flat-spectrum population is of the order $\gtrsim$100-times fainter than the intrinsic radio luminosity of the average steep-spectrum radio-loud quasar.

In Fig. 2 we plot radio luminosity versus black-hole mass with both the original radio luminosities, without any boosting correction, and the same objects with the radio luminosity decreased by a factor of 100. It is worth noting that this amount of Doppler boosting will inevitably mean that some of these radio-loud quasars should in fact be classified as radio intermediate (e.g. Lacy et al. 2001) and in some cases radio-quiet. If we adopt the radio-loudness parameter $\mathcal{R} = f_\nu(5\ \mathrm{GHz})/f_\nu(5100\ \text{Å})$, then many sources drop below the value usually taken as the divide between radio-loud and radio-quiet quasars of $\mathcal{R} = 10$. As highlighted by OWW02, the radio loudness parameter $\mathcal{R}$ also depends on the amount of synchrotron emission which extends into the optical waveband. However, even taking this into consideration, it is still likely that some of the sources will now lie in the radio-quiet regime. It is clear from Fig. 2 that following the correction for Doppler boosting the vast majority of the flat-spectrum sources now lie within the $L_{\rm rad} - M_{bh}$ envelope of the quasar population suggested by Dunlop et al. (2002).

This evidence is in itself enough to account for the major discrepancy between the results of OWW02 and previous work. However, in this Section have have only applied an average Doppler boosting correction factor to the flat-spectrum sample as a whole. Obviously this average correction factor will constitute an overestimate, or underestimate, depending on the orientation of each individual object. This issue is considered further in Section 6. In the next Section we proceed to consider the likely effect upon the estimated black-hole masses of the flat-spectrum quasars due to their inclination close to the line of sight.

5 THE GEOMETRY OF THE BROAD-LINE REGION

An indication of when a quasar is 'misaligned' may also come from the FWHM of the Balmer broad lines. The naive assumption is that narrow ($\leq 4000\ \mathrm{km\,s^{-1}}$) broad lines imply black holes of lower mass. However, there is a wealth of evidence in the literature which supports the view that the BLR has a disk-like geometry, at least for radio-loud sources (e.g. Wills & Browne 1986; Brotherton 1996; Vestergaard, Wilkes & Barthel 2000). Using a sample of 60 radio-loud quasars, Brotherton (1996) showed that the radio core-to-lobe ratio, an indicator of radio source orientation, is strongly correlated with the width of the broad Hβ emission line. The main implication being that pole-on radio sources have narrower broad lines than their misaligned counterparts. Indeed, McLure & Dunlop (2002) have shown that the Hβ FWHM distribution of a sample of 72 AGN, both radio-loud and radio-quiet, in the redshift interval $0.1 < z < 0.5$ can be naturally reproduced by considering the inclination effects expected if the BLR has a flattened disk-like geometry.

If we now apply these results to the flat-spectrum sample considered in this paper, the consequence is that the majority of the measurements of M_{bh} are essentially lower limits. Indeed, if the BLR in these flat-spectrum sources are orientated within $\sim 7^\circ$ of the line of sight, then the black hole masses may be underestimated by a factor $\gtrsim$20 (see e.g. McLure & Dunlop 2002).

However, here we adopt a conservative approach and use a low-frequency radio selected quasar survey to predict what the mean FWHM of the broad Balmer lines should be, given no spectral-index selection criteria. We use the quasars from the Molonglo Quasar sample (MQS; Kapahi et al. 1998) for which line-width measurements are available in the literature (Baker et al. 1999). The mean FWHM of the Hβ line in the MQS is $\approx$ 7000 km s^{-1}. In contrast, the mean FWHM of the Balmer lines in the OWW02 flat-spectrum sample is $\sim$ 3500 km s^{-1}. We therefore choose to adopt a correction factor of two for the flat-spectrum FWHMs to compensate for orientation effects. Given that $M_{bh} \propto \mathrm{FWHM}^2$, this increases the black-hole mass estimates for the flat-spectrum sample by a factor of four. The predicted position of the flat-spectrum quasars on the $M_{bh} - L_{\rm rad}$ plane after application of the inclination correction is shown in Fig. 3, from which it can be seen that the flat-spectrum quasars are now even more consistent with the upper and lower radio power envelopes suggested by Dunlop et al. (2002).

6 RADIO SPECTRAL INDEX AND ORIENTATION

Radio spectral index may be used to gain information on the orientation of a radio source. As stated earlier, flat-spectrum sources ($\alpha \sim 0$) are generally assumed to arise because of the superposition of many optically thick regions along our line-of-sight, whereas the emission from steeper-spectrum sources is usually associated with optically thin radio lobes.

Therefore, although not explicitly applicable on a source-by-source basis, there should be a general trend for steeper spectrum sources to be orientated with the jets pointing away from our line-of-sight and for the flatter-spectrum sources to be orientated with their jets beamed along our line-of-sight.

Therefore, it interesting to note that the three sources which lie closest to the lower envelope in Fig. 2 are sources with spectral indices steeper than $\alpha = 0.5$, and therefore should not strictly be in the flat-spectrum sample. Furthermore, in agreement with the inclination arguments outlined above, these three sources also have the largest Hβ FWHMs in the OWW02 sample. If these three sources are in reality not aligned with their jets pointing within 7° of our line of sight, then the correction for Doppler boosting could be significantly less than the value of ~ 100 assumed throughout. Whereas, the sources with the narrowest broad lines in the OWW02 sample may be those in which the jet is pointing very close to our line-of-sight, and will therefore have had their Doppler boosting correction factor underestimated. Together, these two factors work to push the pole-on sources (i.e. those with $\theta < 7^{\circ}$) toward the bottom right of Fig. 3, and the misaligned sources (with $\theta > 7^{\circ}$) toward the top left of Fig. 3. It is possible therefore that if each of the flat-spectrum quasars could be corrected for Doppler boosting and BLR inclination on an object-by-object basis, then they may actually be consistent with the steep dependence of radio power on black-hole mass suggested by previous studies (e.g. Franceschini et al. 1999; Laor 2000; Lacy et al. 2001; Dunlop et al. 2002).

7 CONCLUSIONS

We have re-analysed the data of Oshlack et al. (2002) on a sample of flat-spectrum radio-loud quasars. Contrary to their conclusions we find that, by correcting for the effects of inclination upon both the radio luminosity and estimated black-hole mass, the black holes harboured by intrinsically powerful flat-spectrum quasars are of comparable mass to those found in other quasars of similar *intrinsic* radio luminosity, i.e. $M_{bh} > 10^{8}$ M$_{\circ}$.

We also find that although many of the flat-spectrum quasars occupy the region of intrinsic radio luminosity comparable to the FRII radio sources (Fanaroff & Riley 1974) found in low-frequency selected radio surveys, some of the sources may occupy the lower-luminosity regime of radio-intermediate and radio-quiet quasars. Therefore, we conclude that by consideration of source inclination and intrinsic radio power, flat-spectrum quasars may well be consistent with the $L_{\rm rad} \propto M_{bh}^{2.5}$ relation found in previous studies.

Further work is obviously essential to make firm statements regarding the black-hole masses in flat-spectrum radio-loud quasars. This may be achieved by utilizing the bulge luminosity versus black-hole mass correlation to determine the black-hole mass independent of any orientation biases, and this is investigated in a subsequent paper (Jarvis, McLure & Rawlings in prep.).

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