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The $M_{\rm BH}-L_{\rm rad}$ Relation for Flat-spectrum Quasars

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Abstract

In this proceedings we summarize our recent letter (Jarvis & McLure 2002) where we suggested that by correcting for the inevitable effects of inclination, the black-hole masses of flat-spectrum quasars (FSQ) with intrinsically powerful radio jets are confined, virtually exclusively, to $M_{\rm BH} > 10^8$ M$_\odot$. After considering realistic Doppler boosting factors, many of the FSQ 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 $L_{\rm 5GHz} \propto M_{\rm BH}^{2.5}$.

1.1 Introduction

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.

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 $M_{\rm BH} > 10^9$ M$_\odot$, whereas the majority of quasars with black hole masses $M_{\rm BH} < 3 \times 10^8$ 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. However, the substantial over-lap between the black-hole mass distributions of the two quasar samples indicated in addition that black-hole mass could not be the sole parameter controlling radio power.

In contrast to the studies outlined above, Ho (2002) 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 ($10^6 \rightarrow 10^9$M$_\odot$).

Following their study of the black-hole masses and host-galaxy properties of low redshift radio-loud and radio-quiet quasars, Dunlop et al. (2003) proposed an alternative view of the $M_{\rm BH}-L_{\rm rad}$ plane. They argue that the location of both active and non-active galaxies on the $M_{\rm BH}-L_{\rm rad}$ plane appears to be consistent with the existence of an upper and lower envelope, both of the approximate form $L_{\rm 5GHz} \propto M_{\rm BH}^{2.5}$, 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.

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 $M_{\rm BH}-L_{\rm rad}$ plane. OWW02 found that their flat-spectrum quasars harbour black-hole masses in the range $10^6 \rightarrow 10^9 M_{\odot}$, and therefore lie well above the upper $L_{\rm 5GHz} \propto M_{\rm BH}^{2.5}$ boundary proposed by Dunlop et al. (2003). 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.

Here we use the OWW02 sample to re-examine the position of these flat-spectrum radio-loud objects on the $M_{\rm BH}-L_{\rm rad}$ plane when both Doppler boosting effects and the likely geometry of the broad-line region are taken into account.

1.2 Measuring Black Hole Masses

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:

$$M_{\rm BH} = R_{\rm BLR} V^2 G^{-1}, \tag{1.1}$$

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 (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 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.

Here we adopt the calibration of the correlation between $R_{\rm BLR}$ and λL_{5100} from McLure & Jarvis (2002; see also these proceedings), i.e.

$$R_{\rm BLR} = (25.4 \pm 4.4)[\lambda L_{5100}/10^{37}{\rm W}]^{(0.61\pm0.10)}, \tag{1.2}$$

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

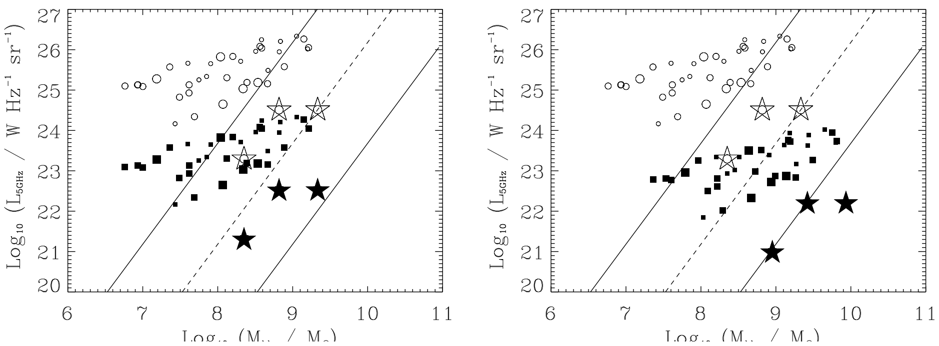

Fig. 1.1. (*left*) Total radio luminosity at 5 GHz versus black-hole mass for the FSQ from OWW02. Open circles are the original points of OWW02. Filled squares are the same sources with their radio flux density decreased by a factor of $\sim$ 100, in accordance with the expected Doppler boosting factor. The size of the symbols are scaled according to radio spectral index and the stars are the three FSQ with the steepest spectral indices (see Jarvis & McLure 2002 for a full description). The lines are relations of the form $L_{5GHz} \propto M_{\rm BH}^{2.5}$ offset by 2.5 dex from each other and represent the envelopes discussed in Dunlop et al. (2003). (*right*) The same plot but with a horizontal shift to account for the probable effect of orientation on the FWHM of the Hβ broad emission line if the BLR has a disk-like geometry.

$$\frac{M_{\rm BH}}{\rm M_{\odot}} = 4.74 \left(\frac{\lambda L_{5100}}{10^{37}{\rm W}}\right)^{0.61} \left(\frac{{\rm FWHM}(H\beta)}{\rm km\ s^{-1}}\right)^{2}. \tag{1.3}$$

1.3 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, Giga-Hertz Peaked Spectrum sources and Compact Steep Spectrum sources. However one population is thought to dominate, the Doppler boosted sources. 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 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:

$$\Gamma = \gamma^{-1}(1-\beta\cos\theta)^{-1}, \tag{1.4}$$

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. 1.1 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 clear from Fig. 1.1 that following the correction for Doppler boosting the vast majority of the flat-spectrum sources now lie within the $L_{\rm rad}-M_{\rm BH}$ envelope of the quasar population suggested by Dunlop et al. (2003).

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. 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.

1.4 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 (≤ 4000 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. Brotherton 1996).

To account for a disk-like geometry we 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 $M_{\rm BH} \propto {\rm FWHM}^2$, 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 $M_{\rm BH}-L_{\rm rad}$ plane after application of the inclination correction is shown in Fig. 1.1, 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. (2003).

1.5 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. $M_{\rm BH} > 10^8$ $\mathrm{M}_{\circ}$. We also find that although many of the flat-spectrum quasars occupy the region of intrinsic radio luminosity comparable to the FRII radio sources 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 $L_{\rm rad} \propto M_{\rm BH}^{2.5}$ relation found in previous studies.

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