Evidence for the evolution of quasar nuclei via accretion

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Abstract

According to a popular paradigm, nuclear activity in quasars is sustained *via* accretion of material onto supermassive black holes located at the quasar nuclei. A useful tracer of the gravitational field around such black holes is available in the form of extremely dense gas clouds within the broad emission-line region (BLR) on the scale of ~ 1 parsec. Using five homogeneously observed (and processed) sets of lobe dominated radio-loud quasars, taken from literature, we show that a positive correlation exists between the radio sizes of the quasars and the widths of their broad $H\beta$ emission lines, and this correlation is found to be significantly stronger than the other well known correlations involving radio size. In quantitative terms, this statistical correlation is consistent with the largest (and, hence, very possibly the oldest) radio sources harbouring typically an order-of-magnitude or even more massive central black holes, as compared to the physically smaller and, hence, probably much younger, radio sources. Thus, though not unique, this interpretation of the correlation is at least consistent with the simple expectation from the 'accreting black-hole model' for the quasar nuclei.

1 Introduction

In many studies, the FWHM of the broad emission lines have been used as a tracer of the mass of the central engine, possibly due to supermassive black holes, SMBH (e.g., Dibai, 1984, Padovani & Rafanelli, 1988). The accretion of material required to sustain the high quasar luminosity is expected to steadily increase the mass of the central engine. The question arises: **do we see any evidence for the growth of the central mass?** Here we examine this by employing the published $H\beta$ measurements for several sets of radio-loud, steep-spectrum quasars, and treating their overall radio size as a *statistical* measure of their ages.

2 The datasets of quasars

We minimize the projection effects on the radio sizes, by confining our study to lobe-dominated quasars (LDQs). Measurement of the other parameter, namely, W, the FWHM of the broad Hβ emission line, is rather complicated, due to the contamination arising from the lines of Fe II and the narrow component of Hβ. Therefore, adoption of a uniform observing strategy and profile extraction procedure for the entire sample is important for a meaningful interpretation of the data. It is therefore preferable to look for any statistical trends involving W *within* individual samples (instead of merging the samples to form a single large database). Accordingly, we consider here five sets of LDQs for which we could find measurements of W(Hβ) in the literature, as well as the requisite radio observations to determine the core-fraction, f_c (the ratio of the core to the extended flux density, measured at 5 GHz in the rest-frame of the quasar), and radio size, l. These five sets are internally homogeneous individually, as all the quasars in each set have been observed with about the same spectral resolution and reduced following the same profile extraction procedure. The largest linear sizes, l, of the quasars and the core-fractions are derived from the published radio maps. We have adopted $H_o = 50$ km s^{-1} Mpc^{-1} and $q_o = 0$. The five sets of lobe-dominated quasars (all having $M_v \leq -23$) are:

(a) B(96): The first set is derived from the sample of Brotherton (1996), which itself was based on the QSO compilation by Véron-Cetty & Véron (1988). His selection criteria were: (i) core-fraction, f_c should be available in literature, (ii) $V \leq 18$ mag, (iii) $z \leq 0.95$ and (iv) declination $> -20°$. For the selected 60 quasars, optical spectra were taken with a typical spectral resolution of 2.5 Å. Out of these, we have selected all the 31 LDQs ($\log f_c < 0$).

(b) JB(91): This set is derived from Jackson & Browne (1991a,b), whose sample consists of low-resolution (20 – 25Å) spectra of 53 radio-loud quasars selected using the following criteria: (i) $\log(R) \geq 1$ [R is defined as the ratio of the flux densities at 6 cm and 4400 Å, in the rest-frame], (ii) $V \leq 18$ mag, (iii) $z \leq 0.86$, (iv) right ascension between 16 and 13 hr, and (v) declination $> -30°$. The sample contains 23 LDQs with available H β profile measurements. Jackson & Browne (1991b) measured W using two different profile extraction procedures; we adopt here the values of W obtained using the four Gaussian

Table 1: The consolidated list of all 48 LDQs used in the present study

QSO	sample codes	z	LAS (arcsec)	$\log(f_c)$	$\log(R_v)$	M_v	$W(H\beta)$ (km s^{-1}) B(96)	JB(92)	M(96)	BG(92)	CB(96)
0003+158	(a,d)	0.450	36.0(1)	−0.38(a)	1.95	-26.0	4760	...	...	4760	...
0026+129	(d)	0.142	1.0(1)	−1.47(e)	2.40	-24.0	...	...	...	1860	...
0042+101	(b)	0.583	59.0(3)	−0.50(b)	1.79	-24.8	...	17774	...	...	...
0044+030	(a,c)	0.624	18.6(5)	−0.42(a)	0.83	-27.2	5100	...	5480	...	...
0110+297	(b)	0.363	76.2(2)	−0.80(b)	1.59	-24.8	...	8702	...	...	...
0115+027	(a,b)	0.670	13.1(2)	−0.50(b)	2.25	-26.5	5000	7591	...	...	...
0118+034	(b)	0.765	45.0(4)	−1.20(b)	2.17	-25.1	...	22403	...	...	...
0133+207	(b,e)	0.425	68.0(2)	−1.00(b)	2.51	-24.0	...	17403	...	...	3420
0134+329	(a,b)	0.367	1.3(3)	−1.14(a)	2.50	-25.7	3800	5863	...	...	...
0349−146	(c)	0.614	114.0(2)	−1.68(a)	1.34	-24.0	...	...	9470	...	...
0405−123	(a,c)	0.575	31.7(6)	−0.23(a)	2.36	-28.4	4800	...	4830	...	...
0414−060	(a,b,c)	0.781	36.4(4)	−0.50(a)	1.68	-27.8	8200	16602	14820	...	...
0454−220	(c,e)	0.534	85.0(12)	−1.19(a)	1.86	-26.1	...	...	6920	...	5820
0518+165	(b)	0.759	0.8(9)	−0.90(b)	3.94	-24.1	...	4876	...	...	...
0538+498	(b)	0.545	0.2(7)	−1.40(b)	3.43	-24.2	...	3456	...	...	...
0710+118	(a,b,c)	0.768	48.0(2)	−1.85(a)	1.09	-27.1	20000	17774	19530	...	...
0800+608	(b)	0.689	25.0(10)	−0.60(b)	2.65	-24.2	...	6912	...	...	...
0837−120	(a)	0.200	169.0(2)	−0.70(a)	1.80	-24.7	6060	...	...	...	...
0838+133	(a,b,c)	0.680	10.0(7)	−0.50(b)	3.16	-25.4	3000	4197	3090	...	...
0903+169	(a)	0.410	50.0(8)	−1.40(c)	1.70	-24.5	4400	...	...	...	...
0952+097	(a)	0.298	12.5(2)	<−0.50(c)	<1.90	-24.1	3800	...	...	...	...
0955+326	(a,c)	0.530	115.0(3)	−0.07(a)	2.23	-27.1	1380	...	4730	...	...
1004+130	(a,b,d)	0.240	115.0(2)	−1.68(a)	0.43	-25.7	6300	9998	...	6300	...
1007+417	(a,b,c)	0.613	32.0(2)	−0.39(a)	2.17	-27.0	3560	6912	2860	...	...
1048−090	(a,d)	0.334	83.0(2)	−1.31(a)	1.66	-24.9	5620	...	...	5600	...
1100+772	(a,b,c,d)	0.311	30.0(1)	−0.91(a)	1.63	-25.8	6160	7961	7840	6160	...
1103−006	(a,c,d)	0.423	21.0(2)	−0.14(a)	2.20	-25.8	6560	...	6600	6190	...
1111+408	(b)	0.730	13.2(2)	−1.80(b)	1.89	-25.3	...	9134	...	...	...
1136-135	(e)	0.553	15.5(6)	< −1.17(a)	<4.22	-26.3	...	...	...	...	2620
1137+660	(a,b,c,e)	0.652	44.2(2)	−1.07(a)	1.83	-27.1	6060	8702	4950	...	5560
1223+252	(b)	0.268	67.0(2)	−1.59(b)	0.99	-23.8	...	9319	...	...	...
1250+568	(a,b,e)	0.321	1.5(2)	−1.62(a)	2.01	-23.6	4560	6295	...	...	4740
1305+069	(a)	0.599	46.5(4)	<−1.20(a)	<1.52	-26.1	6440	...	...	...	...
1351+267	(a)	0.310	190.0(2)	−0.27(a)	1.72	-24.3	8600	...	...	...	...
1416+129	(d)	0.129	155.0(1)	−0.71(e)	1.49	-24.1	...	...	...	6110	...
1425+267	(a,d)	0.366	230.0(1)	−0.40(a)	1.03	-26.2	9410	...	...	9410	...
1458+718	(a)	0.905	2.1(2)	−1.00(d)	2.74	-27.3	3000	...	...	...	...
1512+370	(a,c,d)	0.371	54.0(1)	−0.71(a)	1.88	-25.6	6810	...	9360	6810	...
1545+210	(a,c,d,e)	0.264	70.0(1)	−1.32(a)	1.74	-24.4	7030	...	6730	7030	7030
1612+261	(d)	0.131	1.7(1)	−0.52(e)	2.06	-23.5	...	...	...	2520	...
1618+177	(a,c,e)	0.555	48.0(3)	−0.67(a)	1.98	-26.5	7000	...	11530	...	9400
1622+238	(a)	0.927	21.7(2)	−1.72(d)	1.63	-26.7	7100	...	...	...	...
1704+608	(a,c,d,e)	0.371	55.0(1)	−1.91(a)	0.73	-26.6	6560	...	6990	6560	6560
1742+617	(b)	0.523	40.0(11)	−2.00(b)	1.61	-24.0	...	9751	...	...	...
1828+487	(b)	0.691	14.0(11)	−0.50(b)	4.05	-26.2	...	9998	...	...	...
2135−147	(a,b,c)	0.201	150.0(2)	−1.13(a)	1.97	-24.9	7300	11479	7570	...	...
2251+113	(a,b,3,4,5)	0.323	9.8(2)	−1.52(a)	1.00	-25.8	4160	8702	4540	4160	4160
2308+098	(a,3,4,5)	0.432	108.0(1)	−0.78(a)	1.41	-26.3	7970	...	11330	7970	7970

Sample Codes: a : B(96)(31 quasars), b = JB(91)(23 quasars), c = M(96)(19 quasars), d = BG(92) (14 quasars) and e = CB(96)(10 quasars)

Values of LAS and f_c are taken from the literature as cited in Srianand & Gopal-Krishna(1997)

fitting method, as it corrects for the narrow line component.
(c) M(96): This set is derived from Marziani et al. (1996) who compiled their sample for the purpose of comparing the high and low-ionization lines in the BLRs. They obtained optical spectra of all the AGNs (52 in total) for which HST/FOS spectra covering the C IV emission line region were then available. The resolution is in the range 3 – 8 Å. This sample includes 31 radio-loud quasars ($\log R \geq 1$), of which all the 19 LDQs have been included in our set.
(d) BG(92): We derive this set from Boroson & Green (1992) who compiled spectra for all the BQS quasars having $z \leq 0.5$, with a resolution of ~ 6Å (the BQS sample has an average limiting magnitude of $B = 16.2$ and $U - B < -0.44$). There are 87 objects in the sample of Boroson & Green, of which 25 are radio-loud ($\log R \geq 1$), including 11 LDQs which form our set.
(e) CB(96): This set has been derived from Corbin & Boroson (1996) who analyzed a sample of 48 AGNs in the redshift range 0.034 to 0.774. Their sample was complied from the archival HST/FOS spectra (resolution ~ 5 – 11Å) and it includes 10 LDQs which form our last set.

3 Results and discussion

Figure 1 shows the linear size, l, plotted against the other parameters, namely, W, z, R_v ($\log R_v = \log(L_{core}/L_{opt}) = log(L_{core} + M_v/2.5) - 13.69$) and f_c for all the five data sets, and the results of non parametric Spearman rank correlation tests are given in Table 2. For each dataset, the upper line gives the correlation coefficients and the lower line gives the two-sided significance level of its deviation from zero (smaller value implies a stronger correlation). The remarkable trend seen is that **for each of the five sets, l correlates more strongly with W than with any of the other parameters, and maintains the same sense of correlation** (in agreement with the preliminary results reported by Gopal-Krishna, 1995). Thus, from this consistent behaviour, the $l - W$ correlation emerges to be of the primary statistical significance. It may be recalled that using a more limited dataset, Miley & Miller (1979) had earlier noticed a positive correlation between l and W. However, almost ~ 40% of their sample being core-dominated quasars, the linear-sizes used by them are likely to be influenced by projection effects to a much greater degree and, consequently, rendered less suitable as a measure of source age. From the general consensus that extragalactic radio sources grow in linear size with increasing age, the observed linear size, l, can be regarded as a fairly meaningful *statistical* indicator of the age (e.g., Best et al., 1996). It may be recalled that l is known

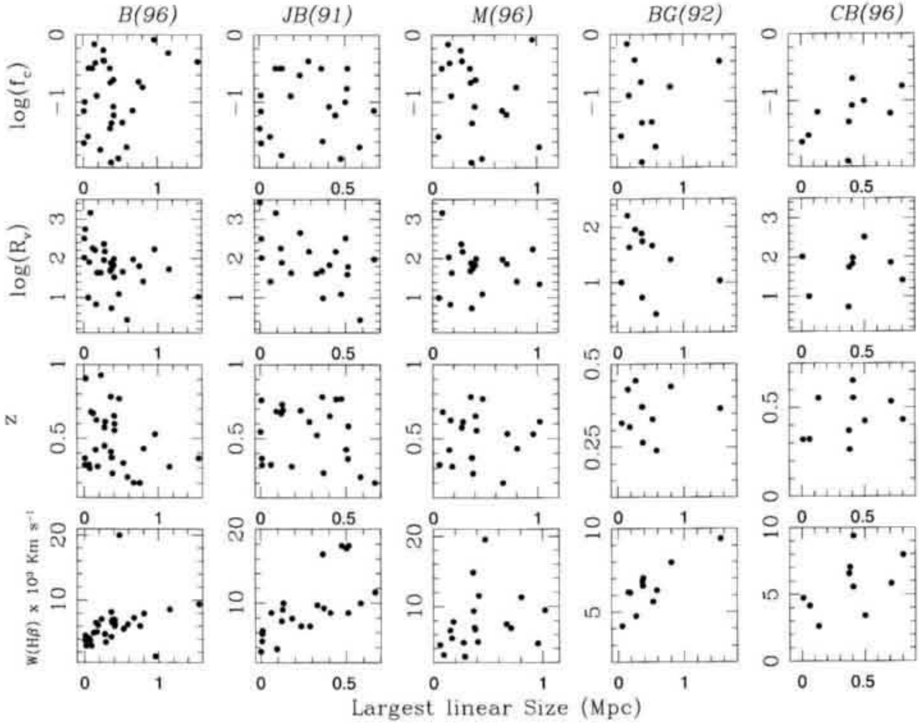

Figure 1. The plots of $W(\mathrm{H}\beta)$, z, R_V and f_c *versus* the radio size (l) for the five sets of lobe-dominated quasars.

to *anti-correlate* with z (e.g., Wardle & Miley, 1974) and also with the radio core prominence, f_c, which is consistent with the idea of beamed core radiation (e.g., Kapahi & Saikia, 1982; Browne & Perley, 1986; Lister et al., 1994). For such a case, the anti-correlation observed between W and R_v has led Wills & Brotherton (1995) to infer a disk-like geometry for the BLR. However, all these statistical trends are at best only weakly present in our datasets, in accord with the expectation that projection effects should be of minor importance for LDQs.

Table 2: Spearman rank–order correlation coefficients

Sample	Size	$l-z$	$l-log(f_c)$	$l-log(R_v)$	$l-W$	$log(f_c)-W$	$log(R_v)-W$
B(96)	31	−0.137	−0.042	−0.275	0.621	−0.254	−0.397
		0.456	0.829	0.128	10^{-4}	0.161	0.024
JB(92)	23	−0.024	−0.157	−0.341	0.810	−0.302	−0.288
		0.913	0.464	0.010	10^{-6}	0.152	0.173
M(96)	19	0.143	−0.407	0.086	0.546	−0.484	−0.217
		0.546	0.075	0.719	0.013	0.030	0.359
BG(92)	11	0.156	−0.314	−0.055	0.763	−0.168	0.128
		0.621	0.319	0.862	0.003	0.602	0.697
CB(96)	10	0.582	0.282	0.236	0.600	−0.055	−0.109
		0.064	0.401	0.484	0.051	0.873	0.749

4 A consistency check on the accretion paradigm

From Figure 1, we can infer that over the lifetime of a typical powerful double radio source [$10^8 yr$ (Scheuer, 1995)], a roughly 3-4 times increase takes place in the width of the Hβ emission line which is thought to trace the gravitational field in the vicinity of the SMBH.

Assuming that the BLR does not shrink with age, the simplest inference from the 3–4 fold increase in $W(\mathrm{H}\beta)$ found here, would be that the mass of the SMBH grows by roughly an order-of-magnitude over the radio source lifetime, $\tau \sim 10^8$ ($v^2 \propto GM_{BH}/r$). Such an increase is consistent with the expectation for a central black-hole accreting at the Eddington rate and radiating with a typical efficiency, $\eta = 0.1$, since the e-folding time for the growth of the mass of such black-holes is: $t_{Edd} = |\dot{M}_{Edd}/M|^{-1} = (4.5 \times 10^7 \text{ yr})\ (\eta/0.1)$.

A potential caveat to such an interpretation of the $l-W$ correlation lies in the possibility that over the source lifetime, the effective physical domain of the BLR shrinks by roughly an order-of-magnitude. There is no robust argument at present either for, or against this possibility, and so an unambiguous interpretation of our result is not possible at this stage. It is nonetheless encouraging that both the magnitude and the sense of the $l-W$ correlation found here are consistent with the expectation of growth of the central mass in the accretion-powered AGN paradigm for powerful double radio sources.

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