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Do the central engines of quasars evolve by accretion ?

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Abstract. According to a currently popular paradigm, nuclear activity in quasars is sustained *via* accretion of material onto super-massive black holes located at the quasar nuclei. A useful tracer of the gravitational field in the vicinity of such central 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. Likewise, the radio sizes of the lobe-dominated radio sources are believed to provide a useful statistical indicator of their ages. Using two 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. This statistical correlation is shown to be consistent with the largest (and, hence, very possibly the oldest) radio sources harboring typically an order-of-magnitude more massive central engines, as compared to the physically smaller and, hence, probably much younger radio sources. This inference is basically in accord with the "accreting central engine" picture for the radio-loud quasars.

Key words: Line: profiles– Galaxies: active–Galaxies: nuclei –quasars: emission lines–quasars: general–radio continuum: galaxies

1. Introduction

Being too compact to be resolved with even the most advanced optical telescopes, the structure and kinematics of the broad emission line region (BLR), a prime feature of quasars, continues to be a major enigma in the AGN research (see, e.g., Brotherton, 1996; Marziani et al., 1996; Corbin, 1992). Nonetheless, it is a key ingredient to the theoretical models that seek to explain various observable properties of quasars, e.g., their intense γ-ray emission (e.g., Dermer & Schlickeiser, 1993; Ghisellini & Madau, 1996). Deciphering the BLR geometry has therefore been a key objective of many observational programmes. One strategy for this is the so called 'reverberation mapping' (e.g., Peterson, 1993; Koratkar & Gaskell, 1991), from which a positive dependence of the BLR size on the bolometric luminosity has been inferred: $r \sim 0.06 L_{46}^{0.5}\ pc$ (Netzer & Laor 1993), where L_{46} is the luminosity expressed in the units of $10^{46} erg.s^{-1}$.

An early indication about the BLR geometry came from an empirical study of a heterogeneously selected sample of radio-loud quasars with the characteristic core-lobe type radio structure. The study revealed a statistically significant anti-correlation between the *prominence* of the radio core relative to the lobe, and the FWHM of the $H\beta$ broad emission line (W). It was thus inferred that the BLR clouds are predominantly confined to a rotating disk-shaped region surrounding the quasar nucleus and oriented roughly perpendicular to the jet axis (Wills & Browne, 1986; hereafter WB86). The significance of this correlation was found to be considerably lower in a subsequent study, however (Jackson & Browne, 1991b). In a recent work, it has been proposed that the absolute *visual* magnitude, M_v, of the quasar (plus its host galaxy) provides a more reliable measure of the intrinsic power of the central engine, and therefore the beamed radio core flux normalized by M_v is a better indicator of the orientation of the jet relative to the line-of-sight (Wills & Brotherton, 1995; Brotherton, 1996). Adopting this new parameter for the core-prominence and employing a larger sample of quasars , these authors have found a conspicuous anti-correlation between the core-prominence and the $W(H\beta)$, thereby supporting the disk-like BLR geometry inferred earlier by WB86 (at least for the $H\beta$ emitting clouds).

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Table 1: Sample of lobe-dominated quasars (42 quasars)

QSO	z	LAS	log(f_c)	log(R$_v$)	M$_v$	W(Hβ) (km s^{-1})		ξ
		(arcsec)				B(96)	JB(91)	
0003+158	0.450	36.0(1)	−0.38(a)	1.95	-26.0	4760	...	...
0042+101	0.583	59.0(3)	−0.50(b)	1.79	-24.8	...	17774	...
0044+030	0.624	18.6(5)	−0.42(a)	0.83	-27.2	5100	...	...
0110+297	0.363	76.2(2)	−0.80(b)	1.59	-24.8	...	8702	...
0115+027	0.670	13.1(2)	−0.50(b)	2.25	-26.5	5000	7591	0.66
0118+034	0.765	45.0(4)	−1.20(b)	2.17	-25.1	...	22403	...
0133+207	0.425	68.0(2)	−1.00(b)	2.51	-24.0	...	17403	...
0134+329	0.367	1.3(3)	−1.14(a)	2.50	-25.7	3800	5863	0.65
0405−123	0.575	31.7(6)	−0.23(a)	2.36	-28.4	4800	...	...
0414−060	0.781	36.4(4)	−0.50(a)	1.68	-27.8	8200	16602	0.49
0518+165	0.759	0.8(9)	−0.90(b)	3.94	-24.1	...	4876	...
0538+498	0.545	0.2(7)	−1.40(b)	3.43	-24.2	...	3456	...
0710+118	0.768	48.0(2)	−1.85(a)	1.09	-27.1	20000	17774	1.13
0800+608	0.689	25.0(10)	−0.60(b)	2.65	-24.2	...	6912	...
0837−120	0.200	169.0(2)	−0.70(a)	1.80	-24.7	6060	...	...
0838+133	0.680	10.0(7)	−0.50(b)	3.16	-25.4	3000	4197	0.71
0903+169	0.410	50.0(8)	−1.40(c)	1.70	-24.5	4400	...	...
0952+097	0.298	12.5(2)	<−0.50(c)	<1.90	-24.1	3800	...	...
0955+326	0.530	1.0(3)	−0.07(a)	2.23	-27.1	1380	...	...
1004+130	0.240	115.0(2)	−1.68(a)	0.43	-25.7	6300	9998	0.63
1007+417	0.613	32.0(2)	−0.39(a)	2.17	-27.0	3560	6912	0.52
1048−090	0.334	83.0(2)	−1.31(a)	1.66	-24.9	5620	...	...
1100+772	0.311	30.0(1)	−0.91(a)	1.63	-25.8	6160	7961	0.77
1103−006	0.423	21.0(2)	−0.14(a)	2.20	-25.8	6560	...	...
1111+408	0.730	13.2(2)	−1.80(b)	1.89	-25.3	...	9134	...
1137+660	0.652	44.2(2)	−1.07(a)	1.83	-27.1	6060	8702	0.69
1223+252	0.268	67.0(2)	−1.59(b)	0.99	-23.8	...	9319	...
1250+568	0.321	1.5(2)	−1.62(a)	2.01	-23.6	4560	6295	0.72
1305+069	0.599	46.5(4)	<−1.20(a)	<1.52	-26.1	6440	...	...
1351+267	0.310	190.0(2)	−0.27(a)	1.72	-24.3	8600	...	...
1425+267	0.366	230.0(1)	−0.40(a)	1.03	-26.2	9410	...	...
1458+718	0.905	2.1(2)	−1.00(d)	2.74	-27.3	3000	...	...
1512+370	0.371	54.0(1)	−0.71(a)	1.88	-25.6	6810	...	...
1545+210	0.264	70.0(1)	−1.32(a)	1.74	-24.4	7030	...	...
1618+177	0.555	48.0(3)	−0.67(a)	1.98	-26.5	7000	...	...
1622+238	0.927	21.7(2)	−1.72(d)	1.63	-26.7	7100	...	...
1704+608	0.371	55.0(1)	−1.91(a)	0.73	-26.6	6560	...	...
1742+617	0.523	40.0(11)	−2.00(b)	1.61	-24.0	...	9751	...
1828+487	0.691	14.0(11)	−0.50(b)	4.05	-26.2	...	9998	...
2135−147	0.201	150.0(2)	−1.13(a)	1.97	-24.9	7300	11479	0.63
2251+113	0.323	9.8(2)	−1.52(a)	1.00	-25.8	4160	8702	0.48
2308+098	0.432	108.0(1)	−0.78(a)	1.41	-26.3	7970	...	...

References for LAS: 1 : Kellermann et al. (1994), 2 : Nilsson et al. (1993), 3 : Singal (1988), 4 : Kapahi (1995), 5 : Price et al. (1993), 6 : Morganti et al.(1993), 7 : Bogers et al. (1994), 8 : Bridle et al (1994),9 : Akujor et al. (1993), 10 : Jackson et al. (1990), 11 : Reid et al. (1995)
References for f_c: a : Wills & Browne (1986), b : Jackson & Browne (1991a), c : Brotherton (1996), d : Wills et al. (1992), e : Kellermann et al. (1994)

It is now widely believed that the large widths of the BLR emission lines are a manifestation of the deep gravitational potential at the centers of quasars, possibly due to super-massive black-holes. The accretion of the material postulated for sustaining the quasar luminosity is expected to steadily increase the mass of the central engine during the lifespan of the nuclear activity. If this conjecture is basically right, the question arises: *do we see in the data any evidence for the postulated growth of the central mass* (e.g, in the dynamics of the BLR clouds) ? In the present study we shall examine this issue by employing published measurements of radio-loud, steep-spectrum quasars. While the needed reliable estimator of the age is generally not available for individual sources, the overall radio size can serve as a useful statistical measure of age (since most radio sources are believed to steadily grow in size with time; cf. Sect. 3). Thus, we wish to examine here the nature of any relationship between the observed linear sizes of steep-spectrum radio quasars and the widths of their broad Hβ emission lines.

2. The datasets of radio-loud quasars

In order to minimize the projection effects on the measured radio sizes, we confine 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, adopting uniform observing strategy and profile extraction procedure for the entire sample is an important pre-requisite for a meaningful interpretation of the data. Using two such datasets on Hβ line widths available in the literature (Brotherton, 1996; Jackson & Browne, 1991), for which we could also find the requisite radio data, we investigate the relationship between different radio properties and W(Hβ) (Table 1). The largest linear sizes, l, of radio emission associated with these quasars are taken from published radio maps (Table 1); these correspond to the cosmological parameters: $H_o = 50$ km s^{-1} Mpc^{-1} and $q_o = 0$, as adopted throughout this paper. Details of the two sets of LDQs (all having $M_v \leq -23$) are:

(a) B(96): This 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 the literature (f_c is defined as the ratio of the core to extended flux density, measured at 5 GHz in the rest-frame of the quasar), (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 (logf_c < 0) having an absolute magnitude M_v brighter than -23.

(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 by Jackson & Browne (1991b) who determined W using two different profile extraction procedures. We adopt here the values of W obtained using the four Gaussian fitting method as it corrects for the the narrow line component.

As seen from the last column of Table 1, twelve quasars are common to the two datasets. The ratio of Hβ line-width determined by B(96) to that by JB(91), designated as ξ, has a mean value of 0.68±0.16. Thus, in most of the cases, ξ is close to the mean value, the only exception being the quasar 0710+118 (see, Sect. 3). We form a combined dataset by merging the quasars present exclusively in the set JB(91) with the set B(96), after multiplying their quoted Hβ widths by the mean value of ξ found above.

Table 1 gives a consolidated list of all the LDQs used in our study. The information provided includes: the IAU name of the quasar, its redshift (taken from Véron-Cetty & Véron, 1993), the largest angular size (LAS) measured from the radio maps (references are cited in the footnote). Column (4) tabulates the value of log f_c. Column (5) gives log R_v, defined by Wills & Brotherton (1995) as $\log R_v = \log(L_{core}/L_{opt}) = log(L_{core} + M_v/2.5) - 13.69$, where the absolute visual magnitude, M_v, is taken from Véron-Cetty & Véron (1993) and listed in column (6). Columns (7)&(8) tabulate the published widths of the broad Hβ emission line, taken from the two datasets discussed above. Column (9) lists the value of ξ, the ratio of W($H\beta$) measured by B(96) to that by JB(91) for the 12 quasars which are common to the two data sets.

3. Results

Fig. 1 shows the radio size, l, plotted against the parameters, R_v, f_c, $W(H\beta)$ and z for our sample of 42 LDQs. The filled circles are the data from B(96) and the open circles refer to the data from JB(91). The values of W shown by the open circles have been rescaled, as discussed above. Table 2 shows the results of the non-parametric Spearman rank correlation tests between the different parameters, for B(96) as well as the combined dataset. For each case, 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 noticed from Fig. 1 and Table 2 is that l is found to correlate more strongly with W than with any of the other parameters, namely f_c, R_v, and even redshift, z. The $l - W(H\beta)$ correlation thus emerges to be of the primary statistical significance , in agreement with the preliminary results reported by Gopal-Krishna (1995) (see, also, Gopal-Krishna & Srianand, 1998). It may be recalled that using a much more limited dataset, Miley & Miller (1979) had earlier noticed a positive correlation between l and $W(H\beta)$. However, almost $\sim 40\%$ of their sample was comprised of core-dominated quasars and hence, the linear sizes used by them are likely to be influenced by projection effects to a much greater degree (and, consequently, be rendered less suitable as a measure of source age, *vis-a-vis* the present study where only lobe-dominated quasars have been considered). Note that the quasar 0710+118 (marked with an arrow in Fig 1c) shows a large deviation from the general trend. Since this quasar is the only case where W(Hβ) measured by B(96) is larger than that found by JB(91) (Table 1), we have also plotted in Fig 1c the scaled JB(91) value of its W(Hβ) [the open

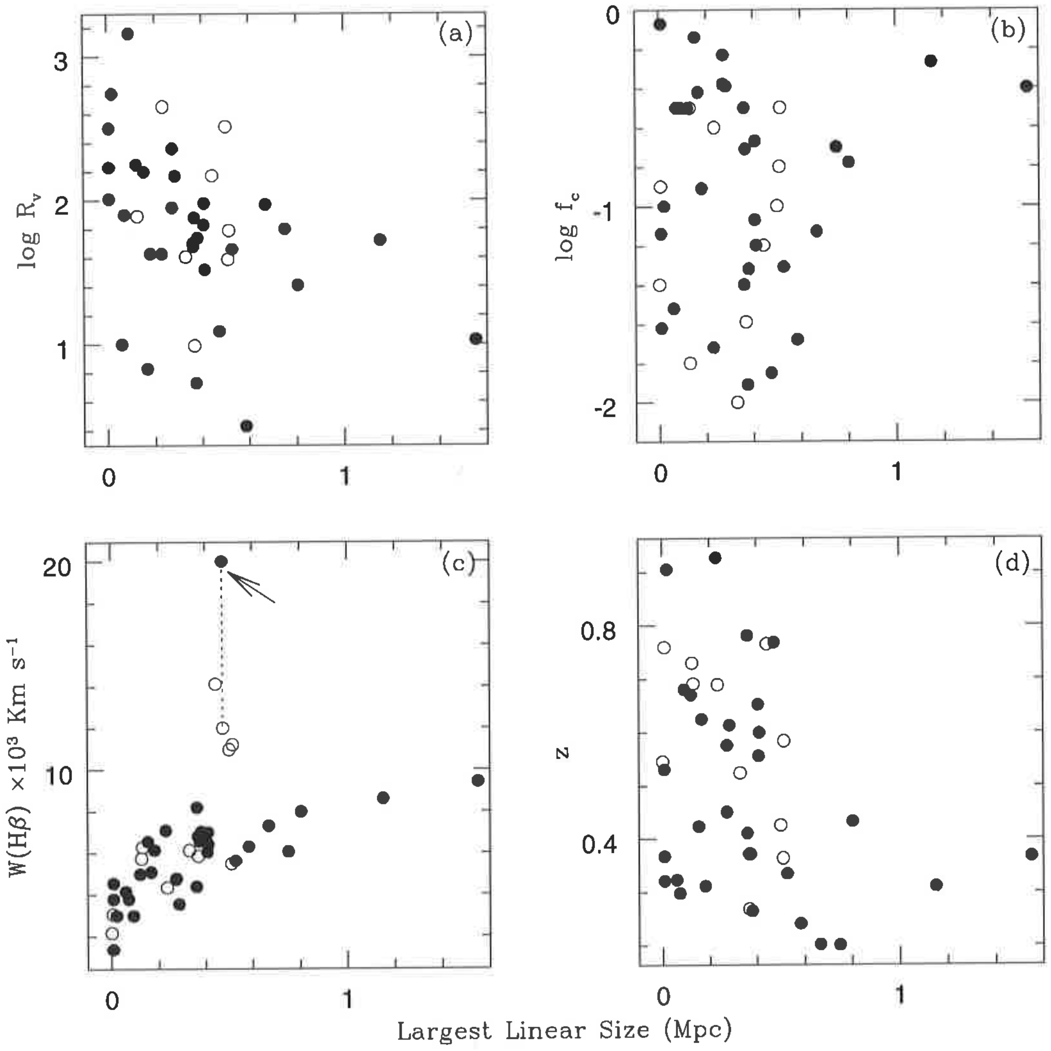

Fig. 1. (a-d) The plots of R_v, f_c, $W(H\beta)$, and z, *versus* the radio size (l) for our combined dataset of lobe-dominated quasars. The filled circle are the data from B(96) and the open circles represent the data from JB(91) (Sect. 2 and 3).

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	−0.163	−0.207	−0.376	0.771	−0.254	−0.397
		0.373	0.254	0.030	2.4×10^{-7}	0.161	0.024
combined	42	−0.237	−0.111	−0.420	0.765	−0.183	−0.324
dataset		0.127	0.447	0.005	2.3×10^{-9}	0.240	0.034

circle connected by a dotted line] and this point is fully consistent with the general trend.

In order to understand possible implication of the $l-W$ correlation, we first recall the general consensus that a vast majority of powerful extragalactic radio sources grow in linear size with increasing age (e.g., Readhead, 1995; Fanti et al., 1995). Thus, to a first order, the observed linear size, l (i.e., the separation between the outermost peaks in the radio lobe-pair) can be regarded as a meaningful statistical indicator of the age (e.g., Best et al., 1996). For individual sources, radio spectral gradient is also used as a measure of the age (sect. 4). However at present such data are largely confined to very extended radio sources with prominent diffuse lobes, mainly radio galaxies where the contamination of the lobe emission by the jet component is usually quite small (e.g., Alexander & Leahy, 1984; Carilli et al., 1991; Liu & Pooley, 1992; Rawlings & Saunders, 1991).

A potentially complicating factor in the use of l is the foreshortening caused due to the (unknown) projection effects. However our selection criterion, which excludes core-dominated quasars, would effectively minimize the role of projection. It may be recalled that l is known to *anti-correlate* with z for quasars, as reported, e.g., by Wardle & Miley (1974), which is usually interpreted in terms of an increase in the density of the ambient medium. However, this may not play a major role in our data as it covers a much smaller range in redshift (Table 1). This expectation is supported by the apparent weakness of the $l-z$ correlation in our data (Table 2). Radio size, l, is also known to be anti-correlated 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). Again, this trend is at best only weakly present in our datasets (Fig. 1; Table 2), which is in accord with the expectation that projection effects should be of minor importance in the case of lobe-dominated quasars. This is further supported by the apparent weakness of $l - R_v$ anti-correlation in our datasets (Fig. 1; Table 2).

4. Discussion

An important inference from Fig. 1 is that over the lifetime of a typical powerful double radio source, the FWHM of the $H\beta$ emission line from the BLR undergoes an increase by roughly a factor of 3–4. This broad line is presumed to arise from the vicinity of the central super-massive black-hole (SMBH) and its width is commonly attributed to the gravitational influence of the SMBH, in accordance with the standard paradigm for AGN (however, for radio-quiet AGN, alternative schemes have been put forward by, e.g., Terlevich et al., 1992). In the past, widths of the BLR emission lines have often been used as the key tracer of the mass of the central engine of AGN (e.g., Dibai, 1984; Wandel & Yahil, 1985; Padovani & Rafanelli, 1988, Perry, 1992).

Here it may be recalled that the radio spectral mapping programmes have yielded typical lifetime of order $10^7 yr$ for powerful double radio sources (e.g., Alexander & Leahy, 1987; Carilli et al., 1991; Liu & Pooley, 1992). However, independent considerations based on the dynamics of the radio hot-spots suggest that the true ages are probably an order-of-magnitude larger (i.e., $\sim\ 10^8\ yr$). This is borne out, for instance, from a recent analysis of the lobe-length asymmetry, in which the near-side radio lobe in individual sources could actually be identified using the observed one-sided jet (Scheuer, 1995). Indeed, several authors have argued that the analyses of spectral gradients in radio lobes could substantially underestimate the ages, since they usually incorporate the simplistic assumption of a uniform magnetic field. As indicated by the well-resolved maps of radio lobes and jets, the field is likely to be concentrated in filaments occupying just a tiny fraction of the total volume of the lobes (e.g., Perley, Dreher & Cowan, 1984; Owen, Hardee & Cornwell, 1989). Consequently, the energetic particles would spend most of the time in the weak-field region, thereby reducing the synchrotron losses by a large factor (see, e.g., Eilek, Melrose & Walker, 1997 and references therein; Gopal-Krishna, 1980). Likewise, the spectral ages may also get underestimated if (large-scale) spatial gradients of magnetic field are present within the radio lobes/jets (Wiita & Gopal-krishna, 1990). Based on all these considerations, it seems more likely that the true ages of powerful radio sources are close to $10^8 yr$. For the case of Eddington accretion rate one would then expect typically an order-of-magnitude increase in the mass of the SMBH during the lifetime of the radio sources, since the e-folding time for the black-hole mass is:

$$t_{Edd} = |\dot{M}_{Edd}/M|^{-1} = (4.5 \times 10^7\ yr)\ (\eta/0.1), \tag{1}$$

where η is the radiative efficiency. We argue below that even though the persistence of an Eddington accretion rate is not supported by the data, the inference about an order-of-magnitude increase in the mass of the central engine (i.e. the region within the BLR) during the radio source lifetime probably still holds.

In the event of Eddington accretion rate the increase in the mass of the central black-hole with time would result in a similar increase in the luminosity. As a result, one would expect a positive correlation between L_{opt} and l, which is not evident in our combined data set (Fig. 2a). This weakens considerably the case for a persistent accretion at the Eddington rate. On the other hand, in order to estimate the increase in the mass of the central engine one needs to take into account the result from the 'reverberation mapping' of nearby AGNs, which has revealed a positive dependence of the BLR radius (r) on the luminosity(L): $r\ \sim 0.06 L_{46}^{0.5}\ pc$ (Netzer & Laor 1993), where L_{46} is the bolometric luminosity expressed in the units of $10^{46} erg.s^{-1}$. Combining this with the relation $v^2 \propto GM/r$ gives: $M \propto v^2 \sqrt{L_{46}}$. Fig. 2b shows a plot of M *versus* linear size, l which is a measure of age of the quasar (note that L has been approximated by optical luminosity, cf. Joly et al., 1985). A positive correlation between M and l at a 4.5σ level is seen in our combined dataset of LDQs. This suggests that over the lifetime of a typical radio quasar, the mass of the region inside the BLR does go up by about an order-of-magnitude. These estimates could be further sharpened when the estimates of bolometric luminosity for the individual quasars become available. Another interesting improvement to this study would be to induct additional quasars with very large radio structures. That would shed light on the late evolutionary stages of the central engine of quasars.

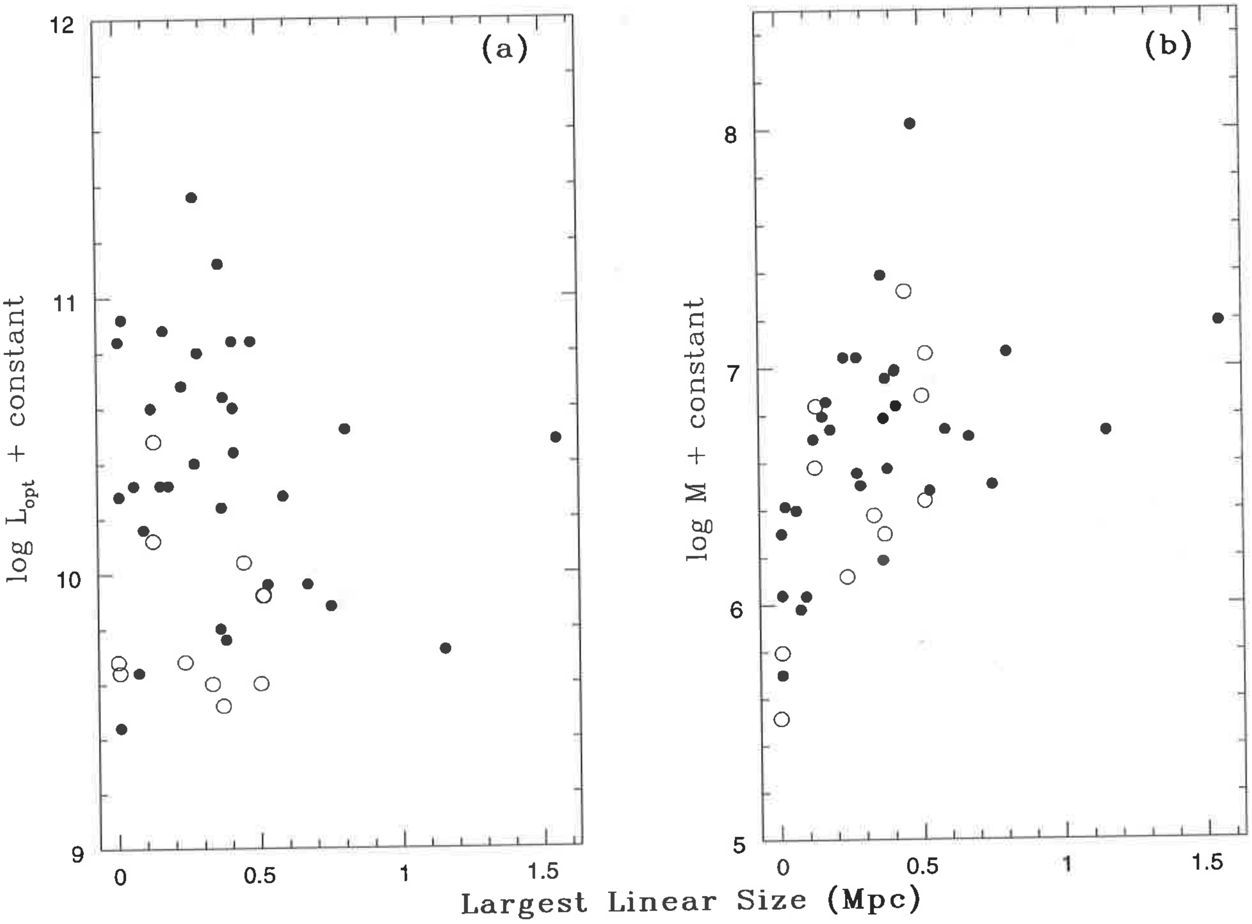

Fig. 2. (a,b): Plots of radio size (l) *versus* the optical luminosity and the mass of the central engine, respectively, for our combined dataset (see Sect. 4). The filled circle are the data from B(96) while the open circles refer to the data from JB(91), as explained in Sect. 2.

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