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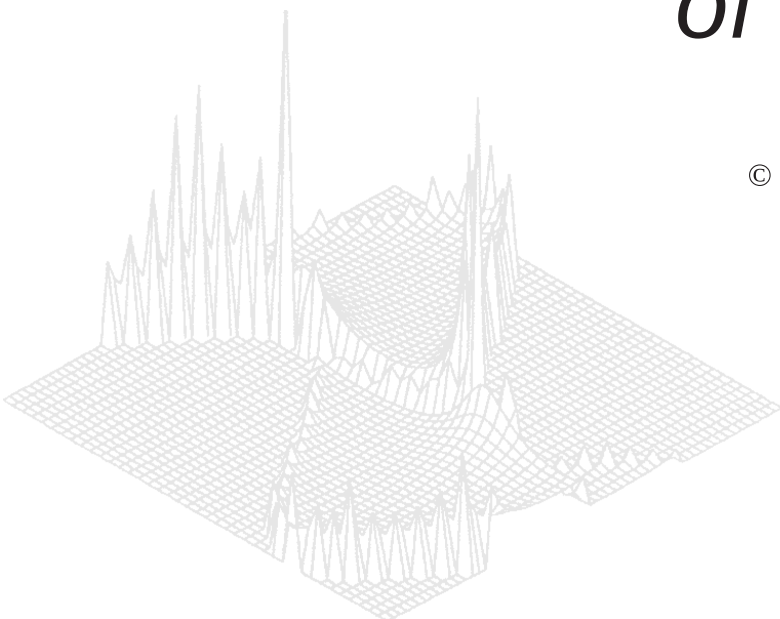

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Luminosity Selection Effects and Linear Size Evolution in the Quasar/Galaxy Unification Scheme

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Abstract

The implications of linear size evolution and luminosity selection effects in the quasar/galaxy unification scheme have been investigated. We show that both radio galaxies and quasars undergo similar size evolution above some low redshift cut-off $z_c = 0\cdot2$–$0\cdot3$. However, this evolution can be attributed largely to the strong luminosity selection effects present in the sample. We also observe that there is a marked difference in the luminosity–redshift slope between low and high redshift sources, which may be responsible for the conflicting results in the literature as to whether or not radio galaxies and quasars have similar linear size versus luminosity/redshift relationships. Our present result seems consistent with the quasar/galaxy unification scheme in which the two classes of object are expected to have similar linear size versus luminosity/redshift relationships.

1. Introduction

Linear size evolution has often been invoked to explain the observed variation of angular sizes θ of extragalactic radio sources with redshift z. Earlier analyses (e.g. Kapahi 1987) have shown that the distributions of θ with z are indistinguishable for quasars and radio galaxies taken together. Moreover, a linear size evolution of the form $D \sim (1+z)^{-x}$ with $x = 1$–2, depending on the value of the density parameter Ω_0, was usually required to interpret the observed data (see e.g. Okoye and Onuora 1982; Kapahi 1985; Barthel and Miley 1988). The θ–z data for quasars were also interpreted by Masson (1980) in terms of an inverse correlation between linear size and radio luminosity without requiring any linear size evolution. Later analyses have, however, revealed that the evolution is steeper ($x = 3\cdot0\pm0\cdot5$), at least for radio galaxies, than was earlier inferred (e.g. Oort *et al.* 1987; Singal 1988; Kapahi 1989).

Recently, Singal (1993) has shown that radio galaxies and quasars undergo different size evolution with $x \sim 3\cdot0$ for radio galaxies and $x \sim 0\cdot3$ for quasars. In addition, he found that the two classes of object also show a different linear size–luminosity (D–P) relationship. This result appears to provide strong evidence against the unification scheme (cf. Barthel 1989) in which both radio galaxies and quasars are expected to differ only in their aspect-dependent properties. Since then, a number of papers have been published either in support or against his results (see e.g. Nilsson *et al.* 1993; Saikia and Kulkarni 1994; Kapahi *et al.* 1995, 1996; Neeser *et al.* 1995; Chyzy and Zieba 1995; Singal 1996). The

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situation is still far from being resolved. We show in the present paper that this discrepancy stems not only from the different statistical methods employed by different authors in their analyses but also from the quality of source samples used.

2. Variation of Radio Luminosity with Redshift for Radio Galaxies and Quasars

The nature of the dependence of the linear sizes D of radio galaxies and quasars in the luminosity–redshift (P–z) plane has been shown (e.g. Ubachukwu 1997*a*) to have some contribution toward resolving the apparent discrepancies in the results currently in the literature regarding whether or not these two classes of object have similar D–P/z relationships. Ubachukwu *et al.* (1993) have studied the luminosity evolution of extragalactic radio sources and noted that the P–z relation can be approximated to a power-law function of the type

$$P = P_0(1+z)^{\beta}, \tag{1}$$

where β can be assumed constant only above some redshift cut-off ($z_c = 0\cdot2$–$0\cdot3$).

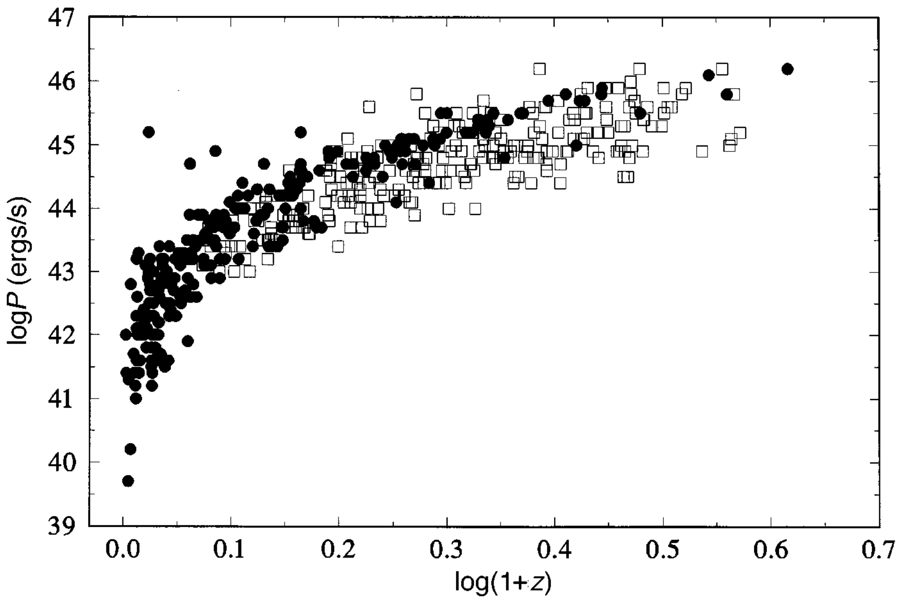

Fig. 1. Plot of luminosity against redshift for both quasars (squares) and radio galaxies (circles) in the Nilsson *et al.* (1993) sample.

Generally, radio galaxies and quasars are not equally represented, especially below z_c in virtually all the samples used so far in investigating the form of their D–P/z relationships. One of the major considerations when investigating the quasar/galaxy unification scheme is to ensure that the two classes are fairly matched in the P–z plane. As an illustration, we show in Fig. 1 a plot of the P–z data used by Nilsson *et al.* (1993, hereafter NVKJ93), where different symbols have been used to represent radio galaxies (circles) and quasars (squares). However, Ubachukwu (1997*b*) has shown that the linear sizes of flat spectrum quasars appear to be independent of radio luminosity and/or redshift in contrast to their lobe-dominated counterparts (e.g. Singal 1993). Furthermore, Onuora and Ubachukwu (1995) have shown that compact steep spectrum sources seem to have a steeper D–P/z relationship than the more extended sources. Out of the 540 double radio sources (267 galaxies and 273 quasars) in the NVKJ93 sample, 31 have flat spectra (26 quasars and 5 galaxies) and 19 (12 galaxies and 7 quasars) belong to the compact steep spectrum class, and were therefore excluded from the analyses. It may be pointed out that since the number of these sources is small, their inclusion or exclusion may not have significant effects on our result. The position of the core-dominated quasars in the quasar/galaxy unification scheme has been investigated elsewhere (Ubachukwu 1996) using a better defined sample of core-dominated quasars. The plots shown in Fig 1 were therefore based on the 240 quasars and 248 radio galaxies with steep spectra (spectral index $\alpha > 0{\cdot}5$, $S_\nu \sim \nu^{-\alpha}$) and extended linear dimensions ($D > 25$ kpc).

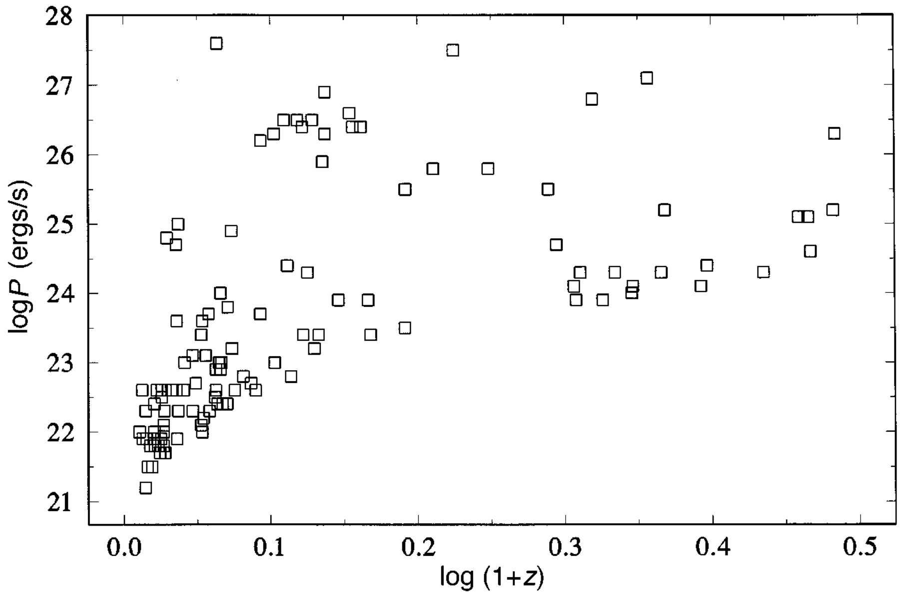

Fig. 2. Plot of luminosity against redshift for quasars in the Kellermann *et al.* (1989) sample.

Fig. 1 shows that quasars and radio galaxies can only be properly matched above $z = 0{\cdot}2$–$0{\cdot}3$. The low redshift sources (largely radio galaxies) appear to have a steeper D–P slope than their higher redshift counterparts. For purposes of comparison, we have also shown in Fig. 2 a similar plot using the bright quasar survey compiled by Kellermann *et al.* (1989) which contains a statistically significant number (71/114) below $z = 0{\cdot}3$. Figs 1 and 2 show similar distributions up to z_c. To show this more quantitatively, we have carried out linear regression analyses of equation (1) for radio galaxies and quasars both with and without redshift cut-off. The results based on the NVKJ93 sample, except for $z < 0{\cdot}3$ where we used the Kellermann *et al.* (1989) sample, are summarised in Table 1.

Table 1. Regression parameters for quasars (Q) and radio galaxies (G)

Redshift	Number (Q/G)	$\beta(Q)$	$\beta(G)$	Correlation (Q/G)
All	242/248	4·7±0·2	8·8±0·4	0·8/0·9
$z > 0{\cdot}3$	229/96	4·3±0·6	5·8±0·3	0·5/0·6
$z < 0{\cdot}3$	71/152	24·9±4·5	21·9±1·7	0·6/0·6

Table 1 clearly demonstrates that the redshift cut-off delineates two distinct populations of radio sources with different luminosity and/or space density evolution. This suggests that any radio source sample that is dominated at low redshift levels (as is often the case with radio galaxies) will show a different behaviour from those dominated by high redshift sources (which are mostly quasars). As we demonstrate below, the difference in the P–z slope between sources that are below and above z_c has serious implications in the amount and nature of linear size evolution found for any radio source sample.

3. Luminosity Selection Effects and Linear Size Evolution

We can generalise the variation of linear sizes of extragalactic radio sources with radio luminosity and redshift in terms of simple power-law functions:

$$\log D(P) = a_0 \pm q \log P \,, \tag{2}$$

$$\log D(z) = b_0 - x \log(1+z) \,. \tag{3}$$

Most analyses usually assume that the exponents x and q are the same everywhere in the P–z plane. But, as we have just demonstrated in the previous section, this assumption is only approximately true above some redshift cut-off. Therefore, the assumption of similarity in the D–P dependences for radio galaxies and quasars (cf. Kapahi 1987; Gopal-Krishna and Kilkarni 1992), or modelling the cosmological evolution of the radio sizes of radio galaxies and quasars at a fixed luminosity (cf. Singal 1993), are likely to be applicable only above z_c. Furthermore, estimating the D–z relationship over some luminosity ranges (e.g. Barthel and Miley 1988) still leaves some residual luminosity effects. Some of these flaws have been pointed out by Neeser *et al.* (1995). A more plausible way out of these problems is given in the rest of this section.

Following Ubachukwu *et al.* (1996), we use equation (1) in (2) to obtain an expression for the D–z relationship independence of luminosity effects:

$$\log D[P(z)] = a_1 \pm q\beta \log(1+z) \,, \tag{4}$$

where $a_1 = a_0 \pm q \log P_0$. Equation (4) therefore suggests that if the observed D–z correlation is entirely a luminosity effect, then comparing equation (4) with (3) we obtain

$$x = q\beta \,. \tag{5}$$

Otherwise, we have

$$n = x \mp q\beta \,, \tag{6}$$

where n is the residual linear size evolution after correcting for that which results from luminosity selection effects.

(3a) Application to Radio Galaxies and Quasars

We show in Figs 3 and 4 the observed D–P and D–z relationships respectively for sources with $z > 0{\cdot}3$ taken from the NVKJ93 source sample. The symbols used are as in Fig. 1. Both figures show a general trend in which the linear sizes of both radio galaxies and quasars tend to decrease towards higher redshift and radio luminosities. For a more quantitative discussion, we have carried out linear regression analyses of the two plots for both radio galaxies and quasars. The regression parameters x and q were obtained by fitting the median value log$D$–log(P) and log$D$–log(1+z) data in different redshift and luminosity bins to equations (2) and (3) independently. The results (together with their standard errors and correlation coefficients) are shown in Table 2. Table 2 actually shows that there is no significant difference in the D–P/z relationships for both radio galaxies and quasars above z_c. However, to estimate the amount of size evolution which can be attributed to the strong luminosity selection effects in the sample, we have also fitted equation (1) to the observed P–z data. The values of β which provide the best fit to the observed data, together with the corresponding values of n calculated using equation (6), are also shown in Table 2. It can be clearly seen from the values of n (see Table 2) that the observed linear size evolution for both quasars and radio galaxies in the sample can be largely attributed to the strong selection effects present in the sample. More specifically, ~70–90% of the observed evolution parametrised by x can be interpreted in terms of the luminosity selection effects alone.

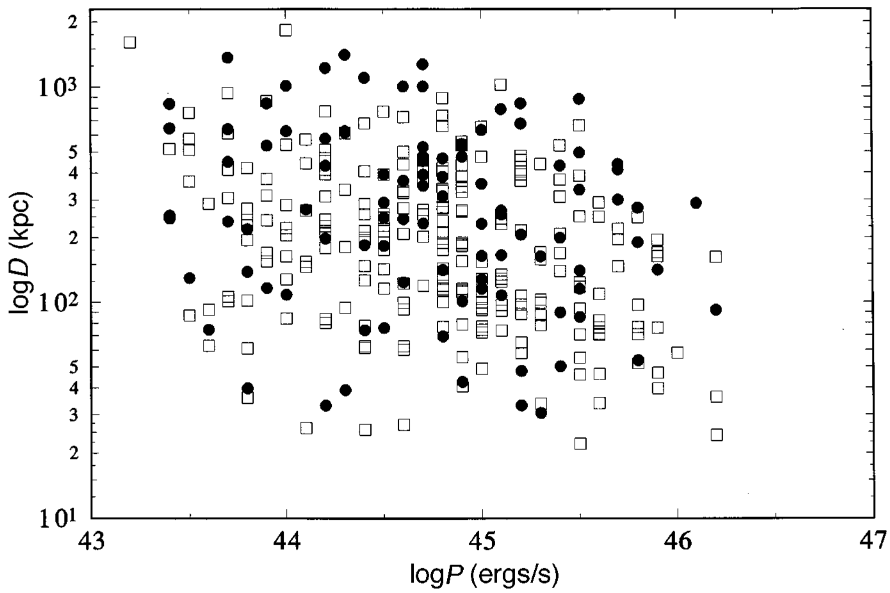

Fig. 3. Linear size versus radio luminosity relation for radio galaxies and quasars with $z > 0{\cdot}3$ (symbols as in Fig. 1).

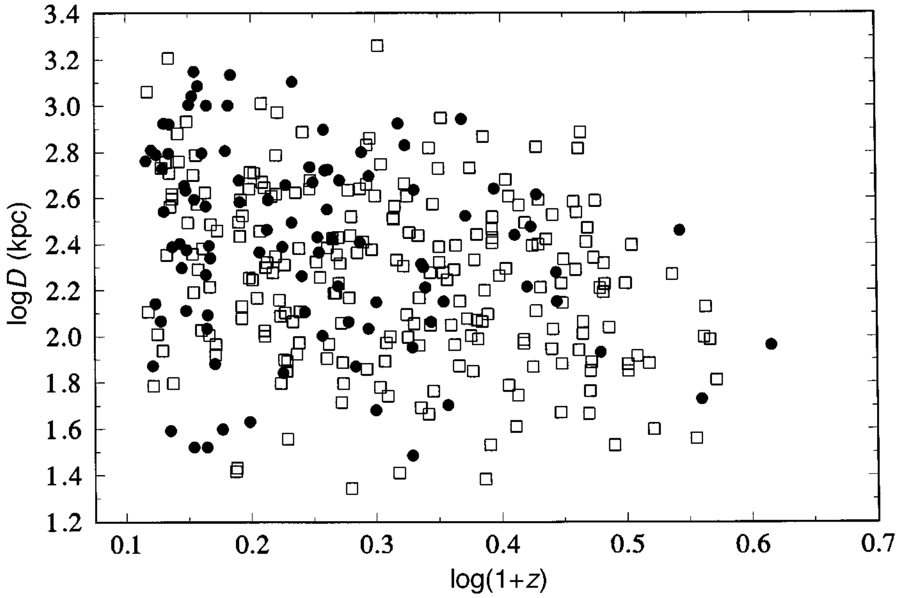

Fig. 4. Linear size versus redshift relation for radio galaxies and quasars with $z > 0{\cdot}3$ (symbols as in Fig. 1).

Table 2. Comparison between quasar and radio galaxy evolution parameters

Parameter	Quasars	Galaxies
q	$0{\cdot}23{\pm}0{\cdot}10$ ($r \sim 0{\cdot}6$)	$0{\cdot}16{\pm}0{\cdot}10$ ($r \sim 0{\cdot}4$)
x	$1{\cdot}1{\pm}0{\cdot}5$ ($r \sim 0{\cdot}9$)	$1{\cdot}5{\pm}0{\cdot}5$ ($r \sim 0{\cdot}9$)
β	$4{\cdot}0{\pm}0{\cdot}2$ ($r \sim 0{\cdot}9$)	$6{\cdot}3{\pm}0{\cdot}2$ ($r \sim 0{\cdot}9$)
n	$0{\cdot}2$	$0{\cdot}5$

(3b) Effect of Low Redshift Sources

We have earlier observed from Figs 1 and 2, and quantitatively demonstrated in Table 1, that there is a tendency for low redshift sources to exhibit a steeper P–z slope than their counterparts at high redshifts. It was suggested that this difference is likely to affect the general behaviour of the linear sizes of extragalactic radio sources in the P–z plane. In particular, we suggested that this difference is likely to cause the observed disparity found by Singal (1993) in the D–P/z relationships between radio galaxies and quasars in his sample. We also pointed out that it is implausible to model the D–P/z relationships using a fixed radio luminosity for all redshift ranges.

We now show in Fig. 5 the medium linear size versus luminosity plot for the entire galaxy sample. The binning was done in such a way as to allow about 30 to 40 sources per bin. It can be seen that there is an indication of an initial increase of D with P up to $P \sim 10^{42\cdot5}$ ergs/s, then a flattening up to $\sim 10^{43}$ ergs/s and a steep decrease thereafter. This tends to confirm our belief that the difference in the D–P/z relationships between radio galaxies and quasars found by some authors can be attributed to the relatively larger number of radio galaxies compared with quasars at lower redshifts. We lack a comparatively large sample of quasars at low redshifts to carry out similar analyses. However, as Fig. 2 indicates, there is every likelihood that the quasar sample will follow a similar trend.

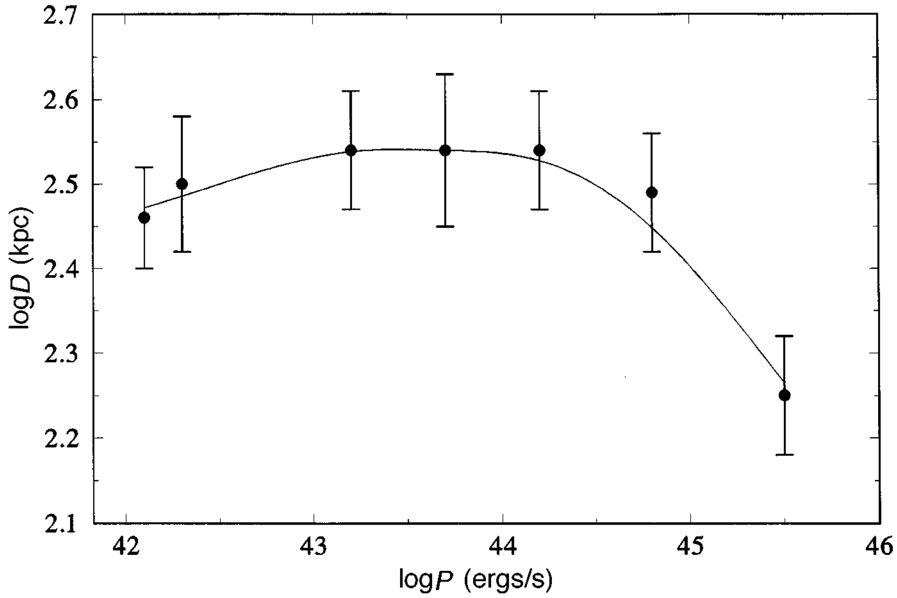

Fig. 5. Plot of the linear size versus luminosity data for radio galaxies for all redshifts.

4. Discussion

The study of the redshift dependence of linear sizes of extragalactic radio sources is not only important for cosmological studies but also for testing the radio source unification schemes. Miley (1968) was the first to observe an obvious relationship between the angular size θ of radio sources and their redshifts. The interpretation of the observed θ–z data has, however, been complicated by the strong luminosity selection effects in most well-studied flux-density-limited source samples. Furthermore, Hough and Readhead (1989) have observed that it is not easy distinguishing the effects of cosmological evolution from those of relativistic beaming and radio source orientation scenarios.

Oort *et al.* (1987) were able to factorise out the dependence of linear size on redshift from that of radio luminosity. They showed that the median linear sizes of radio galaxies up to $z \sim 1 \cdot 0$ follow a bivariate relationship with radio luminosity and redshift of the form; $D \propto P^q(1+z)^{-n}$ with $n \sim 3 \cdot 0$ and $q \sim 0 \cdot 3$. Similar results were also obtained by Kapahi (1989). Singal (1993) later confirmed this result but, in addition, showed that for quasars, $n \sim 0 \cdot 3$ and $q \sim -0 \cdot 2$. This latter result shows that radio galaxies and quasars have different D–P/z relationships. In contrast to Singal (1993), Nilsson *et al.* (1993) found no obvious difference in the D–P/z relationships for both radio galaxies and quasars. More recently, Neeser *et al.* (1995) found a milder evolution for both radio galaxies and quasars ($n = 1 \cdot 2 \pm 0 \cdot 5$), but could not find any evidence of a D–P correlation in their sample. However, they included in their analysis, the compact steep spectrum sources whose evolution appears steeper than their more extended counterparts (see Onuora and Ubachukwu 1995). Also, by the large errors in their results, we believe that the actual amount of evolution present is less than they have inferred.

In the orientation-based unification scheme, both radio galaxies and quasars are expected to be indistinguishable in their D–P/z relationships. Our results have shown that this is the case provided there is a truncation at low redshifts. It is also shown that the previously inferred linear size evolution for both radio galaxies and quasars (above z_c) is largely an artefact of the strong luminosity selection effects present in all flux density limited samples. We have only addressed the problem of the D–P/z relationship. The problem of the relative sizes and numbers of radio galaxies and quasars in different redshift intervals requires additional radio galaxies and quasars at the highest and lowest redshifts, respectively, than are currently available in the literature.

5. Conclusions

We have shown in the present paper that the contradictory results in the literature as to whether or not radio galaxies and quasars have similar D–P/z distributions are partly due to insufficient data, especially for quasars at low redshifts and partly due to a change in the P–z slope from low to high redshifts. In addition, we have pointed out the difficulties in normalising linear sizes at a fixed radio luminosity at different redshifts. Our results also indicate that, above some redshift cut-off, the D–P/z relationships for radio galaxies and quasars are fairly indistinguishable. In addition, our results have indicated that the observed linear size evolution for both radio galaxies and quasars can be attributed largely to the luminosity selection effects in flux-density-limited samples. Within the limits imposed in our analyses, the present results are in conformity with the unified scheme.

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