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LETTER

Letter to the Editor

Beaming models and the correlations between the core dominance parameter and the core and extended powers of quasars

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Abstract. We investigate the recent claim by Qin et al. that the observed correlations (or lack thereof) between the core dominance parameter and the core and extended powers of samples of lobe- and core-dominated quasars is in contradiction with beaming models. Contrary to their conclusion, we find that their results are in perfect agreement with such models, and support this assertion with Monte Carlo simulations.

Key words: galaxies: active – quasars: general – radio continuum: galaxies

1. Introduction

It is widely believed that radio-loud quasars and powerful radio galaxies (FR II-type according to the scheme of Fanaroff & Riley 1974) differ only by the orientation of their radio axes with respect to the observer's line of sight (e.g. Barthel 1989). A related scenario proposes that the cores of these radio sources are dominated by beamed emission which can be significantly enhanced by Doppler boosting, while the extended emission is isotropic (e.g. Orr & Browne 1982). These two models explain why radio loud quasars tend to have more luminous radio cores compared to FR II radio galaxies with similar extended radio luminosities, and has prompted the use of the core dominance parameter, $R \equiv P_5^{\rm c}/P_5^{\rm e}$ as a relative measure of orientation. [In an attempt to have a meaningful, concise, and consistent notation throughout this paper, we employ the superscripts c, e, and t to refer to the core, extended, and total radio emission (power, P, or flux, S) respectively, and subscripts to indicate the rest-frame frequency (in GHz).]

Recently, Qin et al. (1998, hereafter Q98) investigated the core and extended radio properties of four samples of quasars from the literature. They found that in core-dominated quasars, the extended radio power, $P^{\rm e}$, was inversely correlated with R, while the core radio power, $P^{\rm c}$, was not correlated at all. In lobe-dominated quasars, on the other hand, $P^{\rm e}$ was uncorrelated while $P^{\rm c}$ was correlated with R. They claimed that these correlations were in contradiction with the unified schemes and beaming models, and proposed instead that the core emission in core-dominated quasars is unbeamed and isotropic. In this *Letter*, we show that the results found by Q98 *are* in agreement with beaming models, given the selection criteria of the samples they studied, and that core-dominated quasars do not comprise a separate class of active galactic nucleus. In Sect. 2 we explain the reasons for the correlations observed (or unobserved) by Q98, and in Sect. 3 we compare the predictions of Monte Carlo simulations of extragalactic radio sources with the data from the samples analyzed by Q98.

2. Beaming models

In beaming models, it is assumed that all radio sources are intrinsically steep-spectrum, and flat-spectrum sources are merely those where the core is boosted sufficiently strongly to dominate the total flux over the observed frequency range. The extended radio luminosity of *all* radio sources therefore follows the radio luminosity function for steep-spectrum sources, in which the number of sources above a given luminosity decreases sharply with luminosity.

2.1. Core-dominated quasars

We first consider core-dominated quasars (CDQs). Q98 believe that $P^{\rm c}$ should be correlated with R because those sources with the most luminous cores should be those with the strongest beaming. This is obviously true at some level, since both Punsly's (1995) and Murphy, Browne & Perley's (1993) samples, which are selected on core strength, contain only strongly-beamed sources. However, we show by considering the situation in more detail that the presence or absence of correlations is controlled by selection effects, and that this simplistic belief is too naïve.

Beaming models predict that the observed core dominance parameter should depend on the jet speed, βc, the viewing angle, θ, and the transverse (unbeamed) core dominance parameter, $R_{\rm T}$, as

$$R = \frac{1}{2}R_{\rm T}(1-\beta\cos\theta)^{-2} + \frac{1}{2}R_{\rm T}(1+\beta\cos\theta)^{-2}$$

(e.g. Orr & Browne 1982), where the second term can be ignored for small values of θ. Obviously, the orientation of any given source is independent of its extended radio luminosity, and let us assume for the moment that β and $R_{\rm T}$ are also independent of $P^{\rm e}$. In this case, the extended radio luminosity function (ERLF) is separable in some form $\rho = f(P,z)g(R)$ and sources with a given value of R follow the same ERLF as the general source population. Let us examine Punsly's (1995) sample, which is Q98's Sample 1. This consists of RLQs with core powers (integrated over $10\,{\rm MHz} < \nu < 250\,{\rm GHz}$) above 10^{39} W. Consider those sources with, say $R \approx 10^3$; they need to have $P^{\rm e} > 10^{36}$ W to satisfy the selection criterion. The shape of the ERLF is such that about three-quarters of all such sources will lie within a factor two of this limit, and only about 1% will exceed it by an order of magnitude. Most sources with $R \approx 10^3$ will therefore have $P^{\rm e} \approx 10^{36}$ W. If one now considers sources with $R \approx 10^2$, the same arguments indicate that these sources will have $P^{\rm e} \approx 10^{37}$ W. Therefore the extended radio power will be strongly inversely correlated with R, which is exactly what is observed in Punsly's sample. Since the core luminosity is merely $P^{\rm c} \equiv RP^{\rm e}$, the core power will be uncorrelated with R. Exactly the same argument applies for Sample 2 (from Murphy et al. 1992), which is a sample selected on core flux, rather than luminosity. It is the fact that these samples are selected on core strength that causes the observed correlations, and not the fact that the sources are CDQs.

The maximum observable core dominance parameter is $R_{\rm max} \approx \frac{1}{2} R_{\rm T}(1-\beta)^{-2}$. For typical values of $\beta = 0.99$ ($\Gamma = 7$, e.g. Guerra & Daly 1997) and $\log R_{\rm T} = -2.5$ (at 5 GHz, Simpson 1996; see also Morganti et al. 1997), this is about 20 using the defintion and canonical radio spectra of Punsly (1995). To exceed this value by nearly two orders of magnitude (as some of Punsly's sources do), a source must either have an unusually fast jet ($\beta = 0.999$, $\Gamma = 22$) or a much larger than average $R_{\rm T}$. These parameters will therefore be correlated with the observed core dominance, and so could an additional correlation with extended radio power nullify the above argument?

Suppose that β is correlated with the extended radio luminosity. This is not unreasonable since the most powerful radio sources might also produce the fastest jets. If so, sources with large R are more likely to be drawn from the high-luminosity end of the ERLF. On the other hand, $R_{\rm T}$ might be anticorrelated with extended radio luminosity, since the lobe luminosity of a radio source decreases throughout its lifetime despite a constant jet power (e.g. Baldwin 1982). So sources with large R might preferentially be older sources with lower extended radio luminosities. The fact that the anticorrelation between $\log P^{\rm e}$ and $\log R$ appears not to alter its slope at large R indicates that either both these effects are weak, or that they have approximately the same strength and cancel each other out.

2.2. Lobe-dominated quasars

We now turn to lobe-dominated quasars (LDQs). Hooimeyer et al.'s (1992) sample of quasars (Q98's Sample 3) is selected on a minimum angular size, thereby requiring measurable emission from the radio lobes and excluding the most strongly-boosted, pole-on sources, but also has a bright core radio flux limit ($S_5^{\rm c} > 0.1$ Jy), which means that it will include many CDQs. In addition, the sample is drawn from the Hewitt & Burbidge (1987) optical quasar catalogue and is therefore subject to uncertain selection effects. The fact that in reality it is a mix of CDQs and LDQs can serve to explain why it displays both correlations, but at a much weaker level than in samples of CDQs or LDQs alone. We do not consider it further.

Instead, we turn to the well-defined Sample 4, from Hough & Readhead (1989) which contains all double-lobed quasars from 3CRR (Laing, Riley & Longair 1983) whose cores were bright enough to be mapped with the Mark III VLBI system. All sources therefore have $S_{0.178}^{\rm t} > 10.9$ Jy and $S_5^{\rm c} > 5$ mJy. Unlike the core-selected samples, the total flux at the selection frequency (178 MHz) has a negligible contribution from the flat-spectrum core, and therefore $S_{0.178}^{\rm t}$ has no dependence on R. Neither does $P_{0.178}^{\rm t}$, which can be assumed to be the extended luminosity alone. The spectral index of the lobes is not expected to be physically related to core dominance, and we confirm that this is so in the sample of radio galaxies from Hardcastle et al. (1998) by using the generalized Spearman's rank order correlation coefficient (Isobe, Feigelson & Nelson 1986), where we find that the two quantities are uncorrelated at greater than 90% confidence. Therefore, $P_5^{\rm e}$ will be uncorrelated with R. On the other hand, $P_5^{\rm c} = R\,P_5^{\rm e}$, and should therefore be clearly correlated with R, with the linear regression line having a slope of unity, in line with observations. Again, it is not the nature of the sources (LDQs) which produces the result, but the selection criteria.

3. Monte Carlo simulations

In order to test whether the above arguments can explain the observations in a quantitative manner, we perform simulations of radio sources. We start with the steep spectrum radio luminosity function (RLF1) of Dunlop & Peacock (1990), which we assume to be equivalent to the extended luminosity of all radio sources, and consider only those sources with luminosities above the Fanaroff-Riley break (i.e. FR II sources; Fanaroff & Riley 1974), since it is only these which constitute the parent population of quasars (e.g. Urry & Padovani 1995). We assume that the sources are randomly oriented with respect to the observer, and that their $\log R_{\rm T}$ values are drawn from a Normal distribution with mean -2.43 and standard deviation 0.50. This distribution provides a good fit to the observed values of R for FR II radio galaxies and quasars from Laing et al. (1983) with $z < 0.43$, after applying the Orr & Browne (1982) beaming model (Simpson et al. 1998; see also Simpson 1996). It is assumed that the radio cores have $\alpha = 0$ and the extended emission has $\alpha = 0.7$ ($S_\nu \propto \nu^{-\alpha}$). A jet speed $\beta = 0.99$ is assumed for the purposes of simulating Doppler boosting. We then subject the ensemble of sources to the selection criteria of the samples studied by Q98, and compare our regression and correlation analysis with theirs. As the samples of Q98 invariably have a number of sources with incomplete information that pre-

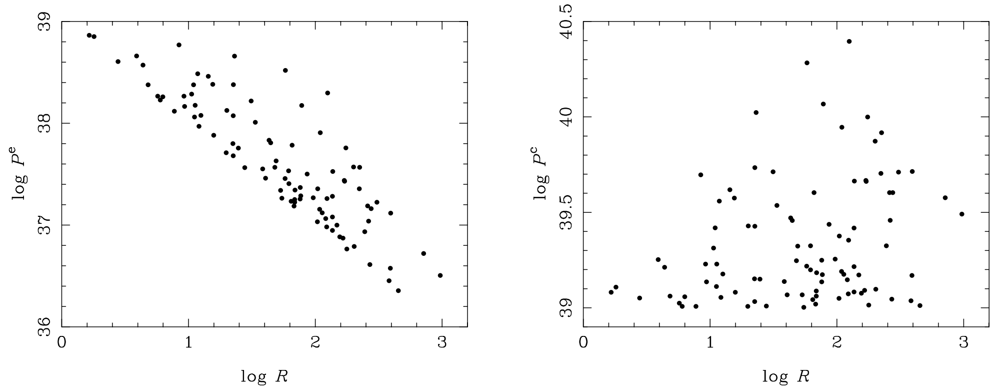

Fig. 1. Plots of extended and core radio luminosity (integrated from 10 MHz–250 GHz) *vs* the ratio of these quantities, for a simulated dataset with the same selection criteria as that of Punsly (1995).

vent them being included in Q98's analysis, we also randomly exclude sources from our complete samples so as to have the same sample size. This ensures that the same level of randomness should exist in our simulated samples as in the real data. All our simulations assume $H_0 = 50\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $q_0 = 0.5$ and $\Lambda = 0$, although the significance of the correlations we find do not depend on our choice of cosmology.

3.1. Sample 1

Sample 1 (Punsly 1995) consists of quasars with core luminosities, integrated over the range $10\,\mathrm{MHz} < \nu < 250\,\mathrm{GHz}$, greater than 10^{39} W. Adopting the typical core spectrum assumed by Punsly, this corresponds to $P_5^{\mathrm{c}} > 8 \times 10^{27}\,\mathrm{W\,Hz^{-1}}$, which we adopt as our selection criterion. In Fig. 1 we plot the extended and core luminosities against the core dominance parameter.

3.2. Sample 2

Sample 2 (Murphy et al. 1992) contains sources with core fluxes $S_5^{\mathrm{c}} \geq 1$ Jy and spectral indices (between 1.4 and 5 GHz) $\alpha \leq 0.5$ which are identified with quasars. This last criterion will exclude nearby sources since they would be classified as (broad line) radio galaxies. Examining Murphy et al.'s sample, we elect to discard all sources from our dataset with $z < 0.25$ to simulate this. There are in fact only about three sources at such low redshifts in a typical dataset, so the results are not strongly affected. The simulated datasets are shown in Fig. 2.

3.3. Sample 3

As discussed earlier, Sample 3 (Hooimeyer et al. 1992) has uncertain selection criteria, and so we make no attempt to simulate it.

3.4. Sample 4

Sample 4 (Hough & Readhead 1989) consists of sources with $P_{0.178}^{\mathrm{t}} > 10.9$ Jy and $S_5^{\mathrm{c}} > 5$ mJy that are classified as quasars. Since this is a much fainter core flux limit than Sample 2, we cannot just apply a redshift cutoff, since many distant narrow line radio galaxies will have sufficiently bright cores. Instead we require (in addition to $z > 0.25$), that $\theta < 45°$ (see Barthel 1989), which produces the sample displayed in Fig. 3.

Table 1. Correlation coefficients, r, and slopes of the best-fit regression lines, a, for the three samples modelled. For each sample, the top line contains the results from the real data determined by Q98, and the bottom line contains the results from the simulated data.

Sample	N	$r_{P^{\mathrm{e}},R}$	$r_{P^{\mathrm{c}},R}$	$a_{P^{\mathrm{e}},R}$	$a_{P^{\mathrm{c}},R}$
1	94	-0.899	0.196	-0.91 ± 0.05	0.09 ± 0.05
		-0.864	0.257	-0.87 ± 0.10	0.13 ± 0.10
2	54	-0.739	0.150	-0.88 ± 0.11	0.12 ± 0.11
		-0.591	0.136	-0.84 ± 0.10	0.16 ± 0.10
4	28	-0.286	0.848	-0.16 ± 0.10	0.84 ± 0.10
		0.056	0.873	0.03 ± 0.10	1.03 ± 0.10

3.5. Discussion

Table 1 presents the results of correlation and regression analysis on the simulated datasets, and clearly shows that the simulated datasets display exactly the same correlations as the real data. Whether it is core or extended radio luminosity that is correlated with core dominance is therefore not due to some physical difference between CDQs and LDQs, but merely an effect caused by the sample selection criteria, as discussed in Sect. 2. We note that our simulated data underproduces the number of highly core-dominated ($R \gtrsim 10^2$) quasars, compared to observations. This is presumably a result of our not having incorporated a range of jet speeds into our model, since with a single speed ($\beta = 0.99$) such sources require a viewing angle close to the line of sight *and* a large value of R_{T}. If the jet speed is a third random variable then such sources can be created if only two out of the three variables have extreme values, and this would therefore increase their frequency in our simulated Universe.

4. Summary

We have investigated the claim by Qin et al. (1998) that the observed correlations between core dominance and core or extended radio luminosity in samples of core- and lobe-dominated quasars are in contradiction with the beaming models which form a part of the unified scheme for extragalactic radio sources.

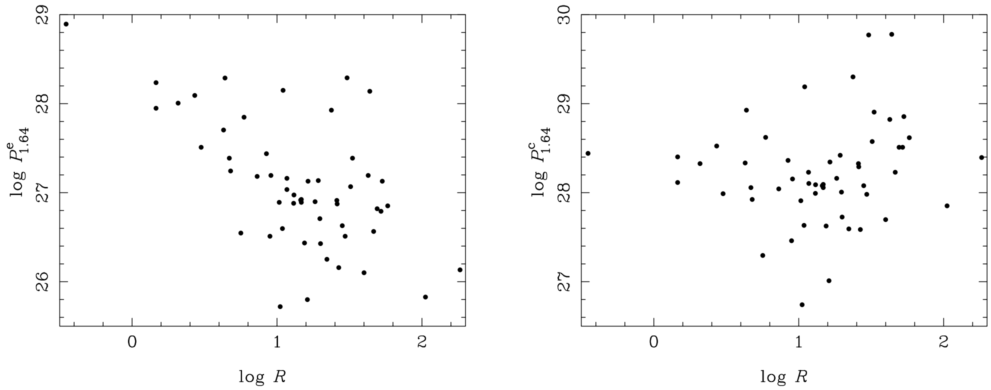

Fig. 2. Plots of extended and core radio luminosity (at 1.64 GHz in the rest frame of the source), *vs* the ratio of these quantities for a simulated dataset with the same selection criteria as that of Murphy et al. (1992).

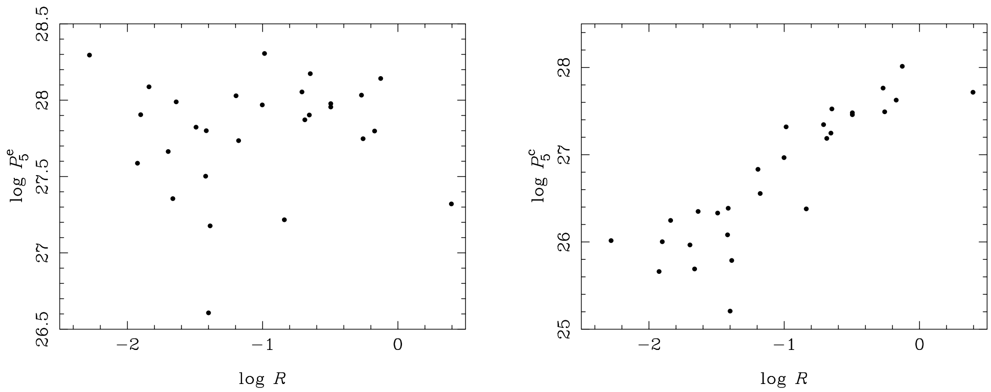

Fig. 3. Plots of extended and core radio luminosity (at rest-frame 5 GHz) *vs* the ratio of these quantities for a simulated dataset with the same selection criteria as that of Hough & Readhead (1989).

We have argued that these correlations are actually *expected* to arise from the beaming models as a natural consequence of the steepness of the (extended) radio luminosity function and the selection criteria of the samples. We have supported our claim by simulating quasar samples using the observed radio luminosity function and the statistics of beaming, and find that our simulated data produce results which are indistinguishable from those produced by the real data on which they are based.

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