J. Astrophys. Astr. (2013) **34,** 61–67

On the Absence of Core Luminosity–Core-Dominance Parameter ($P_C - R$) Correlation in Radio Galaxies and BL Lacs

J. A. Alhassan[1,*], A. A. Ubachukwu[1] & F. C. Odo[1,2]

[1]*Department of Physics & Astronomy, University of Nigeria, Nsukka, Nigeria.*
[2]*National Centre for Energy Research and Development, University of Nigeria, Nsukka, Nigeria.*
[*]*e-mail: jibrinalhassan2002@yahoo.com*

Received 7 February 2012; accepted 28 January 2013

Abstract. We have presented an alternative interpretation for the absence of correlation in the relationship between the core radio power (P_C) and core-dominance parameter (R) for a sample of BL Lacs and radio galaxies found in Fan & Zhang (*Astron. Astrophys*. **407**, 899 (2003)). This is contrary to the predictions of the relativistic beaming and radio source orientation models in which the core luminosity is expected to be Doppler-boosted relative to the extended luminosity which is generally assumed to be isotropic. Our analysis of the $P_C - R$ data indicates a strong luminosity selection effect (reminiscent of bright source samples due to Malmquist bias) in the sample. In particular, we showed that a strong $P_C - R$ correlation exists above some redshift cut-off which may correspond to the flux limit of the sample used.

Key words. BL Lacertae objects: general-quasars—galaxies: Seyfert—galaxies: jets

1. Introduction

The generic model for radio galaxies assumes that extragalactic radio sources are powered by two oppositely directed beams of relativistic outflows of energetic particles released from the central engine of the associated radio galaxy or quasar (e.g. Rees 1971; Blandford & Rees 1974; Scheuer 1974; Luo & Sadler 2010). The beams are assumed to describe a constant opening angle, such that the interaction of the head of the beams or jets with the intergalactic medium gives rise to the observed synchrotron radio lobe emission. The classification of extragalactic radio sources (EGRS) can be attributed to the power and nature of the central engine and also the jet/accretion disc orientation relative to the line of sight of the observer (e.g. Antonucci 1993; Urry & Padovani 1995). Following the above scenario, it can be inferred that several of the properties of the EGRS can be attributed to relativistic Doppler and geometric projection effects at small viewing angles to our line of sight.

It is commonly accepted that radio-loud quasars and high luminosity radio galaxies are intrinsically one and the same radio source but only appear different due to their aspect dependent properties (e.g. Barthel 1989). According to beaming models (Rees 1966; Blandford & Königle 1979; Savolainen *et al.* 2010), the cores of these radio sources are presumed to be dominated by beamed emissions with their radio fluxes accentuated by Doppler boosting while the extended emissions are unbeamed and isotropic (e.g. Orr & Browne 1982). These scenarios form the bedrock for the adoption of the core-dominance parameter (R) often defined as the ratio of the core power (P_{C}) to the extended power (P_{E}) as a suitable statistical measure of orientation.

For a radio source at redshift (z) and with a spectral flux density (S_ν) at observing frequency (ν), the core-dominance parameter is given (e.g. Fan & Zhang 2003) by

$$R = \frac{P_{\mathrm{C}}}{P_{\mathrm{E}}} = \frac{P^{C}_{5\,\mathrm{GHz}}}{P^{T}_{1.4\,\mathrm{GHz}} - P^{C}_{5\,\mathrm{GHz}}} \left(\frac{1.4}{5}\right)^{-\alpha_{\mathrm{E}}} (1+z)^{-\alpha_{\mathrm{E}}}\,, \tag{1}$$

where α_{E} is the spectral index for the extended component defined as $S_\nu \sim \nu^{-\alpha}$ (we have assumed that the core spectral index, $\alpha_{\mathrm{C}} = 0$). Equation (1) predicts (in the absence of any redshift effects) a direct $R - P_{\mathrm{C}}$ correlation once P_{E} is assumed isotropic. On the contrary, Fan & Zhang (2003) found no significant $R - P_{\mathrm{C}}$ correlation, especially for BL Lac and radio galaxy sub-samples in the large sample of Liu & Zhang (2002). Furthermore, they did not observe any correlation for $R - z$ relation. They rather, found an inverse $R - P_{\mathrm{E}}$ correlation in the radio galaxy sub-sample.

However, the effect of Malmquist bias, reminiscent of bright source samples was not taken into account in these analyses. We show in the present paper that the absence of any significant $R - P_{\mathrm{C}}$ correlation, in particular for the BL Lacs and radio galaxies, could be accounted for by the selection effects in the samples used.

2. Selection effects in complete samples of radio sources

The spectral luminosity P_ν of a source at redshift z is related to its spectral flux density S_ν at observing frequency ν according to the relation

$$P_\nu = S_\nu D_{\mathrm{L}}^2 (1+z)^{\alpha-1}\,, \tag{2}$$

where D_{L} is the luminosity distance, which depends on the two cosmological parameters: the Hubble's constant (H_0) and the density parameter (Ω).

Hence for a complete sample with a flux density cut-off at $S_\nu = S_c$, equation (2) can be written in the form (e.g. Ubachukwu *et al.* 1993):

$$P_\nu = 4\pi {D_{\mathrm{L}}}^2 S_\nu H(S_\nu - H_c)(1+z)^{\alpha-1}, \tag{3}$$

where $H(S_\nu - S_c)$ is the Heaviside step function defined by

$$H(S_\nu - S_c) = \begin{cases} 0, & \text{if } S_\nu < S_c, \\ 1, & \text{if } S_\nu > S_c. \end{cases} \tag{4}$$

The implication of equations (1) and (3) is that sources appear to bunch up close to the flux limit S_c, resulting in a strong correlation between P_ν and z. In fact, Ubachukwu & Ogwo (1998) have shown that the $P_\nu - z$ plot appears steeper for $z < z_c = 0.3$ than for $z > z_c$ corresponding to the flux density limit ($S_c \simeq 10$ Jy) for the 3CR source sample used in their analysis.

As an illustration (at least in principle), if we assume the simplest Friedmann cosmology with $\Omega = 0$, the luminosity distance $D_{\rm L}$ is given by (e.g. Ubachukwu & Onuora 1993)

$$D_{\rm L} = \frac{2H_0}{c}(1+z)^2 - 1, \tag{5}$$

so that the spectral luminosity can be written as a function of redshift and (assuming $\alpha = 0$) equation (3) becomes

$$P_\nu = P_0\left(x^3 - 2x + \frac{1}{x}\right), \tag{6}$$

where $P_0 = 4\pi S_\nu H(S_\nu - S_c)$ and $x = 1 + z$. The slope (β) of $\log P_\nu - \log x$ plot therefore gives

$$\beta = \frac{d\log P_\nu}{d\log x} = \frac{3x^4 - 2x^2 - 1}{x(x^2-1)^2}. \tag{7}$$

In the relativistic beaming and radio source orientation paradigm, the core-dominance parameter (R) is not only used as a measure of source orientation, but also as a beaming parameter (e.g. Orr & Browne 1982; Ubachukwu & Chukwude 2002). Usually, P_ν in equation (2) is taken to be the sum of $P_{\rm C}$ and $P_{\rm E}$. In the absence of any redshift effects, we expect a direct $R - P_{\rm C}$ correlation once we assume that the total luminosity is isotropic (see equation (1)). Fan & Zhang (2003) however found little or no $R - P_{\rm C}$ correlation, especially for the radio galaxies and BL Lacs.

The absence of any significant $R - P_{\rm C}$ correlation could have arisen if there is a strong selection effect in the samples used, as shown in equation (7), which predicts a strong change in the $P_\nu - z$ slope between high and low redshift sources. For example, at $z = 0.1$, $\beta \simeq 20$ while at $z = 3$, $\beta \simeq 1$. As we shall show later, this change in the $P_\nu - z$ slope holds the key in our understanding of the apparent lack of any significant $R - P_{\rm C}$ correlation found by Fan & Zhang (2003) for BL Lacs and radio galaxies.

3. Data analysis and results

The data we used for this paper were drawn from Fan & Zhang (2003) originally compiled by Liu & Zhang (2002). These include 27 BL Lac objects and 300 radio galaxies with total luminosity at 1.4 GHz and core luminosity at 5 GHz. Complete information on redshift (z), core-dominance parameter (R) and core luminosity ($P_{\rm C}$) are available for the whole sample. The adopted cosmological parameters are $H_0 = 100\ \text{kms}^{-1}\text{Mpc}^{-1}$ and $\Omega_0 = 1.0$.

For an isotropic distribution of radio sources in the sky, it is expected that $P_{\rm E}$ should be unbeamed and isotropic while $P_{\rm C}$ is beamed and oriented. Theoretically, sources with the most luminous cores should be those with the strongest beaming. In this scenario, we expect $P_{\rm C} - R$ correlation statistically as predicted by equation (1).

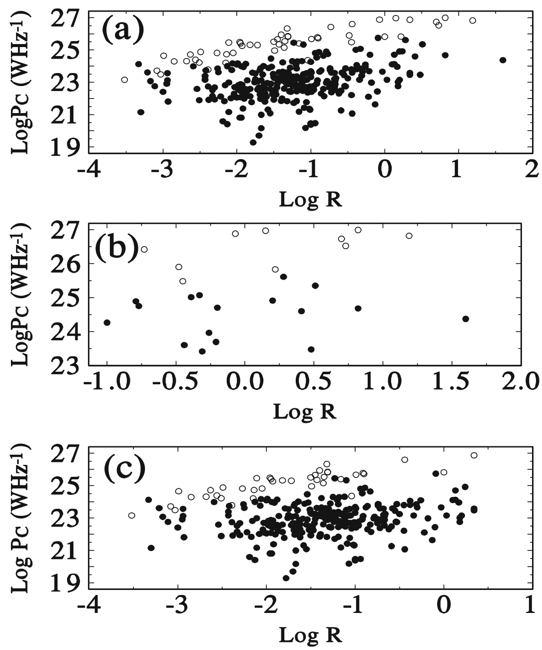

Figure 1. Scatter plot of core radio power (P_C) against core-dominance parameter (R) on logarithm scales for: (**a**) the whole sample of extragalactic radio sources, (**b**) BL Lacertae objects and (**c**) radio galaxies. Key: $\circ = z > 0.3$ sources; $\bullet = z \leq 0.3$ sources.

This, however, was not observed for the present sample (especially for BL Lacs) by Fan & Zhang (2003).

Following Fan & Zhang (2003) we show in Fig. 1 the plots of $\log P_C$ against $\log R$ for the whole sample and for each of the BL Lac and radio galaxy sub-samples for $\alpha_E = 0.5$. In general, the plots show no apparent trend. Simple linear regression analyses of the data give $\log P_C = (23.93 \pm 0.47) + (0.13 \pm 0.09) \log R$; $\log P_C = (23.39 \pm 0.17) + (0.15 \pm 0.10) \log R$ and $\log P_C = (25.19 \pm 0.48) + (0.22 \pm 0.34) \log R$, respectively for the whole sample, radio galaxy and BL Lac sub-samples with corresponding correlation coefficients of 0.3, 0.1 and 0.3.

Figure 2 shows the $P_C - z$ plots for both the whole sample and the sub-samples. Linear regression analyses of the data give $\log P_C = (22.80 \pm 0.07) + (7.02 \pm 0.49) \log(1+z)$, $\log P_C = (24.01 \pm 0.15) + (11.44 \pm 1.06) \log(1+z)$ and $\log P_C = (22.69 \pm 0.06) + (6.45 \pm 0.45) \log(1+z)$, respectively, for the whole sample, BL Lac and radio galaxy sub-samples with correlation coefficients, $r = 0.6$, 0.9 and 0.6 respectively. The strong selection effects in which the slope is dominated by the data in the low $P_C - z$ plane is quite obvious in the plots, which confirms our illustration in the preceding section. To demonstrate this, we truncated the $P_\nu - z$ data at $z = 0.3$, which is shown by dotted line in Fig. 2. For the whole sample in Fig. 2a, the results of the regression analyses are $\log P_C = (22.11 \pm 0.08) + (26.03 \pm 1.98) \log(1+z)$, with $r \sim 0.6$ for $z \leq 0.3$ and $\log P_C = (25.25 \pm 0.31) + (0.30 \pm 0.88) \log(1+z)$, with $r \sim 0.1$ for $z > 0.3$. These analyses suggest about two orders of magnitude

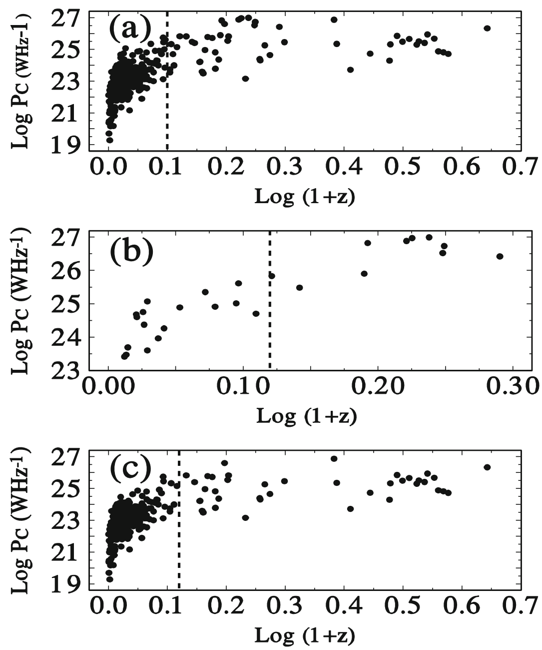

Figure 2. The plots of core radio power (P_C) against redshift $(1 + z)$ for all z on log scales for: (**a**) the whole sample of extragalactic radio source, (**b**) BL Lacertae objects and (**c**) radio galaxies, with dotted line at $z > 0.3$.

difference in the $P_C - z$ slope between the low and high z-data (c.f. Fig. 2) and apparent lack of any $P_\nu - z$ correlation for sources with $z > 0.3$.

To show the effect of the change in the $\log P_C - \log(1+z)$ slope on the $P_C - R$ data, we carried out linear regression analyses of the plots for sources with $z > 0.3$, shown with open circles in Fig. 1. These analyses give the following results: $\log P_C = (26.30 \pm 0.70) + (0.13 \pm 0.07) \log R$; $\log P_C = (26.34 \pm 0.22) + (0.73 \pm 0.11) \log R$; and $\log P_C = (26.36 \pm 0.16) + (0.47 \pm 0.24) \log R$ for the whole sample, radio galaxy and BL Lac sub-samples respectively with corresponding correlation coefficients of 0.8, 0.7 and 0.6. Similar analyses for $z \leq 0.3$ show no significant $P_C - R$ correlation ($r \sim 0.1$). These results therefore show that the observed strong $P_C - z$ correlation is dominated by the low redshift data which swamped and destroyed the expected $P_C - R$ correlation for these low redshift sources.

4. Discussions and conclusion

We have investigated the cause of the apparent absence of core luminosity−core-dominance parameter ($P_C - R$) correlation in BL lacs and radio galaxies previously observed by Fan & Zhang (2003) for a sample of 327 extragalactic radio sources. According to relativistic beaming hypothesis, BL Lacs are believed to have core-dominated radio morphologies (e.g. Antonucci & Ulvestad 1985; Perlman & Stocke 1993; Landt & Bignall 2008; Capetti *et al.* 2010). Consequently, a $P_C - R$ correlation should be envisaged contrary to the results obtained by Fan & Zhang (2003) which show no clear correlation especially for the BL Lac sub-sample. Earlier works by Qin *et al.* (1998) on the other hand argued that when R becomes larger, the correlation between $\log P_C$ and $\log R$ becomes less obvious. In other words, the nuclear region of such sources is dominated by beamed emissions.

It is evident from the R-distribution in Fig. 1 that the vast majority of the present data are lobe dominated and are thus not selected on the basis of P_C. There is also a wide range of lobe luminosity in the population that may tend to swamp any $P_C - R$ correlation, but because the range of P_C is much wider, due to beaming (if one considers the range of Doppler boosting in an isotropic jet distribution with Lorentz factors from a few to $\sim$50), we should expect some $P_C - R$ correlation. Also, equation (1) shows that it is not possible to eliminate the redshift effect because of the $(1 + z)$ k-correction term. The only way to get rid of the latter would be to have a survey in which the flux limit varied with z in such a manner so as to compensate for the redshifting of the rest frame lobe emission.

Our analyses show that the observed absence of any significant $P_C - R$ correlation for BL Lacs and radio galaxies could be attributed to the strong luminosity selection effects in the radio source sample used. Figure 2 shows a strong $P_C - (1 + z)$ correlation, especially at low redshifts, as predicted by equation (7). Ubachukwu & Ogwo (1998) have shown that there appears to be a turnover in the slope of the luminosity−redshift data around $z \simeq 0.3$ which is expected in flux density−limited samples where such samples include, preferentially the luminous sources at high redshifts, with most sources bunching up at low redshifts. In fact, we have shown in equation (7) that there would be a strong change of slope from $\beta \sim 20$ (at $z = 0.1$) to $\beta \sim 1$ (at $z = 3$). The results of our analyses actually show that the $\log P_C - \log(1+z)$ slope changes from 26.03 (with a fairly strong correlation $r \sim 0.6$) for $z \leq 0.3$ to $\sim$0.30 with no apparent correlation ($r \sim 0.1$) for $z > 0.3$. Consequently, we showed that a fairly significant $P_C - R$ correlation exists in the sample for $z > 0.3$ ($r \geq 0.6$) especially for radio galaxies, with little or no correlation ($r \sim 0.1$) for $z \leq 0.3$. The observed luminosity selection effects therefore appear to give insight into the apparent lack of correlation in the observed $P_C - R$ data for samples dominated by sources at low redshifts. Apparently, data in this redshift range may have diluted the correlation results of Fan & Zhang (2003). Actually Fan & Zhang (2003) found a strong $P_C - R$ correlation for quasars for which almost all sources have $z > 0.3$.

In other words, in flux density limited sample, the $z \leq 0.3$ sources will show a much stronger dependence on average luminosity as a function of redshift as compared to the high redshift sources. Below $z = 0.3$, therefore, the luminosity–redshift correlation is expected to easily swamp the predicted $P_C - R$ correlation, which is based on relativistic beaming. Beyond $z = 0.3$, the luminosities are primarily affected by the k-correction, which has a much milder dependence on z. The apparent lack of any discernible $P_C - R$ correlation for $z > 0.3$ in the BL Lac sub-sample (Fig. 2) could be attributed to the absence of lobe-dominated BL Lacs above $z = 0.3$ in the sample. Actually, it could be shown that radio galaxies show no $P_C - R$ trend over the region of $\log R$ covered by the BL Lacs ($-0.8 < \log R < 1.2$).

In conclusion, we have studied the correlation between the core-dominance parameter (R) and core radio power (P_C) for BL Lacs and radio galaxies in the Liu & Zhang (2002) source sample. We showed that the absence of significant $P_C - R$ correlation previously observed by Fan & Zhang (2003), could be attributed to the strong selection effects present in the sample used. The strong $P_C - R$ correlation obtained after accounting for the strong selection effects in the sample can be interpreted to mean that P_C is not isotropic, but beamed and oriented. A larger sample, especially of BL Lacs, with $z > 0.3$ would be required to put these conclusions on a firmer ground.

Acknowledgement

The authors are grateful to the anonymous referee for invaluable comments and suggestions which helped in improving this paper.

References

Antonucci, R. 1993, *Ann. Rev. Astron. Astrophys.*, **31**, 473.
Antonucci, R. R. J., Ulvestad, J. S. 1985, *ApJ*, **294**, 158.
Barthel, P. D. 1989, *ApJ*, **336**, 606.
Blandford, R. D., Königle, A. 1979, *ApJ*, **232**, 34.
Blandford, R. D., Rees, M. J. 1974, *MNRAS*, **169**, 395.
Capetti, A., Raiteri, C. M., Buttiglione, S. 2010, *A&A*, **516**, 59.
Fan, J. H., Zhang, J. S. 2003, *A&A*, **407**, 899.
Landt, H., Bignall, H. E. 2008, *MNRAS*, **391**, 967.
Liu, F. K., Zhang, Y. H. 2002, *A&A*, **381**, 757.
Luo, Q., Sadler, E. M. 2010, *ApJ*, **713**, 398.
Orr, M. J. L., Browne, I. W. A. 1982, *MNRAS*, **200**, 1067.
Perlman, E. S., Stocke, J. T. 1993, *ApJ*, **406**, 430.
Qin, Y. P., Xie, G. Z., Bai, J. M., Fan, J. H., Zheng, Y. T., Wu, S. M. 1998, *A&A*, **333**, 790.
Rees, M. J. 1966, *Nature*, **211**, 468.
Rees, M. J. 1971, *Nature*, **229**, 312.
Savolainen, T., Homan, D. C., Hovatta, T., Kadler, M., Kovalev, Y. Y., Lister, M. L., Ros, E., Zensus, J. A. 2010, *A&A*, **512**, 24.
Scheuer, P. A. G. 1974, *MNRAS*, **166**, 513.
Ubachukwu, A. A., Ogwo, J. N. 1998, *Aust. J. Phys.*, **51**, 143.
Ubachukwu, A. A., Chukwude, A. E. 2002, *J. Astrophys. Astr.*, **23**, 235.
Ubachukwu, A. A., Okoye, S. E., Onuora, L. I. 1993, *Proceedings of the Nigerian Academy of Sciences*, **5**, 62.
Ubachukwu, A. A., Onuora, L. I. 1993, *Ap&SS*, **209**, 169.
Urry, C. M., Padovani, P. 1995, *PASP*, **107**, 803.