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On the Relativistic Beaming and Orientation Effects in Core-Dominated Quasars

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Abstract. In this paper, we investigate the relativistic beaming effects in a well-defined sample of core-dominated quasars using the correlation between the relative prominence of the core with respect to the extended emission (defined as the ratio of core- to lobe- flux density measured in the rest frame of the source) and the projected linear size as an indicator of relativistic beaming and source orientation. Based on the orientation-dependent relativistic beaming and unification paradigm for high luminosity sources in which the Fanaroff-Riley class-II radio galaxies form the unbeamed parent population of both the lobe- and core-dominated quasars which are expected to lie at successively smaller angles to the line of sight, we find that the flows in the cores of these core-dominated quasars are highly relativistic, with optimum bulk Lorentz factor, $\gamma_{opt} \sim 6$–16, and also highly anisotropic, with an average viewing angle, $\sim 9^\circ$–16°. Furthermore, the largest boosting occurs within a critical cone angle of $\approx 4^\circ$–10°.

Key words. Galaxies: active, jets, quasars: general.

1. Introduction

The phenomenology of active galactic nuclei (AGNs) involves a supermassive black hole which releases relativistic outflows of energetic particles by accretion of matter through an accretion disk surrounded by an optically thick torus. These relativistic outflows form well-collimated symmetric twin jets or beams that feed the radio lobes (Rees 1971; Blandford & Rees 1974; Scheuer 1974; Blandford & Königl 1979). The interaction of the head of the beams/jets with the intergalactic medium produces the observed synchrotron lobe emission (Scheuer 1977). The classification of AGNs depends on the power and geometry of the central engine as well as the jet/disk orientation with respect to our line of sight. (e.g., Antonucci 1993; Gopal-Krishna 1995; Falcke *et al.* 1995a,b; Urry & Padovani 1995). Thus, many properties of quasars and AGNs can be attributed to relativistic Doppler and geometric projection effects at small angles to our line of sight.

In low frequency surveys, the emission from high luminosity extragalactic radio sources is usually dominated by the lobe which has steep spectra (spectral index, $\alpha \geq 0.5$, $S_\nu \sim \nu^{-\alpha}$). These sources include the lobe-dominated quasars (LDQs) and Fanaroff & Riley (1974) class-II (FRII) galaxies. The lobe emission is usually assumed to be isotropic so that radio source samples selected on the basis of their lobe emission should be orientation-unbiased. This means that, for the lobe-dominated sources, the ratio of the core flux density to that of the lobe (R) should usually not exceed unity (i.e., $R \leq 1$).

In contrast, high frequency source samples appear to be dominated by their core emissions so that radio sources selected from high frequency surveys tend to contain mostly core-dominated sources characterized by flat spectra ($\alpha < 0.5$) due to synchrotron self-absorption. These high luminosity radio sources are largely quasars and are called core-dominated quasars (CDQs). For these sources, the core emission depends on the viewing angle and can be Doppler boosted if the source axis is oriented close to the line of sight (i.e., $R > 1$). In addition, the projected linear sizes (D) of the CDQs are expected to be foreshortened due to geometrical projection effects at small viewing angles. The notable exception to the core-dominated objects observable at high frequencies are the compact steep spectrum sources which are of galactic dimensions and whose radio properties appear to be less dependent on orientation (Fanti *et al.* 1990).

Several statistical tests have been carried out which confirmed that R is indeed a good statistical measure of relativistic beaming in the cores of high luminosity sources (e.g., Orr & Browne 1982; Kapahi & Saikia 1982; Hough & Readhead 1989; Saikia & Kulkarni 1994; Saikia *et al.* 1995). In previous papers (Ubachukwu 1998; 2002, hereafter paper I), we studied the statistical consequences of relativistic beaming and geometric projection effects in high luminosity lobe-dominated sources using their observed $R - D$ data. In this follow-up paper, we wish to extend the $R - D$ analysis to their core-dominated counterparts.

2. Doppler boosting and geometrical projection effects in core-dominated sources

The simplest relativistic beaming and radio source unification model predicts that both the projected linear size, D, and the core dominance parameter, R, should depend on the viewing angle according to the following equations;

$$D = D_0 \sin\phi, \tag{1}$$

and

$$R = f\gamma^{-n}[(1 - \beta\cos\phi)^{(-n+\alpha)} + (1 + \beta\cos\phi)^{(-n+\alpha)}], \tag{2}$$

where D_0 is the intrinsic size of the source, f is the ratio of the intrinsic core luminosity to the unbeamed extended luminosity, β is the velocity of the radiating material in units of the velocity of light, α is the spectral index and $\gamma = (1 - \beta^2)^{-1/2}$ is the bulk Lorentz factor. The exponent n depends on whether the radiating material consists of a continuous jet ($n = 2$) or blobs ($n = 3$); in general $2 \leq n \leq 3$ if the emission is isotropic in the rest frame of the source. For the purposes of the present study which involves the core-dominated sources, we shall assume $\alpha = 0$ throughout. At small angles to the line of sight, relativistic beaming in active galactic nuclei (the ratio of the observed core luminosity to it's emitted value) is fundamentally characterized by the Doppler factor given by,

$$\delta = [\gamma(1 - \beta\cos\phi)]^{-1}. \tag{3}$$

Generally, the relativistic beaming hypothesis is based on two parameters, the bulk Lorentz factor/jet velocity (γ/β) and the viewing angle, ϕ. Equation (2) therefore suggests that the distribution of R should provide us with an indication of the range of values of viewing angle as well as the Lorentz factor which can be used to test specific beaming models once f is known. Consequently, the median angle to the line of sight can be calculated from the median value (R_m) of the R-distribution (from equation (2)) through

$$\cos\phi_m \approx 1 - \left(\frac{2^{n-1}R_m}{R_T}\right)^{-1/2} \tag{4}$$

(for $\gamma >> 1$), where $R_T = \frac{2f}{\gamma^n}$ is the value of R at $\phi = 90^\circ$ (i.e., the value of R for a source whose jet axis lies along the plane of the sky). The last equation is actually to a first approximation and is applicable to beamed sources whose radio axes are expected to lie close to the line of sight.

In addition, equation (3) has the implication that, for angles between $\phi = 0^\circ$ and some critical angle, $\phi_{\rm crit}$, the relativistic boosting is optimized and this can be obtained by setting $\frac{d\delta}{d\beta} = 0$. This yields (e.g., Vermeulen & Cohen 1994; Ubachukwu 1999)

$$\phi_{\rm crit} \approx \sin^{-1}\left(\frac{1}{\gamma_{\rm opt}}\right), \tag{5}$$

where $\gamma_{\rm opt}$ is the Lorentz factor which can be derived from equation (2) as

$$\gamma_{\rm opt} \approx \left[\frac{1}{2^{n-1}}\left(\frac{R_{\rm max}}{R_T}\right)\right]^{1/2n}. \tag{6}$$

Here, $R_{\rm max} = R(\phi = 0^\circ) \approx f(2\gamma)^n$.

Furthermore, comparing equation (1) with equation (2) shows that R should be anti-correlated with D. A graph of R against D for a well-defined source sample is expected to yield,

$$R = R_{\rm max} - mD. \tag{7}$$

The last two equations suggest that we can deduce the value of the beaming parameter, γ, from the regression analyses of R on D for any assumed model once R_T is known for a given source sample. This of course presupposes that the observed $R - D$ correlation is entirely due to relativistic beaming. However, linear sizes of extragalactic radio sources have been known to undergo cosmological evolution (e.g., Barthel & Miley 1988; Kapahi 1989; Neeser *et al.* 1995), but whether the observed evolution is real or an artifact of the luminosity selection effects often present in most bright source samples is still unclear (see Singal 1993; Nilsson *et al.* 1993; Ubachukwu & Ogwo 1998). Nevertheless, this effect if present, should be accounted for before D could be used to test the relativistic beaming and radio source orientation scenarios. Following paper I, we test these expectations for a sample of core-dominated sources in the following section.

3. Analysis and results

The present analysis is based on a well-defined sample of powerful core-dominated sources compiled by Murphy *et al.* (1993). All of the sources have 5GHz core flux densities, $S > 1$ Jy. This sample consists of both BL Lacs and quasars which are variable sources. The quasar subsample, which is of interest for the present work, comprises 54 sources with complete R and D information.

The median value data for the R-distribution for the subsample is $R_m = 12.6$. Orr & Browne (1982) have shown that the R-distribution for radio loud quasars is consistent with $R_T = 0.024$, i.e., if the LDQs form the parent population of the CDQs. This would imply (from equation(4)), $\phi_m \approx 14^\circ$ for $n = 2$ or $\phi_m \approx 23^\circ$ for $n = 3$. However, as noted by Padovani & Urry (1992), and Urry & Padovani (1995), there appear to be too few LDQs to form the parent population of the CDQs. In fact, Barthel (1989, 1994) has used the relative number densities and size distributions of radio galaxies and quasars in the $3CR$ sample of Laing *et al.* (1983) to argue that high luminosity radio galaxies and quasars are the same objects seen from different orientation angles. We shall therefore adopt $R_T = 0.003$ which appears to be consistent with the FRII-LDQ-CDQ unification scheme for high frequency surveys (see Padovani & Urry 1992; Simpson 1996; Morganti *et al.* 1997; paper I). Using $R_T = 0.003$ together with $R_m = 12.6$ in equation (4) gives $\phi_m \approx 9^\circ$ for $n = 2$ or $\approx 16^\circ$ for $n = 3$.

To check for possible evolutionary effects, we show the R - z and D - z plots in Fig. 1 and Fig. 2 respectively (where z is the redshift and D is in Kpc). The two plots show no discernible trend. Linear regression analyses give correlation coefficient, $r \sim -0.2$, for each case implying a lack of any significant redshift dependence. Removal of the outlier, 1803 + 784, weakens the correlation further (though not significantly) so we can hence conclude that evolution, if present, is negligible and proceed to use the R - D correlation to test the beaming hypotheses.

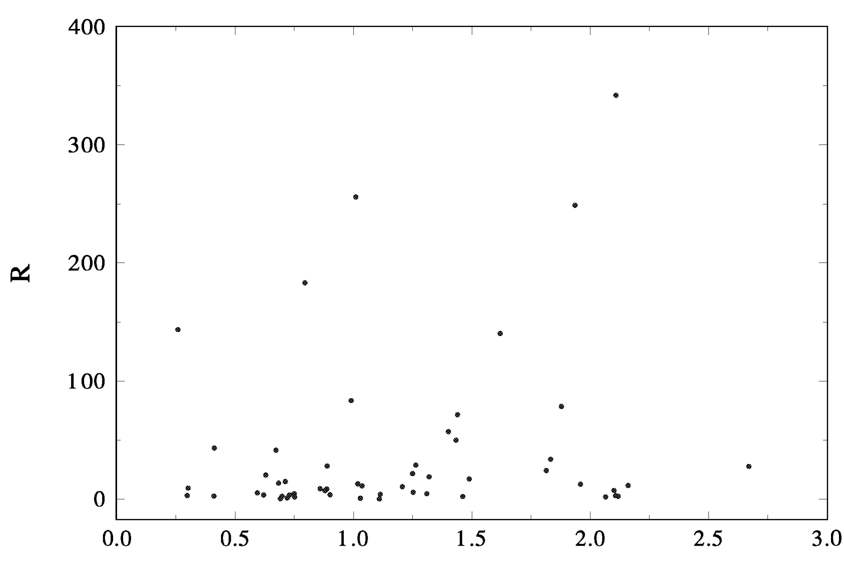

Figure 1. The graph of core dominance parameter against redshift.

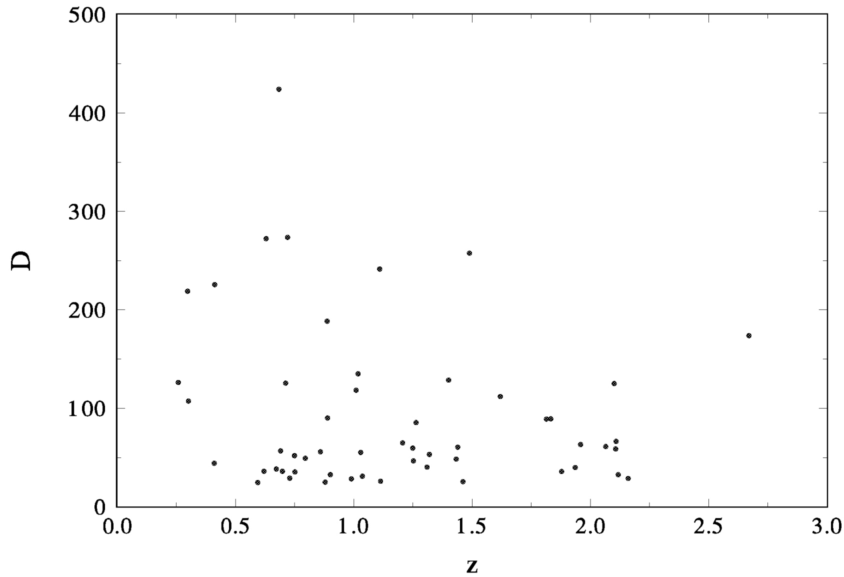

Figure 2. Projected linear size against redshift.

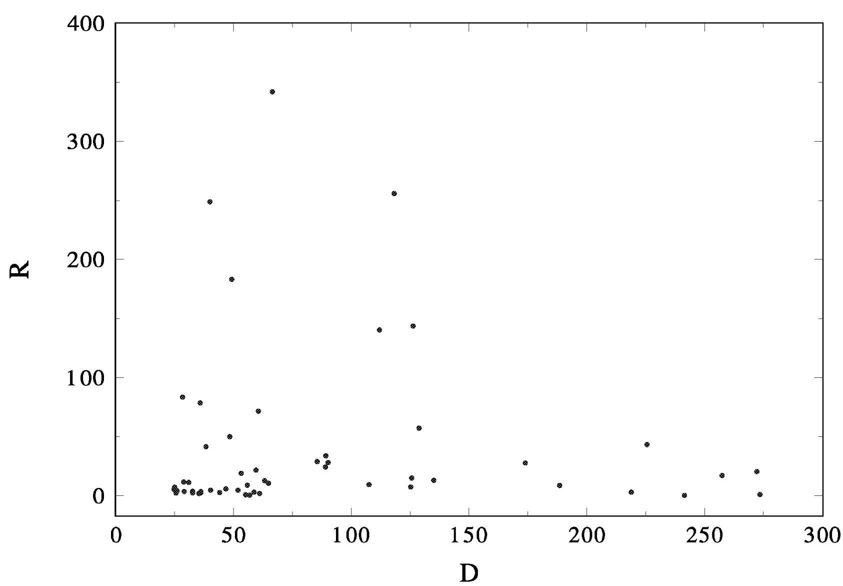

Figure 3. The plot of core dominance parameter against projected linear size.

Figure 3 shows the R - D plot for the present sample (without the outlier). Although the plot shows no obvious general trend, the upper envelope R - D function (which shows the locus of the maximum core dominance parameter as a function of the projected linear size) is well-defined. This function is usually attributed to relativistic beaming and geometric projection effects at small angles with respect to the line of sight (see Ubachukwu 1998; paper I). Linear regression analysis of the upper envelope R-data against D in four ranges of D: $D < 50\,\mathrm{kpc}$; $50 \le D \le 100\,\mathrm{kpc}$; $100 < D \le$

150 kpc and $D > 150$ kpc, gives $R_{\max} = 375.64$ with $r \sim -0.9$. Using $R_{\max} = 375.64$ and $R_T = 0.003$ in equation (6) gives the bulk Lorentz factor (for optimum boosting), $\gamma_{\text{opt}} \approx 16$ and ~ 6 for $n = 2$ and 3 respectively. The corresponding critical beaming angle from equation (5) becomes, $\phi_{\text{crit}} \approx 4^\circ$ (for $n = 2$) or $\approx 10^\circ$ (for $n = 3$).

4. Discussion

Two main results can be derived from the analyses presented in the preceding section. These two results were based on the simple assumption that the relativistic beam emanating from AGNs is narrow and can be described with a single Lorentz factor, γ, once a flow model, which can either be in the form of a continuous jet ($n = 2$) or in form of individual blobs of plasma ($n = 3$), is adopted. Each of these models leads to different values of γ and viewing angle, ϕ. A more general situation may therefore be obtained in-between these two flow models ($2 \le n \le 3$) and this will form the basis for our discussion. It could be noted however, that smaller values of n imply higher γ-values but lower values of the viewing angle, ϕ. Furthermore, it was assumed that the Fanaroff-Riley class-II radio galaxies form the unbeamed parent population of both the LDQs and CDQs, with the latter being the most beamed counterpart (cf. Barthel 1989). However, analysis based on the Orr & Browne (1982) model in which the LDQs form the parent population of CDQs leads to a lower value of the Lorentz factor but a higher value of the orientation angle.

The first main result comes from the distribution of the core dominance parameter, R which shows that, on the average, CDQs are inclined at $\phi \approx 9^\circ$–16°, with respect to the line of sight. The second result is the presence of a strong anti-correlation between R and the apparent linear size, D for the upper envelope $R - D$ data. This correlation was shown to be consistent with an optimum Lorentz factor, $\gamma_{\text{opt}} \approx 6$–16, with corresponding critical beaming angle (i.e., the largest angle for optimum boosting), $\phi_{\text{crit}} \approx 4^\circ$–$10^\circ$. These results are all consistent with the orientation-dependent relativistic beaming and radio source unification paradigm in which the flows from the cores of CDQs are expected to be highly relativistic (even at large scales) and in which Doppler effects generate anisotropic radiation patterns at close angles to our line of sight. The results are also in quantitative agreement with previous works, as discussed below. But before that, a comparison of the results obtained in paper I with those found in the present analysis shows a much higher value of $R_{\max}$ (376) is inferred from the present CDR sample than that obtained from the LDQ sample of Paper I ($R_{\max} = 2.5$). Since $R_{\max} \approx 2R_T\gamma^4$, it follows that for a single value of R_T, a distribution of γ may be required with larger values being ascribed to the CDQs if they are to broadly fit into the FRII $-$ LDQ unification scheme. A simple consequence of this is that apparent jet velocities are higher for CDQs than for LDQs/FRIIs, due to their selection criteria: LDQ/FRII sample was randomly selected while the CDQ sample was selected based on the core emission (see Murphy 1990; Ubachukwu 1999). In fact, Ubachukwu (1999) has observed that the Lorentz factor and proper motion appear to be a factor of ~ 2 larger for core-selected quasars than for lobe-selected quasars.

Based on the assumption that the LDQs form the unbeamed parent population of radio loud quasars, Orr & Browne (1982) showed that the radio luminosity function of CDQs is consistent with a core Lorentz factor, $\gamma = 5$ (see also Kapahi & Saikia 1982; Hough & Readhead 1989). Similar result ($\gamma = 4$) was also obtained by Ubachukwu

(1999) based on the core dominance – proper motion data for LDQs as the parent population of CDQs (see Vermeulen 1995). However, as mentioned in the preceding section, there appears to be too few LDQs to form the parent population of the CDQs; the relativistic beaming and radio source unification hypotheses imply that the parent population must be larger. It is therefore more appropriate to derive the beaming and orientation parameters of CDQs based on the FRII radio galaxies as the parent population and not LDQs.

Padovani & Urry (1992), and Urry & Padovani (1995) have argued that if the high luminosity radio galaxies form the parent population of both the LDQs and CDQs then, it is not possible to fit the luminosity function with a single Lorentz factor but a distribution with a weighted mean, $\gamma_m \sim 11$. They showed that the CDQs should have their radio axes within $\sim 14^\circ$ (with an average $\sim 9^\circ$) of the line of sight. They also noted that high values of the Lorentz factor and lower values of n are necessary to provide better fit to the observed luminosity function. On the other hand, Ghisellini *et al.* (1993) used the synchrotron self-Compton model to estimate the value of γ from the observed and predicted X-ray flux densities and found $\gamma \approx 10$ and a viewing angle of $\sim 8^\circ$ for CDQs. Using the correlation between the accretion disk (UV) luminosity and the radio core emission of a sample of radio-loud quasars, Falcke (1995a) obtained a distribution of $3 \leq \gamma \leq 10$. These results are in close agreement with those obtained here.

5. Conclusion

We have investigated a simple statistical consequence of the relativistic beaming model in which, due to Doppler boosting and geometric projection effects at small viewing angles in core-dominated sources, the core dominance parameter, R, is expected to correlate inversely with the projected linear size, D, if the former is to be used as an orientation indicator. Our result shows a strong anti-correlation in the $R - D$ upper envelope data which offers both qualitative and quantitative support to the hypotheses that jets in core-dominated quasars are highly relativistic. This is consistent with the orientation-dependent relativistic beaming and unification paradigm for high luminosity radio sources in which the FRII radio galaxies form the parent population of the lobe- and core-dominated quasars, with the latter being the most beamed counterpart.

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