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RELATIVISTIC BEAMING AND RADIO SOURCE ORIENTATION EFFECTS IN COMPACT STEEP-SPECTRUM RADIO SOURCES AND QUASAR-GALAXY UNIFICATION

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Abstract
Analytical and statistical methods with some plausible assumptions have been used in this work to investigate relativistic beaming and orientation effects in compact steep spectrum sources (CSSs); and its implications to quasar/galaxy unification paradigm. Results suggestively indicate that jet axes of CSS quasars lie closer to our line of sight than those of CSS galaxies which lie farther away. In addition, the flows from the cores of CSS quasars are highly relativistic with optimum Lorentz factor, $\gamma_{opt} \approx 2.1 - 3.3$; while CSS galaxies are not beamed. These results are consistent with the orientation-dependent relativistic beaming and radio source unification paradigm, in which the flows from the cores of quasars are expected to be highly relativistic; and in which Doppler effects generate anisotropic radiation patterns at close angles to our line of sight. Furthermore, since our estimated results are comparable with those obtained for the more extended core-dominated radio sources in the literature; therefore,CSSs suggestively are scaled-down versions of the conventional extragalactic radio sources.
Key words: *Beaming, unification, galaxies, quasars.*

Introduction

Compact steep spectrum sources (CSSs) are full-fledged extragalactic radio sources (EGRSs), generally referred to as radio-loud active galactic nuclei; and these radio-loud objects constitute a class of galaxies known as Active Galactic Nuclei (Akujor, 1995; Fanti *et al*., 1995; Fanti, *et al.*, 2001; Jackson, 1999; Machalski *et al.*, 2009; Bongiorno, 2012). The major properties that distinguish them from the conventional extragalactic radio sources are as follows: they are just normal EGRSs, but miniaturized, (linear sizes, $D \leq 20kpc$); they consist of both radio galaxies and radio-loud quasars but on sub-galactic dimensions; they show steep spectra (spectral index, $\alpha \geq 0.5$; $S_\nu \sim \nu_P^{-\alpha}$, where S_ν is flux density) at high frequencies (e.g., ≥ 0.02 GHz) from the entire radio morphological structures; they are found at high frequencies; they have high radio luminosities ($P_{5GHz} \geq 10^{26}$ W) and overall luminosities,$P_{bol} \geq 10^{37}$ W (Cavalho, 1998; O'Dea, 1998). Some of their radio properties are discussed by Orienti (2016).

The nature of CSS sources has been discussed for many years. Immediately after their discovery, it was suggested that they might be very young radio sources; that is, the progenitors of the extended doubles (Fanti *et al*., 1995; Readhead *et al*., 1996). However, it has been proposed that CSS sources are, instead, old 'frustrated' sources which have been kept small by a dense confining medium (O'Dea, 1998). Variations on this scheme suggest that CSS sources might be 'smothered' sources in which a large deposition of gas had recently confined an existing radio-loud AGN to a small volume; though this does not have any footing for want of data (O'Dea, 1998).

Relativistic beaming is a usual phenomenon generally observed in extragalactic radio sources; and is believed to be caused by the smallness of the angles of observation of such sources (Orr and Browne, 1982). This makes the orientation of the source to the observer's line of sight imperative in the general unification of quasars and galaxies. However, Ubachukwu and Chukwude (2002) carried out similar work but with the more extended core-dominated radio sources (with $D > 30$ kpc) and found that jets from the cores of these core-dominated sources are highly relativistic. Therefore, since CSS sources have been shown to contain special characteristics that make them considered as a separate class of objects in addition to the more extended extragalactic radio sources, we deem it necessary to investigate, in the present paper, relativistic beaming and orientation effects in these sources; and which hopefully will yield level of comparability of quasars and galaxies in the orientation-based radio source unification paradigm.

Data and Analyses

The analyses in this work are based on 32 CSS sources (i.e., 16 CSS quasars and 16 CSS galaxies) with core dominance parameter, R, obtained from Nilson (1998). Regression analyses are carried out separately on these classes of CSS sources.

Relativistic Beaming and Orientation Effects

The relativistic beaming and orientation effects predict that both the projected linear size, D, and the core dominance parameter, R should depend on the viewing angle according to the following relations (Orr and Browne, 1982; Ubachukwu & Chukwude, 2002):

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

and

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

whereD_0 is the intrinsic linear size of the radio source, ϕ is angle of observation, 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 (defined by $S_\nu \sim \nu^{-\alpha}$) 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 (in which case $n = 2$) or blobs (in this case $n = 3$) (Orr and Browne, 1982; Ubachukwu and Chukwude, 2002).

Generally, in relativistic beaming the ratio of the observed frequency,ν, to the frequency, ν', emitted in the rest frame of the source when the angle of observation, ϕ, is not zero is given by:

$$\frac{\nu}{\nu'} = \frac{\sqrt{1-\beta^2}}{1-\beta\cos\phi} \tag{3}$$

Hence, at small angles of observation, relativistic beaming in radio sources can basically be expressed by this ratio called Doppler factor, δ, as:

$$\delta = \frac{1}{\gamma(1-\beta\cos\phi)}, \tag{4}$$

Equations (2) and (4) suggest that relativistic beaming is based on two parameters, namely, the bulk Lorentz factor/jet velocity(γ/β) and the viewing angle, ϕ (Ubachukwu & Chukwude, 2002). Therefore, the two equations can be used to find the range of values of viewing angles of CSS sources, as well as, the range of values of critical angles for optimum boosting.

For simplicity, assuming a good relativistic speed (i.e., $v \approx c$), in which case$\gamma \gg 1$implying $\beta \approx 1$, equation (2) becomes:

$$1-\cos\phi \approx \left[\frac{\gamma R}{f} - (1+\cos\phi)^{\alpha-n}\right]^{\frac{1}{\alpha-n}} \tag{5}$$

Since$\gamma \gg 1$, the term at right hand side approximates as follows:

$$\left[\frac{\gamma R}{f} - (1+\cos\phi)^{\alpha-n}\right]^{\frac{1}{\alpha-n}} \approx \left[\frac{\gamma R}{f}\right]^{\frac{1}{\alpha-n}} \tag{6}$$

Therefore, equation (5) becomes:

$$1 - \cos\phi \approx \left[\frac{\gamma R}{f}\right]^{\frac{1}{\alpha - n}}, \tag{7}$$

which implies that:

$$R \approx \frac{f}{\gamma}(1 - \cos\phi)^{\alpha - n} \tag{8}$$

For $\phi = 90°$, we have

$$R_{min} \approx \frac{f}{\gamma}, \tag{9}$$

where R_{min} is the value of R when $\phi = 90°$. Therefore from equations (8) and (9), we obtain for mean value of angle of observation, ϕ_{mean}, that

$$\phi_{\text{mean}} \approx \cos^{-1}\left[1 - \left(\frac{R_{mean}}{R_{min}}\right)^{\frac{1}{\alpha_{mean} - n}}\right], \tag{10}$$

where R_{mean} is average value of core dominance parameter, and α_{mean} is average value of spectral indices in the sample.

Furthermore, equation (4) suggests that for angles between $\phi = 0°$ and ϕ_{crit} (critical angle), the relativistic boosting is optimized. It can be shown that ϕ_{crit} is given by (Longair, 1981; Ubachukwu and Chukwude, 2002)

$$\phi_{\text{crit}} \approx \sin^{-1}\left(\frac{1}{\gamma_{\text{opt}}}\right), \tag{11}$$

where γ_{opt} is the Lorentz factor for optimum boosting. At optimum boosting, equation (2) becomes:

$$R_{\max} = \frac{f}{\gamma_{\text{opt}}}\left[(1 - \beta\cos\phi_{\text{crit}})^{-n+\alpha} + (1 + \beta\cos\phi_{\text{crit}})^{-n+\alpha}\right] \tag{12}$$

Here, $R_{\max} = R(\text{when } \phi = 0°)$. Combining equation (9) and the last equation yields

$$R_{\max} = \frac{\gamma R_{\min}}{\gamma_{\text{opt}}}\left[(1 - \beta\cos\phi_{\text{crit}})^{\alpha-n} + (1 + \beta\cos\phi_{\text{crit}})^{\alpha-n}\right] \tag{13}$$

Hence, at optimum boosting we obtain:

$$\gamma_{\text{opt}} \approx \frac{\gamma R_{\min}}{R_{\max}}\left[(1 - \beta\cos\phi_{\text{crit}})^{\alpha-n} + (1 + \beta\cos\phi_{\text{crit}})^{\alpha-n}\right] \tag{14}$$

R_{max} is similar to the value of the intercept of $R - D$ plot. In this case, since R is maximum, the relation that connects R to D is expected to be an inverse relation expressed as follows:

$$R = R_{max} - mD \tag{15}$$

where m is slope of the plot.

Moreover, from Orr and Browne (1982), Ubachukwu and Chukwude (2002), R_{max} may be written as:

$$R_{max} \approx f\left(2\gamma_{opt}\right)^{n} \tag{16}$$

However, assuming:

$$R_{min} \approx \frac{f}{\gamma_{opt}} \qquad (17)$$

for compact sources; therefore, from the last two equations, we obtain:

$$\gamma_{opt} \approx \left(\frac{R_{max}}{2^n R_{min}}\right)^{\frac{1}{1+n}} \qquad (18)$$

Analyses and Results

The mean value data for the R-distribution for the CSS quasars and galaxies are $R_{mean} = 0.237$ and 0.064 respectively. Using $R_{min} = 0.003$ (which appears to be consistent with the quasar/galaxy unification scheme for high frequency surveys (Orr and Brown, 1982; Ubachukwu & Chukwude, 2002)) together with $R_{mean} = 0.237$ and 0.064 in equation (10) yields $\phi_{mean} \approx 15°$ for $n = 2$ or $\phi_{mean} \approx 32°$ for $n = 3$ for CSS quasars; while for the galaxies, we obtain $\phi_{mean} \approx 23°$ for $n = 2$ or $\phi_{mean} \approx 41°$ for $n = 3$.

However, $R - z$ and $D - z$ plots show that there are no cosmological evolutionary effects on the $R - D$ relation. The two plots show no apparent trend – linear regression analyses give correlation coefficient, $r \approx -0.2$ and $r \approx -0.4$ for $R - z$ (CSS quasars and galaxies respectively); while for $D - z$, $r \approx -0.1$ and $r \approx -0.3$ for CSS quasars and galaxies respectively. Each case implies lack of any significant redshift dependence. Therefore, we can conclude that there are no evolutionary effects; hence, we proceed to find the ranges of critical angles of observation and Lorentz factors for optimum boosting.

Figures 1 and 2 show the $R - D$ plots for the CSS quasars and galaxies respectively. Figure 3 shows $R - D$ plot for the quasars when the two outliers in figure 1 are removed. Although, the plot (figure 3) 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 distinct (which is indistinct in figure 2 for the galaxies). This function is usually attributed to relativistic beaming and projection effects at small angles with respect to the line of sight of the observer (Orr and Brown, 1982; Ubachukwu and Chukwude, 2002).

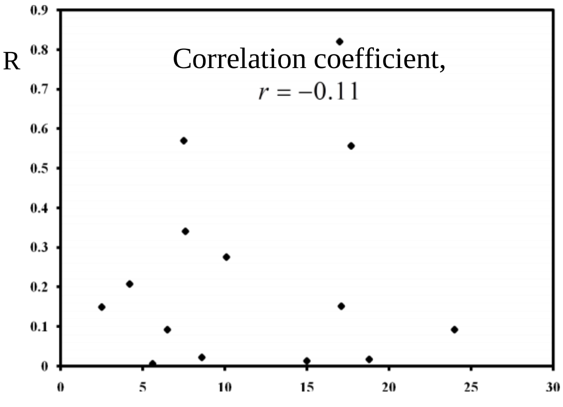

Fig. 1: R – D plot for CSS quasars

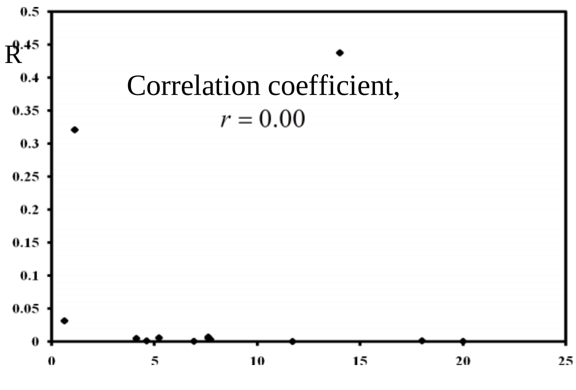

Fig. 2: R – D plot for CSS galaxies

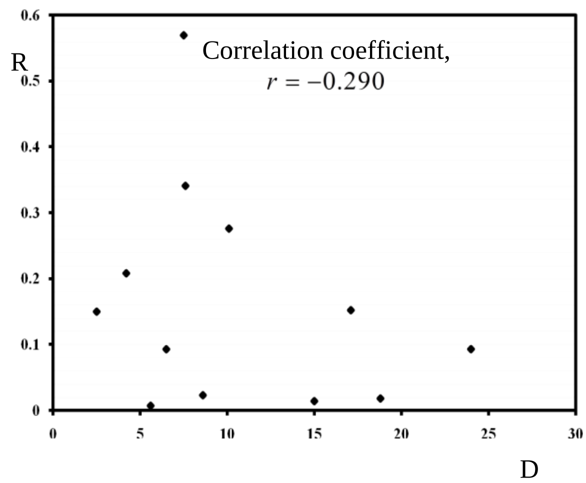

Fig. 3: R – D plot for CSS quasars
(The two outliers are absent here)

Linear regression analysis of the upper envelope R-data against D in four ranges of D in figure 3 ($D < 5\ kpc; 5 \leq D \leq 10\ kpc; 10 < D \leq 15\ kpc$and $D > 15\ kpc$) gives $R_{max} = 0.44$with $r = 0.62$. Using $R_{max} = 0.44$, $\alpha_{mean} \approx 0.7$ (mean value of spectral indices) and $R_{min} = 0.003$ in equation (18) for quasars gives the bulk Lorentz factor (for optimum boosting), $\gamma_{opt} \approx 3.3$ and $\gamma_{opt} \approx 2.1$ for$n = 2$ and 3 respectively. The corresponding critical beaming angle from equation (10) becomes,$\phi_{crit} \approx 18°$ (for$n = 2$) or $\phi_{crit} \approx 29°$ (for $n = 2$). These results are summarized in Table 1.

Table 1: Values of the Beaming and Orientation Parameters Obtained

Parameters	**Quasars**		**Galaxies**	
R_{mean}	0.237		0.064	
α_{mean}	0.7		0.8	
R_{max}	0.44		No distinct upper envelope $R-D$ function	
n	**2**	**3**	**2**	**3**
ϕ_{mean}	15°	32°	23°	41°
γ_{opt}	3.3	2.1	No R_{max}	
ϕ_{crit}	18°	29°	No R_{max}	

Discussion

The purpose of this work, as stated earlier, is to investigate relativistic beaming and orientation effects in CSS sources. This is imperative since CSS sources have been shown in the literature to contain special properties different from their more extended counterparts. Moreover, Ubachukwu and Chukwude (2002) carried out similar work but on the core-dominated conventional radio sources. Their results suggest that the flows from the cores of these sources are highly relativistic with optimum Lorentz factor, $\gamma_{opt} \approx 6 - 16$, and also highly anisotropic, with average viewing angle, $\approx 9° - 16°$; and largest boosting occurs within a critical cone angle of $\approx 4° - 10°$. Therefore, there is a need to estimate the values of these parameters for the CSS sources. These estimates, hopefully, will yield level of comparabilityof quasars and galaxies in orientation-dependent unification scheme; as well as, to the conventional extragalactic radio sources.

The results of our analyses show that, on the average, CSS quasars (i.e. lobe- and core-dominated quasars combined) and galaxies are inclined at angles $\phi \approx 15° - 32°$ and $\phi \approx 23° - 41°$ respectively, with respect to the line of sight. Another result is the presence of an inverse correlation between core-dominance parameter, R, and linear size, D, for the upper envelope $R - D$ data. This relation yields optimum Lorentz factors, $\gamma_{opt} \approx 3.3$ and 2.1 (for $n = 2$ and 3 respectively), with the corresponding critical beaming angles (i.e., the largest angle for optimum boosting), $\phi_{crit} \approx 18° - 29°$ for the CSS quasars only. Notably, there is no distinct upper envelope $R - D$ function in figure 2, which suggestively indicates that radio galaxies are not beamed. The results are consistent with the orientation-dependent relativistic beaming and radio source unification paradigm in which the flows from the cores of quasars are expected to be highly relativistic; and in which Doppler effects generate anisotropic radiation patterns at close angles to our line of sight. In addition, our results are compatible with those obtained by Ubachukwu and Chukwude (2002) for the conventional core-dominated radio sources; and suggest that CSS sources are simply miniaturized versions of the more extended radio sources.

Conclusion

Deductions from our analyses indicate that jet flows from the CSS quasars are highly relativistic, while those from the CSS galaxies are not. Also, while the jet axes of the quasars lie closer to our line of sight, those of the CSS galaxies lie farther away. These two findings conform to quasar/galaxy orientation-dependent unification scheme. Finally, since our results are comparable to those obtained by Ubachukwu and Chukwude (2002) for the more extended core-dominated extragalactic radio sources, we can infer that CSS sources are scaled-down versions of the larger radio sources.

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