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Relativistic bulk motion in hotspots of extra galactic radio quasars

Abstract

Using the observed asymmetry parameters (arm-length ratio (Q) and apparent flux ratio (R)) usually observed at kilo parsec region and the observed apparent expansion speed (β_a) of the components seen with the parsec regions of jets of radio sources, we obtained an analytical expression that allowed us to constrain the Lorentz factor of jet in hotspots of extragalactic radio sources. Our result indicates that relativistic bulk motion persists even in the kilo parsec regions of hotspots of extragalactic radio sources. The average value of the estimated Lorentz factor of $(\gamma) \sim 12 \pm 6$ was obtained using the arm-length ratio. For sources with observed apparent flux ratio (R), the estimated average Lorentz factor is $(\gamma) \sim 15 \pm 8$. Correlation analysis indicates that the estimated bulk speed is independent of extended luminosity (P) and source projected linear size (D).

Key Words

Galaxies: General; Galaxies: Active; Galaxies: Jets; Methods: Analytical; Methods: Statistical; Methods: Data analysis.

INTRODUCTION

Many fundamental physical properties of Active Galactic Nuclei (AGN) jets remain uncertain, such as the nature of the energy-carrying particles, whether the particle energy densities are in equipartition with the local magnetic field energy densities (e.g.[10,13]), the bulk expansion speed in the parsec and kilo parsec regions (e.g.[1,2,18,42]). From the observation of superluminal motion with the Very Long Baseline Interferometers (VLBI) technique, it is generally agreed that the jets of parsec regions of most AGN are highly relativistic, with bulk Lorentz factors $\gamma \sim 10$ - 30 (e.g.[27,32]). It is now well established that particles in the plasma emitting these radio radiation through synchrotron process are initially accelerated in the vicinity of a compact supermassive object (probably a black hole (e.g.[31])) located at the core of the AGN. From there, they are transported out to kilo parsec or even Mega parsec distances in the forms of collimated jet-like features, giving rise to a pair of lobes of non-thermal emission on the opposite sides of the nucleus (e.g.[4]). In powerful radio galaxies and quasars, the jets are seen to terminate in compact bright regions, called hotspots[18].

Observational evidence that supports the idea that the radio jets in AGN contain material in relativistic motion include morphology (the usually observed one-sided jet), estimated brightness temperature (e.g.[11,22,30,50]). Others include X-rays and superluminal motion speed (e.g.[9,26,27,37,46]), interstellar scintillations[14,38]. Though these are largely independent, but when taken together makes a case for relativistic motion especially on parsec regions. However, it is not certain whether most jets at the kilo parsec regions also have high Lorentz factors in bulk motion and whether the jets are oriented close to our line of sight, as inferred for PKS 0637-752[12,44] because of its X-ray bright knots[43]. Gopal-Krishna et al. (2001)[19] posit that any model in which relativistic electrons are generated solely within the active nucleus must ensure their survival against the radiative losses suffered during their transit to the hotspot.

Radio observations alone make a convincing case that the jets in these objects often decelerate from relativistic to sub-relativistic bulk speeds (that is, speeds of the whole jet fluid, as opposed to random speeds of individual particles) on kilo parsec regions[1,29,42]. The detections of X-ray emission from bright hotspots of powerful sources were widely taken to be Inverse-Compton (IC) in origin because of their flat X-ray spectra and believed to originate from relativistic plasma in the hotspot region[21]. A long debated key issue is whether the ultra-relativistic particles radiating within the kilo parsec regions of hotspots and lobes are largely directly supplied by the nucleus in the form of jets or whether a significant amount of relativistic particle acceleration occurs in situ within the hotspots and lobes (e.g.[5-8,16,28,41]).

The brightness asymmetry in the X-ray regime observed in the hotspots of quasars and broad line radio galaxies has been argued by Georganpoulos & Kazanas (2003)[17] as arising from the Inverse Compton (IC) boosting of the radio photons inside the hotspots. This brightness asymmetry caused by energy dependent beaming furnishes an important piece of evidence that bulk motion of jets may remain relativistic all the way to the hotspots[18,35,36,45,48].

In this article, using the asymmetry parameters – the arm-length ratio (Q) and the apparent flux ratio (R) usually observed at kilo parsec regions, and the superluminal motion speed (β_a) observed at parsec regions, we which to obtain an expression that would enabled us estimate the bulk Lorentz factor in hotpots of radio sources. The combination of parsec observation (superluminal motion speed) and kilo parsec observed parameters (arm-length ratio and the apparent flux ratio) in the determination of radio source intrinsic parameter (Lorentz factor) is a reasonable assumption. Zensus & Porcas (1986) reported that orientation memory is found between features on parsec- and kilo parsec-regions. This rest of the paper is organized as follows. In section 2, we present the theoretical formulation. Source of data, analysis and results are presented in Section 3 followed by a brief discussion and conclusion in section 4.

THEORY OF RELATIONSHIP

The arm-length ratio (Q) given by $Q = D_{app}/D_{rec}$, where D_{app}/D_{rec} is the ratio of the approaching side core-lobe length to that of receding side core-lobe length. In framework of simple kinematic model it is defined as (e.g.[18,39])

$$Q = \frac{1+\beta\cos\theta}{1-\beta\cos\theta} = \frac{1+x}{1-x} \tag{1}$$

with β the bulk speed of the radio emitting plasma (assumed for simplicity to be the same on both sides (e.g.[18]) and defined in units of c– the velocity speed of light), θ is the angle between the motion of the radio emitting plasma and the line of sight of the distant observer, and $x = \beta\cos\theta$ (see[3]) is the fractional separation difference. The bulk speed is related to the bulk Lorentz factor by,

$$\gamma = \frac{1}{\sqrt{1-\beta^2}} \tag{2}$$

The apparent flux ratio (R) is defined as the ratio of the brightness/luminosity of the approaching lobe to that of the receding lobe and in the context of beaming theories (e.g.[39]) is given by

$$R = \left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^k = \left(\frac{1+x}{1-x}\right)^k \tag{3}$$

where $k = n + \alpha$; $n = 3$ for blobs, $n = 2$ for continuous injection model (jets) and α is the spectral index defined as $S_\nu = \nu^{\alpha}$ where S_ν is the flux density at the frequency (ν) of observation.

The apparent speed (β_a) from geometric consideration is defined as (e.g.[15,27])

$$\beta_a = \frac{\beta\sin\theta}{1-\beta\cos\theta} = \frac{\sqrt{\beta^2-x^2}}{1-x} \tag{4}$$

From equation (1) following Banhatti (1980)[3], we can write,

$$x = \frac{Q-1}{Q+1} \tag{5}$$

Solving for x in equation (4) and making use of equation (2) we have

$$x = \frac{\gamma\beta_a^2 \pm \sqrt{\gamma^2-(1+\beta_a^2)}}{\gamma(1+\beta_a^2)} \tag{6}$$

Urry & Padovani (1995)[46], defined a minimum Lorentz factor (γ_{min}) responsible for the observed superluminal speed as

$$\gamma_{\min} = \sqrt{\beta_a^2+1} \tag{7}$$

Making use of equations (5) and (7) in equation (6), the minimum bulk Lorentz factor of jets in extragalactic radio source hotspot can be written as

$$\gamma_{\min} = \sqrt{\frac{\beta_a^2(Q+1)}{Q-1}} = \sqrt{\frac{\beta_a^2}{x}} \tag{8}$$

Similarly, re-defining $R^* = R^{\frac{1}{n+\alpha}}$, implies that we can write $x_R = \frac{R^*-1}{R^*+1}$, and combining this with equation (6) we have,

$$\gamma_{\min} = \sqrt{\frac{\beta_a^2(R^*+1)}{R^*-1}} = \sqrt{\frac{\beta_a^2}{x_R}} \tag{9}$$

Equations (7) is valid for relativistic beam model (e.g.[46]) with the assumption that the bulk relativistic speed responsible for the observed superluminal speed persist in kilo parsec regions and is also responsible for the observed radio source asymmetry (e.g.[18]). Equations (8) and (9) uniquely provide theoretically, a method of determining the bulk Lorentz factor for each source if the arm-length ratio (Q), apparent flux ratio (R) and the apparent superluminal speed (β_a) of the source are known. In general a regression fit to equations (8) and (9) of the form

$$\log\beta_a = \frac{1}{2}\log x + \log\gamma_{min} \qquad (10)$$

will provide in general, an average value of the Lorentz factor observed in the kilo parsec regions of a sample of extragalactic radio sources.

DATA, ANALYSIS AND RESULT

We test these expectations using a sample of superluminal sources compiled from Vermeulen & Cohen (1994)[47], Kellermann et al. (2004)[27], Britzen et al. (2008)[9] and Nilsson (1998)[33]. The apparent superluminal speed (β_α) of the jet components were obtained from Vermeulen & Cohen (1994)[47], Kellermann et al. (2004)[27] and Britzen et al. (2008)[9], while the corresponding arm-length ratio (Q), apparent flux ratio (R) and spectral index (α) were obtained from Nilsson (1998)[33]. The selection criteria being that the superluminal radio source have corresponding Q-value or R-value. Most of the superluminal sources are observed to have more than one moving components, thus for sources with more than one component, we selected the component with fastest speed, believing that it is the component most likely to be a representative of the bulk speed of the beam (see[11]). The final sample consists of 26 radio quasars.

We display in TABLE 1 the source parameters and our result (the estimated Lorentz factor) using the fastest apparent speed. The estimated Lorentz factors using the arm-length ratio parameter is on the average similar to that obtained using the apparent flux ratio. The median value of the estimated Lorentz factor for such an inhomogeous sample is 15 ± 8 and 17 ± 8 respectively for arm-length ratio and apparent flux ratio. Figure 1 is the $\log\beta_\alpha$ - $\log x$ plot. Regression analysis of plot gives: $\log\beta_\alpha = (0.4 \pm 0.2)\log x + (1.1 \pm 0.2)$ and $\log\beta_\alpha = (0.6 \pm 0.2)\log x + (1.3 \pm 0.2)$ for x_Q and x_R respectively. These results imply an average Lorentz factor of $\langle y\rangle = 13 \pm 2$ using x and $\langle 20 \pm 2\rangle$ using x_R. Further regression analysis, indicates that the estimated Lorentz factor is independent of extended luminosity (P) and source projected linear size (D), with correlation results of $r_{P\gamma} = 0.05$, $r_{D\gamma} = -0.17$ and $r_{P\gamma} = 0.32$, $r_{D\gamma} = -$

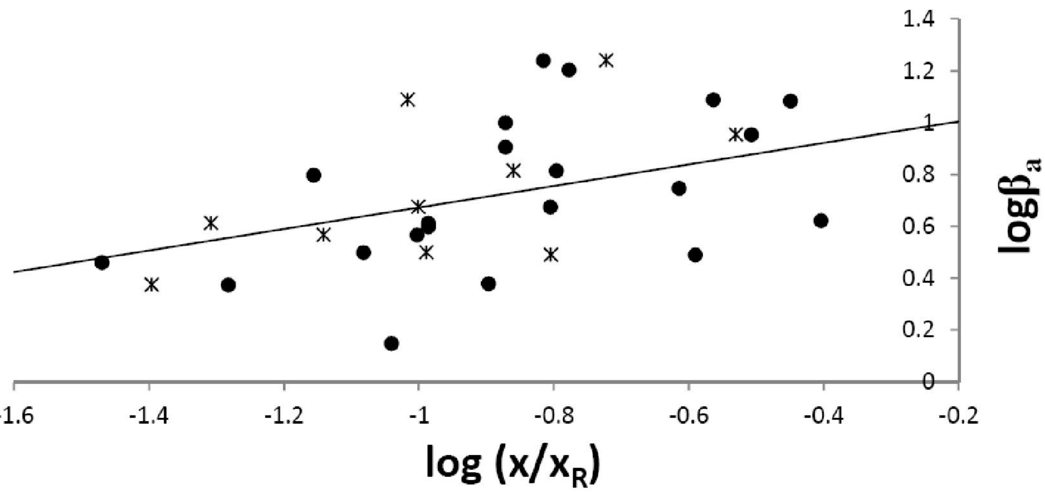

Figure 1 : Plot of $\log\beta_\alpha$ - $\log x$ (Solid Circle for x; Star for x_R)

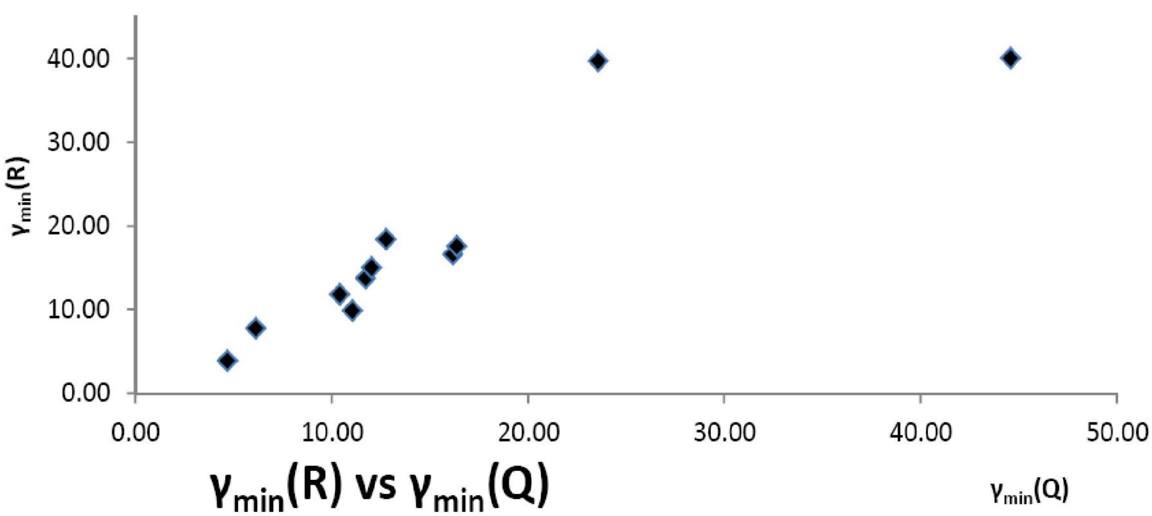

Figure 2 : Plot of Lorentz factor estimated using R-parameter ($\gamma_{min}(R)$) vs Lorentz factor estimated using Q-parameter ($\gamma_{min}(Q)$)

TABLE 1 : Source parameters and estimated Lorentz factor

S/N	*IAU*	β	α	Q	R	$\gamma_{min}(Q)$	$\gamma_{min}(R)$
1	0133+207	3.7	0.95	1.22	1.77	11.72	13.74
2	0723+679	4.8	0.59	1.37	2.05	12.02	15.05
3	0738+313	2.4		1.29		6.74	
4	0833+654	1.2		1.42		2.83	
5	0835+580	3.2	0.88	1.18	2.22	11.03	9.91
6	0923+393	4.0		1.23		12.36	
7	0923+392	4.1	-0.10	1.23	1.33	12.75	18.48
8	1012+232	9.0	0.34	1.90	7.59	16.16	16.59
9	1040+123	3.1	0.70	1.69	3.22	6.12	7.83
10	1055+018	1.7		1.60		3.54	
11	1055+201	10.0		1.31		27.30	
12	1137+660	1.3		1.94		2.21	
13	1222+216	1.4	0.50	1.20	2.43	4.68	3.97
14	1302-102	5.6		1.64		11.37	
15	1458+718	6.5	0.54	1.38	2.67	16.34	17.59
16	1611+343	4.2		2.30		6.69	
17	1618+177	1.9		1.64		3.82	
18	1633+382	12.0		2.10		20.45	
19	1642+690	16.0		1.40		39.19	
20	1656+571	8.1		1.31		22.03	
21	1721+343	2.4	0.55	1.11	1.33	10.38	11.83
22	1807+698	2.9		1.07		15.77	
23	1830+285	2.6		1.02		25.73	
24	1954+513	17.0	0.27	1.36	3.50	44.55	40.00
25	2201+315	6.3		1.15		23.85	
26	2230+114	12.0	0.11	1.75	1.82	23.55	39.70

0.21 respectively for estimated Lorentz factor using arm-length ratio and apparent flux ratio.

Usually, in relativistic beaming, the longer arm, is assumed to be the brighter arm (Laing and Garrington effect –[16,28]), thus we expect a strong correlation between Lorentz factor estimated using arm-length ratio and that using apparent flux ratio. The plot of Lorentz factor estimate using arm-length ratio against Lorentz factor estimate using apparent flux ratio is shown in figure 2, with correlation coefficient result of r_{QR} = 0.89

DISCUSSION AND CONCLUSION

We have estimated the jet minimum Lorentz factor using arm-length ratio and apparent flux ratio usually observed at kilo parsec regions and superluminal speed seen within the parsec regions of radio sources. The estimated Lorentz factors using the arm-length ratio and apparent flux ratio parameters are similar. The estimated Lorentz factor ranges $2 \leq \gamma_{min} \leq 45$ for the arm-length ratio, while for the apparent flux ratio, we have $4 \leq \gamma_{min} \leq 40$. The results indicate that jets of AGN are still relativistic at kilo parsec regions. This is in agreement with other work found in literature (e.g.[5,7,8,16,28]). Jorstad & Marscher (2004)[25] noted that blazar jets appear to retain roughly the same Lorentz factor all the way out to kilo parsec regions when reasonable estimates can be. Urry & Padovani (1995)[46] showed that for their derived luminosity function of matched the observed Flat Spectrum Radio Quasars luminosity function if there is a distribution in Lorentz factor in the range of $5 \leq \gamma \leq 40$ with a mean value of $\langle\gamma\rangle = 11$. These results generally are in agreement with our result. Our mean Lorentz factors are in agreement with those of Hovatta et al. (2009)[24], who obtained $\langle\gamma\rangle = 16.24$ for Flat Spectrum Radio Quasars and Yang et al. (2012)[49] who obtained $\langle\gamma\rangle = 12.85 \pm 5.70$ for quasars in their sample.

One major issue against relativistic particles at kilo parsec regions of extra galactic radio sources is the synchrotron lifetime of the particles produced in the nuclear region since electrons of Lorentz factor ($\gamma > 10^5$) correspond to a lifetime of $\leq 10^3\, yr$ against synchrotron losses even in a magnetic field as weak as a few microgauss[19]. In their analysis of PKS0637-752 observation by Chandra, Tavecchio et al. (2000)[44] and Celotti et al. (2001)[12] showed that Inverse Compton scattering of the cosmic microwave background is consistent with equipartition of magnetic field for a Doppler factor $\delta \simeq 10$. This process is plausible since VLBI observations reveal superluminal motion on parsec regions, implying $\theta < 6°$. This interpretation implies that the bulk motion of the jet is relativistic at nuclear distances up to several hundred kilo parsecs, a result consistent with systematic polarization asymmetries in powerful radio galaxies and quasars[16,28].

Our regression analysis suggests that our estimated Lorentz factor is independent of source size and extended luminosity (though there seems to be a mild correlation between luminosity and Lorentz factor using apparent flux ratio - $r_{P\gamma} = 0.32$). The lack of inverse correlation between bulk speed and source size supports the assumption that hotspot/lobe advance speed remains fairly constant an assumption usually made in estimating the kinematic ages of extra galactic radio sources (e.g.[20]), though Hjellming & Han (1995)[23] noted that speed should reduce as jets advance away from the core, probably due to deceleration as the expanding plasmon interacts with the environment. The mild correlation between luminosity and estimated Lorentz factor using apparent flux ratio is expected since the more powerful sources are expected to have higher jet power, and thus higher bulk speed. The lack of correlation between estimated Lorentz factor using arm-length ratio and extended luminosity suggests that other factors (environmental/intrinsic – e.g.[34,40]) are needed in the interpretation of observed structural asymmetries in radio sources.

In conclusion, using the observed arm-length ratio, apparent flux ratio and apparent superluminal motion, we estimated the minimum bulk Lorentz factor of hotspots of quasars. Our result indicates that bulk relativistic motion persists in jets of AGN, which is widely believed to be maintained all the way out to multi-kilo parsec regions (e.g.[5,7,8,16,28])

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