KINEMATIC MODEL FOR ASYMMETRY: PROJECTED HOTSPOT/LOBE ADVANCE SPEED

C. C. Onuchukwu,[1,2] A. A. Ubachukwu[2], and F. C. Odo[2]

RESUMEN

Presentamos un modelo cinemático para las asimetrías en las radiofuentes, el cual nos permite estimar la velocidad proyectada (mancha caliente/avance del lóbulo) en fuentes de radio de alta luminosidad usando el cociente entre las longitudes de los brazos (Q) y el cociente de los flujos aparentes (R). Obtenemos una velocidad media proyectada a lo largo de la visual $\langle\overline{\beta}\rangle = 0.15 \pm 0.05$ para todas las fuentes de nuestra muestra utilizando el parámetro Q, y $\langle\overline{\beta}\rangle \sim 0.12 - 0.32$ para $\rho = 2\alpha + 1$ (donde ρ es el índice del espectro de la energía de los electrones) usando el parámetro R. Nuestros resultados indican que el modelo adoptado para la evolución del brillo del elemento de plasma afecta los valores de la velocidad proyectada. Mediante análisis de regresión se encuentra que las velocidades estimadas usando los parámetros Q y R tienen cierta correlación con la distancia (L) y con la luminosidad (P), especialemente en el caso de los cuasares.

ABSTRACT

We present a kinematic model for asymmetries in radio sources, which enabled an estimation of the projected hotspot/lobe advance speed for high-luminosity radio sources using the arm-length ratio (Q) and apparent flux ratio (R). We obtain a mean projected speed along the line of sight $\langle\overline{\beta}\rangle = 0.15 \pm 0.05$ for all the sources in our sample, using the Q parameter and $\langle\overline{\beta}\rangle \sim 0.12 - 0.32$ for $\rho = 2\alpha + 1$ (where ρ is the electron energy spectrum index) using the R parameter. Our results indicate that the adopted model of brightness evolution of plasma element affects the values of projected speed. Regression analyses indicate that the estimated speeds using the Q and R parameters show some correlation with distance (L) and luminosity (P), especially for quasars.

Key Words: galaxies: active — galaxies: general — galaxies: kinematics and dynamics — methods: data analysis

1. INTRODUCTION

The observed radio emission from the lobes of active galactic nucleus (AGN) has been modeled as a twin ejection of energy from its nucleus in opposite directions (e.g. Blandford & Rees 1974; Scheuer 1974). It is assumed that in the rest frame of the AGN, energy is released symmetrically on both sides and two identical beams are created, a situation which, in general, is assumed to be responsible for the observed large scale symmetries in size, shape, structure and radio luminosities of AGN, especially, the low luminosity FR I radio sources (Fa-

naroff & Riley 1974). In powerful radio sources (FR II type) structural asymmetries and misalignment of the hotspots/lobes about the core are commonly observed and in almost all cases, jets are observed only on one side of the lobes (e.g. Hargrave & McEllin 1975; Gopal-Krishna & Wiita 2004).

Since observations provide us with a 2-dimensional projection of the 3-dimensional extragalactic radio sources (EGRS), asymmetric appearances of EGRS could result from various physical mechanisms – Doppler beaming, orientation, light-travel time and time delay effects (Rees 1967; Ryle & Longair 1967) as well as strong anisotropy in the core (e.g. Zensus 1997). Other possible reasons that can be used to explain these asymmetries include

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[1]Department of Industrial Physics, Anambra State University, Uli, Nigeria.

[2]Department of Physics and Astronomy, University of Nigeria Nsukka, Nigeria.

plasma ejection from the AGN, which could have different properties for each of the jets in terms of confinement, velocity, time of ejection, mass of ejected plasma, passage through different screens (e.g. Garrington et al. 1988; Garrington & Conway 1991; Tribble 1992; Ryś 2000), thus producing different radio source structure/morphology at opposite sides. Also, the external medium through which the jets propagate might not be isotropic, presenting different resistances to the propagation of the jets, and thus, producing asymmetries in both source structure and luminosity.

However, only the luminous part of the matter content in any structure is observed; hence, in describing asymmetry, one looks for differences between position and brightness of corresponding elements on opposite sides of the core of the EGRS structure. These asymmetries have been used to place useful constraints on some models and properties of EGRS (e.g. Best et al. 1995; Scheuer 1995; Arshakian & Longair 2000, 2004). These asymmetries may include the arm-length ratio (Q), the apparent flux ratio (R) and the age ratio (τ). In the context of beaming theories, the arm length-ratio $Q \equiv L_{\mathrm{app}}/L_{\mathrm{rec}}$ is defined to be ≥ 1, where $L_{\mathrm{app}}/L_{\mathrm{rec}}$ is the ratio of the approaching core-lobe length to the receding core-lobe length (Nilsson 1998). We note that due to intrinsic asymmetries, this may not always be true (see discussion in Scheuer 1995). In the framework of a simple kinematic model, Q is given as (e.g. Gopal-Krishna & Wiita 2004),

$$Q = \frac{1 + \beta\cos\theta}{1 - \beta\cos\theta} = \frac{1 + \overline{\beta}}{1 - \overline{\beta}} , \qquad (1)$$

where β is the bulk speed of the emitting plasma and is assumed to be the same for both hotspots/lobes, θ is the angle between the motion of the plasma and the line-of-sight of the observer and $\overline{\beta} = \beta\cos\theta$. The apparent lobe flux ratio (R) is defined in the context of beaming theories as (e.g. Ryle & Longair 1967)

$$R = \left(\frac{1 + \beta\cos\theta}{1 - \beta\cos\theta}\right)^k = \left(\frac{1 + \overline{\beta}}{1 - \overline{\beta}}\right)^k , \qquad (2)$$

where $k = n + \alpha$, $n = 3$ if a jet consists of blobs and $n = 2$ for a continuous injection (jets) model, while α is the spectral index defined as $S_\nu = \nu^{-\alpha}$, where S_ν is the flux density at the frequency of observation ν. In a manner similar to the apparent flux ratio (Miller-Jones, Blundell, & Duffy 2004; Gopal-Krishna & Wiita 2004), the age ratio τ in the observer's frame is defined as

$$\tau = \frac{t_{\mathrm{rec}}}{t_{\mathrm{app}}} = \frac{1 - \beta\cos\theta}{1 + \beta\cos\theta} = \frac{1 - \overline{\beta}}{1 + \overline{\beta}} . \qquad (3)$$

In this paper, we wish to develop a kinematic model that would enable us to obtain an expression which could be used to constrain the projected advance speed of hotspots/lobes and place some useful constraints on the possible models for the evolution of radio source components in particular and for a better understanding of EGRS properties in general.

2. ASYMMETRY MODEL

For an ideally symmetric source, the AGN is expected to eject symmetric jet on opposite sides of the core with identical speed, mass and energy without fluctuation. However, the observed radio source structures do not show such detailed symmetry and any model of EGRS that can produce the double-lobed structure should also account for the substantial differences in the observed component sizes, shapes and luminosities. Following Ryś (2000), we can describe any observable by a function f and its twin function by $\overline{f}$. Introducing the asymmetry generator function $f_i{}^*$ at least on one side of the structure, we can write:

$$f = \overline{f}\sum f_i{}^* , \qquad (4)$$

where the function $\sum f_i{}^*$ is the sum of the functions of the factors determining asymmetries in EGRS. Equation (4) suggests that several factors may be responsible for the observed radio source asymmetries and that these factors may be summed in a simple mathematical combination. For an isotropic environment, and symmetric ejection of plasma element on both sides of the core, orientation/Doppler beaming may be assumed as the cause of asymmetries observed in radio sources. In the following, we will concentrate on source orientation/Doppler beaming (neglecting environmental/intrinsic factors) in explaining the observed asymmetries in radio sources and we will obtain an expression from kinematic considerations that will enable us estimate the projected advance speeds of hotspots/lobes.

2.1. *Arm-Length Ratio* (Q)

The advance speed of the hotspots/lobes for asymmetric radio sources can be approximated using the arm-length ratio (Q) (e.g. Best et al. 1995; Scheuer 1995). Following Ryś (2000), and assuming that in the rest frame of the central engine of the AGN, energy is released symmetrically on both sides with equal power and at the same time, any structural asymmetry may be attributed to source orientation and light travel-time effects. Using Taylor series expansion, we can describe the distance of a plasma element emitting radio waves from the

central engine in the observer's rest frame for the approaching and receding components respectively by,

$$L_{\mathrm{app}}(t) = L_{\mathrm{app}}(t_0) + v_{\mathrm{app}}(t - t_0), \qquad (5)$$

and

$$L_{\mathrm{rec}}(t) = L_{\mathrm{rec}}(t_0) + v_{\mathrm{rec}}(t - t_0), \qquad (6)$$

where v_{app} and v_{rec} are the speeds of the approaching side lobe and receding side lobe respectively; t is the time to traverse $L(t)$ and t_0 is an assumed initial time. We choose the linear form of Taylor series to allow one-to-one correspondence between plasma elements on opposite sides that were supposedly emitted at the same instant from the AGN. For simplicity, we assume $L_{\mathrm{app}}(t_0) = L_{\mathrm{rec}}(t_0) = 0$, at $t = 0$ (though one may argue that in the frame of the observer, $L_{\mathrm{rec}}(t_0)$ may not necessarily be zero when $L_{\mathrm{app}}(t_0) = 0$ due to time delay for the photons emitted from the receding side in reaching the observer). Thus, using $v_{\mathrm{rec}}/v_{\mathrm{app}} = \left(1 - \overline{\beta}\right) / \left(1 + \overline{\beta}\right)$, as suggested by Rybicki & Lightman (1979) and at maximum separation of the lobes from the core of the source (i.e. at $t_{\max}$), we combine equations (5), (6) and (1) to obtain

$$\frac{1}{Q} = \frac{L_{\mathrm{rec}}(t_{\max})}{L_{\mathrm{app}}(t_{\max})} = \left(\frac{1 - \overline{\beta}}{1 + \overline{\beta}}\right). \qquad (7)$$

Here $\overline{\beta}$ is the velocity component in the rest frame of the central engine directed towards the observer which is identified as the advance speed of the hotspot. Equation (7) is similar to that in Banhatti (1980, equation 3) and Ryś (2000, equation 10), with Doppler factor $A = \left(1 - \overline{\beta}\right) / \left(1 + \overline{\beta}\right)$, $B = 0$, and $L_{\mathrm{rec}}(t_{\max})/L_{\mathrm{app}}(t_{\max}) = f/\overline{f}$ is the ratio of the length of the two core-to-lobe distances. Inverting equation (7) yields

$$\overline{\beta} = \frac{Q - 1}{Q + 1}, \qquad (8)$$

which will enable us place a useful constraint on the projected lobe/hotspot advance speed.

2.2. Lobe-Luminosity Ratio (R)

To account for the brightness asymmetry, one needs to consider the evolution in the brightness of the twin jets according to the assumed model of evolution that describes their energy evolution in time. In the literature, there are two cases of temporal evolution of the flux of emitted radio waves: the power-law temporal evolution, where the temporal evolution of any function f can be written as $f(t) = f(0)t^{-\lambda}$, and the exponential-law form, where

$f(t) = f(0) \exp\left(-t/T\right)$. This evolution includes adiabatic expansion losses, energy losses due to synchrotron emission, inverse Compton scattering, free-free radiation, and environmental effects (see e.g. Pacholczyk 1970; Ryś 2000). Thus, λ may depend on the spectral index (α). T is the characteristic age of the source. We may assume $T \sim t_{\max}$ where $t_{\max}$ is the source maximum age, and $f(0)$ is the value of the function at $t = 0$ (see Pacholczyk 1970; Jackson 1975; Nilsson et al. 1993; Ryś 2000).

2.2.1. Power-Law Form

Let F_{app} and F_{rec} respectively denote the flux emitted by the plasma element on the approaching and receding sides of the AGN core in the frame of the observer. In the power-law model, the temporal evolution of any function f can be written as $f(t) = f(0)t^{-\lambda}$, where the index of decline (λ), will depend on the spectral index (α), if synchrotron mechanism is the dominant loss process. The flux emitted in the frame of the plasma element can be written as $\overline{F}(\overline{t}) = \overline{F}(0)\overline{t}^{-\lambda}$ for both arms, assuming symmetric release of energy. Transforming to the observer's frame using $\overline{t}_{\mathrm{app}} = D_{\mathrm{app}}t_{\mathrm{app}}$ for the approaching arm and $\overline{t}_{\mathrm{rec}} = D_{\mathrm{rec}}t_{\mathrm{rec}}$ for the receding arm (see Ryś 2000), respectively, yields

$$F_{\mathrm{app}}(t) = F_{\mathrm{app}}(0) \left(\frac{D_{\mathrm{app}}}{\gamma}\right)^{\mathrm{k}} (D_{\mathrm{app}}t_{\mathrm{app}})^{-\lambda}, \qquad (9)$$

and

$$F_{\mathrm{rec}}(t) = F_{\mathrm{rec}}(0) \left(\frac{D_{\mathrm{rec}}}{\gamma}\right)^{\mathrm{k}} (D_{\mathrm{rec}}t_{\mathrm{rec}})^{-\lambda}, \qquad (10)$$

where $D_{\mathrm{app}} = (1 - \overline{\beta})^{-1}$ for the approaching arm, $D_{\mathrm{rec}} = (1 + \overline{\beta})^{-1}$ for the receding arm (Ryś 2000) and γ is the Lorentz factor. Equations (9) and (10) combine to give

$$\frac{F_{\mathrm{app}}(t)}{F_{\mathrm{rec}}(t)} = \frac{F_{\mathrm{app}}(0)}{F_{\mathrm{rec}}(0)} \left(\frac{1 + \overline{\beta}}{1 - \overline{\beta}}\right)^{k - \lambda} \left(\frac{t_{\mathrm{rec}} + \Delta t}{t_{\mathrm{rec}}}\right)^{-\lambda}, \qquad (11)$$

where we have assumed $t_{\mathrm{app}} = t_{\mathrm{rec}} + \Delta t$. Assuming that the energies released on both sides initially are the same and at the same time (i.e., $\Delta t = 0$), using equation (3), we can write

$$R = \left(\frac{1 - \overline{\beta}}{1 + \overline{\beta}}\right)^{\lambda - k}, \qquad (12)$$

where $R = F_{\mathrm{app}}/F_{\mathrm{rec}}$. In the Doppler beaming scenario, the approaching flux should be greater than

the receding flux, so that, $\lambda < k$, except for sources whose radio axes lie on the plane of the sky, in which case $\lambda = k$. Our definition is slightly different from the standard definition given in equation (2) having included the temporal decline in our analysis, but is similar to equation (5) of Miller-Jones et al. (2004), obtained from different argument. If we can estimate the value of the temporal evolution index λ, we can turn around equation (12) to obtain the projected expansion speed of the lobes/hotspots. It has been shown (Miller-Jones et al. 2004) that the ratio of flux densities of a synchrotron emitting plasma as seen by a distant observer is given by

$$R = \left(\frac{1-\overline{\beta}}{1+\overline{\beta}}\right)^{\rho-k} . \qquad (13)$$

Here, $\rho = 2\alpha + 1$ is the electron spectrum index and has values between $2-3$ (e.g. Blundell, Rawlings, & Willott 1999; De Young 2002). Comparing equations (12) and (13) gives $\lambda = \rho$. Using these values of λ, in equation (12) for $k = 3 + \alpha$ (we have chosen $n = 3$ since we are considering the lobes) we can write

$$R = \left(\frac{1-\overline{\beta}}{1+\overline{\beta}}\right)^{\alpha-2} . \qquad (14)$$

Hence, inverting equation (14) yields

$$\overline{\beta} = \frac{1 - (R)^{\frac{1}{\alpha-2}}}{1 + (R)^{\frac{1}{\alpha-2}}} . \qquad (15)$$

Equation (15) suggests that the average projected advance speed of the lobes/hotspots could be estimated from the apparent lobe flux ratio (R) distribution for a well-defined source sample. The interesting thing about equation (15) is that it incorporates the decline parameter. In general, the spectral index of the lobes of high-luminosity radio sources is assumed to lie in the range $0.5 \le \alpha = 1.0$. Thus, for $\alpha = 0.5$, using the median value of the apparent lobe flux ratio (R_{med}) of any sample, we have

$$\overline{\beta} = \frac{1 - (R_{\mathrm{med}})^{-2/3}}{1 + (R_{\mathrm{med}})^{-2/3}} , \qquad (16)$$

while for $\alpha = 1.0$, we have

$$\overline{\beta} = \frac{1 - (R_{\mathrm{med}})^{-1}}{1 + (R_{\mathrm{med}})^{-1}} . \qquad (17)$$

2.2.2. *Exponential-Law Form*

The temporal exponential evolution of brightness of a radio emitting plasma in the observer's frame for the approaching arm can be written as

$$F_{\mathrm{app}}(t) = F_{\mathrm{app}}(0)\left(\frac{D_{\mathrm{app}}}{\gamma}\right)^{\mathrm{k}} \exp\left(-\frac{D_{\mathrm{app}}t_{\mathrm{app}}}{T}\right) , \quad (18)$$

and for the receding arm as

$$F_{\mathrm{rec}}(t) = F_{\mathrm{rec}}(0)\left(\frac{D_{\mathrm{rec}}}{\gamma}\right)^{\mathrm{k}} \exp\left(-\frac{D_{\mathrm{rec}}t_{\mathrm{rec}}}{T}\right) . \quad (19)$$

Combining equations (18) and (19) gives

$$\frac{F_{\mathrm{app}}(t)}{F_{\mathrm{rec}}(t)} = \left(\frac{1+\overline{\beta}}{1-\overline{\beta}}\right)^{k} \exp\left(\left(\frac{1}{T}\right)\left(\frac{t_{\mathrm{rec}}}{1+\overline{\beta}} - \frac{t_{\mathrm{app}}}{1-\overline{\beta}}\right)\right) . \qquad (20)$$

Assuming $t_{\mathrm{rec}} = t_{\mathrm{app}} + \Delta t$, at a long enough time, $t_{\mathrm{app}} = t_{\mathrm{max}} \gg \Delta t$ (except if there is a continuous disruption of the motions of the lobe/hotspot in anisotropic environment). One can also assume $\Delta t = 0$, for twin ejection so that $t_{\mathrm{app}}/T = 1$, since $T \equiv t_{\mathrm{max}}$. Hence, we can write,

$$R = \left(\frac{1+\overline{\beta}}{1-\overline{\beta}}\right)^{\mathrm{k}} \exp\left(\frac{-2\overline{\beta}}{1-\overline{\beta}^2}\right) , \qquad (21)$$

with the solution as

$$\overline{\beta} = \frac{\ln R}{2k - 2} . \qquad (22)$$

For $0.5 \le \alpha \le 1.0$, the solution to equation (21) using the median value of each class of source can be approximated as

$$\frac{\ln R_{\mathrm{med}}}{6} \le \langle\overline{\beta}\rangle \le \frac{\ln R_{\mathrm{med}}}{5} . \qquad (23)$$

Equation (22) can be used to put some useful constraints on the projected expansion speed of hotspots/lobes of a given sample of radio sources.

We note that in our formulation, the estimated speed $(\overline{\beta})$ did not explicitly exclude the angle to the line of sight. Its exclusion will modify the estimated speed for individual sources. Moreover, the values of $\overline{\beta}$ estimated for individual sources may have underestimated the true bulk speed (β), and for randomly oriented sources this will broaden the spread about the estimated average value.

3. DATA, ANALYSIS AND RESULTS

To estimate the hotspot/lobe projected advance speed using our model, we make use of the high luminosity edge-brightened double-lobed EGRS sample from Nilsson (1998). The sample comprises 1038 FR-II type radio sources that are quite heterogeneous;

TABLE 1

ESTIMATED MEAN VALUES OF $\overline{\beta}$ WITH STANDARD ERRORS

Source Class	Q	R (PL)			R (EL)		
	$\overline{\beta}$	$\overline{\beta}(\alpha)$	$\overline{\beta}(\alpha=0.5)$	$\overline{\beta}(\alpha=1.0)$	$\overline{\beta}(\alpha)$	$\overline{\beta}(\alpha=0.5)$	$\overline{\beta}(\alpha=1.0)$
ALL	0.15 ± 0.05	0.28 ± 0.10	0.23 ± 0.08	0.33 ± 0.12	0.13 ± 0.05	0.14 ± 0.05	0.12 ± 0.05
Quasars	0.17 ± 0.06	0.32 ± 0.11	0.27 ± 0.10	0.38 ± 0.13	0.15 ± 0.06	0.17 ± 0.07	0.14 ± 0.06
Galaxies	0.11 ± 0.03	0.19 ± 0.07	0.15 ± 0.06	0.22 ± 0.08	0.08 ± 0.03	0.09 ± 0.03	0.07 ± 0.03

Calculated Using Arm-Length Ratio (Q) and Apparent Lobe Flux Ratio (R). (PL:-Power-law Model; EL:-Exponential-law Model).
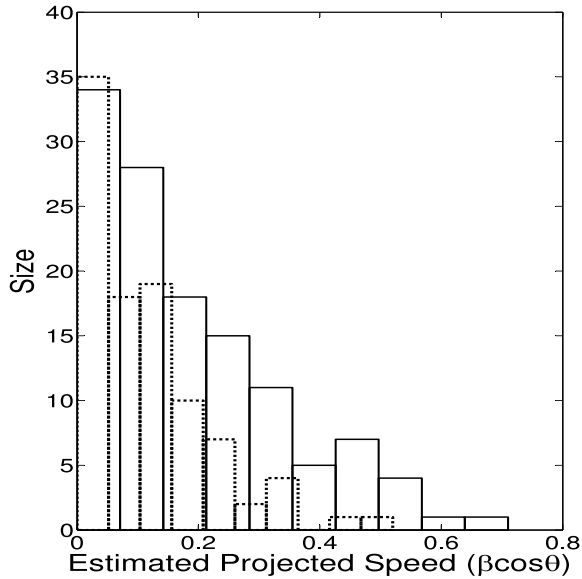
Fig. 1. Distribution plot of estimated speed $\overline{\beta}$ using the Q parameter (quasars: solid line; galaxies: dashed line).
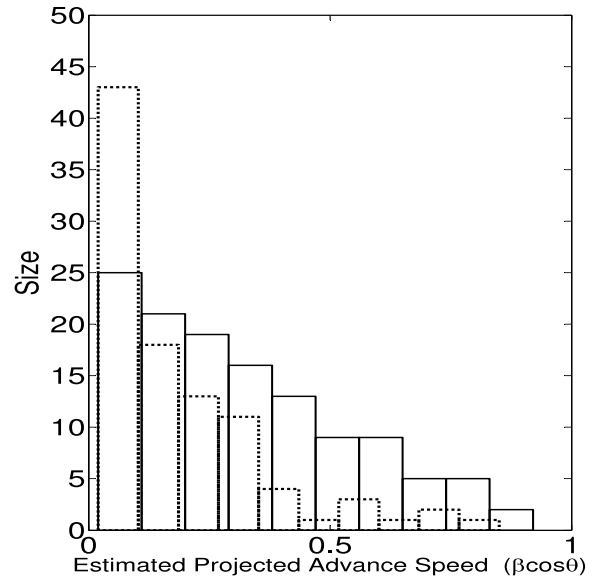

Fig. 2. Distribution plot of estimated speed $\overline{\beta}$ using the R parameter. Power-law model (quasars: solid line; galaxies: dashed line).

544 are galaxies, 365 are quasars and 129 are unclassified. The redshift is known for 334 galaxies and 335 quasars. Under the relativistic beaming hypothesis, it is believed that $Q \geq 1$ and $R \geq 1$ (assuming that the approaching side is brighter than the receding side). Thus, we selected sources with $Q/R \geq 1$. Our final sample consists of 124 quasars and 97 galaxies with complete structural and cosmological information.

Beside heterogeneity of the original sample, we note that high luminosity radio sources sample a wider and plausibly different set of host galaxies with differing environment, namely, $(0.016 \leq z \leq 2.877)$ and $(40.21 \leq \log P_{178\mathrm{MHz}} \leq 45.89)$. Thus, we believe that binning will smooth out randomly induced characteristics/values (especially due to environmental factors). In our interpretation of observed radio source asymmetries, we assume that Doppler beam-

ing and orientation are the main factors responsible for the observed asymmetries in radio sources. Neglecting environmental factors in the interpretation of radio source asymmetries might be an oversimplification as it might possibly increase the error in the estimated values. One possible problem is the binning range, so as to obtain equal representation in each bin. In the study of the orientation effect using radio source size (L) and the asymmetry using apparent flux ratio (R) of radio sources, Ubachukwu (1997) argued that the most appropriate form of $R - L$ relationship is the upper envelope to the data which were obtained in three bins of L for a sample of 28 lobe dominated quasars. In our analyses, we binned the sample in 7 ranges of L (kpc): $0 < L \leq 50; 51 \leq L \leq 100; 101 \leq L \leq 200; 201 \leq L \leq 300; 301 \leq L \leq 400; 401 \leq L \leq 700$
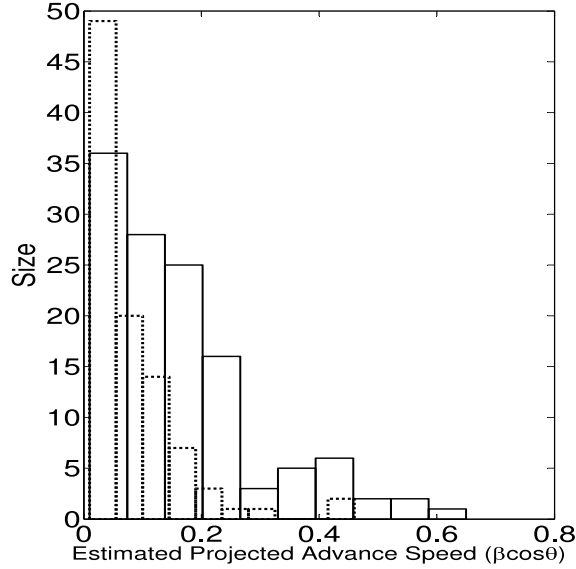
Fig. 3. Distribution plot of estimated speed $\overline{\beta}$ using the R Parameter. Exponential-law model (quasars: solid line; galaxies: dashed line).
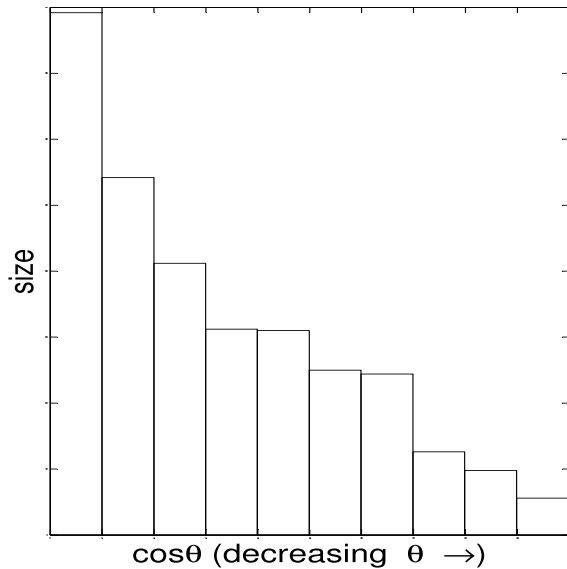

Fig. 4. Plot of random uniformly distributed cosine of inclination angle.

and $L > 701$. For every bin, we obtain the median value for each of the parameters which we used in our analyses. We choose the median value which is a more robust measure of the central tendency than the arithmetic mean, since it minimizes the contributions from outliers.

Our estimated average values of projected hotspot/lobe advance speed ($\overline{\beta}$) based on equations (8), (15), (16), (17), (22) and (23) are shown in Table 1. The histogram plots of the estimated projected speed for the entire sample, quasars and galaxies sub-samples (without binning) are shown in Figures 1–3, respectively. Since the estimated value of $\overline{\beta}$ is not exclusive of θ, the plot of the cosine of randomly uniformly distributed inclination angle is shown in Figure 4, for comparison. We note that the lobe/hotspot advance speed obtained here depends on the level of asymmetry in the source. The error associated with the estimated mean speed could be a result of both random and systematic errors in obtaining the value of the arm-length ratio (Q) and the apparent lobe flux ratio (R). Banhatti (2009) pointed out that these errors broaden the distribution of the estimated lobe/hotspot separation speed.

4. SEARCHING FOR A CORRELATION BETWEEN ESTIMATED PROJECTED SPEED $\overline{\beta}$ AND RADIO SOURCE PARAMETERS: LUMINOSITY (P) AND RADIO SOURCE SIZE (L)

The study of the correlations among various parameters of extragalactic radio sources is important in understanding the physics of radio source components. We carried out correlation analyses to check the dependence of the estimated projected speed ($\overline{\beta}$) on the linear size (L) and the luminosity (P) of the radio sources of our sample.

The correlation coefficient obtained using the speed data estimated from arm-length ratio indicates that $\overline{\beta}$ anti-correlates significantly with radio source size L, with a correlation coefficient $r \sim -0.7$ and chance probability $p = 2.2 \times 10^{-4}$ for all the sources. When the sample was separated into quasars and galaxies we have $r \sim -0.7$ with $p = 6.3 \times 10^{-5}$ and $r \sim -0.5$ with $p = 0.02$ respectively. Similarly, using the apparent lobe luminosity ratio, the estimated hotspot speed ($\overline{\beta}$) shows strong anti-correlation with source size (L), which appears stronger for radioloud quasars than for radio-loud galaxies. For the whole sample, $r \sim -0.6$ with $p \leq 0.003$; for quasars $r \sim -0.6$ with $p \leq 0.001$; while for galaxies we have $r \sim -0.2$ with $p \leq 0.04$ for both power-law model and exponential law model. Hjellming & Han (1995) noted that the speed should decrease as the lobes advance away from the core, probably due to deceleration as the expanding plasmon interacts with the environment, though in estimating the kinematic ages of EGRS (e.g. Gugliucci et al. 2005) the hotspot/lobe advance speed is assumed to remain fairly constant.

The hotspot projected advance speed ($\overline{\beta}$) estimated from the arm-length ratio (Q) also correlates with the radio source luminosity P with $r \sim 0.6$ with $p = 0.009$ for the entire sample, $r \sim 0.7$ with $p = 0.0001$ for quasar sub-sample and $r \sim 0.2$ with $p = 0.06$ radio galaxy sub-sample. There is also a strong correlation between radio luminosity and speed estimated using R generally, with a correlation coefficient $r \sim 0.6$ with $p = 0.003$ for the entire sample, $r \sim 0.6$ with $p = 0.003$ for quasars and $r \sim 0.4$ with $p = 0.03$)for galaxies for the power-law model. Similar results were obtained for the exponential-law model. This result is expected since the more powerful sources are expected to have higher jet power, and thus higher hotspot advance speeds.

5. DISCUSSION AND CONCLUSION

Using the arm-length ratio together with temporal evolution in defining the apparent flux ratio allowed us to obtain the mean advance speed of hotspot/lobe for a sample of extragalactic radio sources. The mean advance speed obtained for all the sources using the arm-length ratio (Q) is $\langle\overline{\beta}\rangle = 0.17 \pm 0.06$. Using the apparent flux ratio (R) the estimated projected advance speed for all the sources is $\langle\overline{\beta}\rangle = 0.28 \pm 0.10$ and $\langle\overline{\beta}\rangle = 0.13 \pm 0.05$ for the power-law and exponential-law model, respectively. These results compare favorably with other work found in the literature (e.g. Banhatti 1980; Liu, Pooley, & Riley 1992; Best et al. 1995; Polatidis and Conway 2003), which show mean velocities $\langle\beta\rangle \geq 0.2$. This is comparable with that obtained using the power-law model for apparent lobe luminosity ratio (Ryś 2000).

Furthermore, our estimated $\langle\overline{\beta}\rangle$ using the Q parameter and that using R for the exponential-law model are comparable with the upper limit $\beta \leq 0.15$ obtained by Scheuer (1995) and Ryś (2000). We point out that one major drawback in using the asymmetry parameters (especially R) to constrain $\overline{\beta} = \beta\cos\theta$ as discussed in Miller-Jones et al. (2004) lies in the expansion mode; by implication the time decay of the flux density may change, if there is transition from retarded to free expansion (Hjellming & Johnston 1988) which may be different for both arms, especially in anisotropic environments. Thus, the values estimated here are average values, though the most important influence on the values of the estimated speed component ($\overline{\beta}$) was induced by the adopted model of brightness evolution of plasma elements.

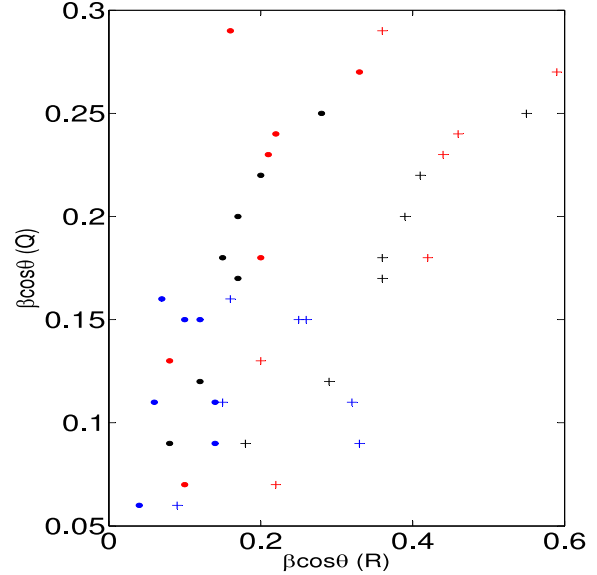In our analysis, we neglected environmental/intrinsic factors in the interpretation of observed

Fig. 5. Plot of $\overline{\beta}(Q)$ vs $\overline{\beta}(R)$ ('+' power-law; circles exponential-law; black: all sources; red: quasars only; blue: galaxies only). The color figure can be viewed online.

asymmetries in radio sources (Ryś 2000; Teerikorpi 2001; Saikia et al. 2002; Gopal-Krishna & Wiita 2004; Jeyakumar et al. 2005), by implication we should expect the advance speed ($\overline{\beta}$) calculated using the arm-length ratio (Q) to correlate with that calculated using the apparent lobe flux ratio (R). The correlation coefficient between these two quantities for all the sources in the sample and also for the quasar sub-sample lies in the range $r \sim 0.77 - 0.81$ with a chance probability $p \sim 2.2 \times 10^{-7} - 1.2 \times 10^{-5}$ for both power-law and exponential-law models. The result for radio galaxies only gives $r \sim 0.5 - 0.6$ with $p \sim 0.01 - 0.02$. The plot of $\overline{\beta}(Q)$ and $\overline{\beta}(R)$ is shown in Figure 5.

Furthermore, beaming theory predicts that the brighter arm should systematically be the longer arm. To check for this trend, we plot the arm-length ratio against the apparent flux ratio (Figure 6). The plot indicates the tendency for longer arm to be brighter, with a correlation coefficient $r \sim 0.8$, which is quite consistent with the beaming hypothesis.

In our formulation, we included the index of decline, which made our definition of apparent flux ratio different from that of the standard formalism. For comparison, we inverted equation (2) and obtained

$$\overline{\beta} = \frac{(R^*)^{\frac{1}{3+\alpha}} - 1}{(R^*)^{\frac{1}{3+\alpha}} + 1} \ . \tag{24}$$
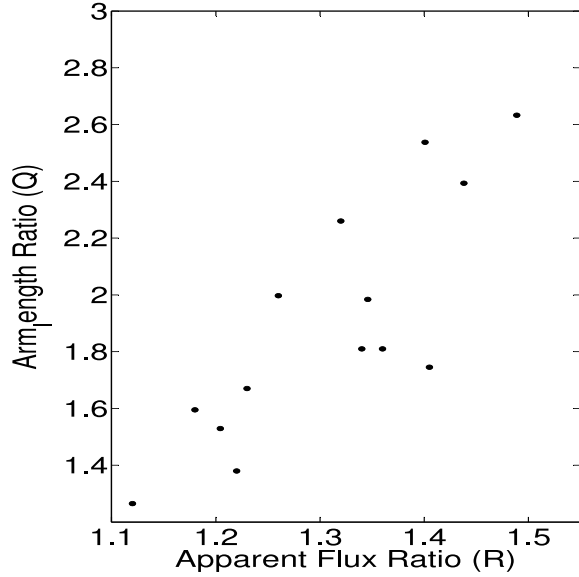
Fig. 6. Plot of arm-length ratio against apparent flux ratio.

Further analysis using the sources in our sample with $R^* > 1$, but with this expression for $\overline{\beta}$ obtained from the standard definition of apparent flux ratio, gives a mean projected advance speed of 0.10 ± 0.05, for all the sources taken together, 0.13 ± 0.05 for quasars only, and 0.07 ± 0.03 for galaxies. These values are on the average statistically less than that those obtained with our re-definition of apparent flux using the power-law model, but similar to the values obtained using the exponential-law model. Miller-Jones et al. (2004) applied an equation similar to our power-law model (equation 15) to the jet flux ratio of Cygnus X-3 and predicted a better value to the observed flux ratio than that obtained from the standard formalism.

The distribution plot shown in Figure 4 indicates that sources appear to preferentially lie on the plane of the sky (small values of $\cos\theta$). By implication, $\overline{\beta}$ will underestimate β exclusive of θ. Thus, our estimated values may be regarded as the lower limit to the true speed in the plane of the sky for these sources.

We point out that the higher projected expansion speeds obtained for quasars than for galaxies do not imply that quasars are generally more powerful that galaxies. A better interpretation is due to the quasars not being oriented preferentially to the plane of the sky (Barthel 1989), and to their being expected to be more asymmetric than they really are. Thus, a higher speed is obtained since our es-

timated speed depends strongly on the value of the asymmetric parameter.

In conclusion, using the model introduced by Ryś (1994, 2000), we obtained an expression that allowed us to estimate the projected lobe/hotspot expansion speed of high luminosity radio sources from their asymmetry parameters. The result obtained shows that the speed estimated from asymmetries depends on the degree of asymmetry, with higher speeds obtained for highly asymmetric sources. The expression we obtained for the lobe luminosity ratio differs from the standard definition, since we included temporal evolution in our scheme. This yields lobe/hotspot advance speed estimates for radio sources comparable to results generally obtained in the literature and suggests that the observed asymmetry in radio sources may be explained as due to Doppler effect, orientation and/or light travel time considerations.

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Onuchukwu C. Chika: Dept of Physics, Anambra State University, Uli, Anambra State, PMB 02, Nigeria (onuchukwu71chika@yahoo.com).

Ubachukwu A. Augustine and Odo C. Finbar: Department of Physics And Astronomy, University of Nigeria Nsukka, Nigeria.