Compact Steep Spectrum Sources: Jet Internal Pressure, Blackhole Power, and Ambient Density

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ABSTRACT

Using analytical methods with some plausible assumptions, we show that if every other factor is kept constant, jet internal pressure (p_j) relates with blackhole power (P_{bh}) and source ambient density (ρ) according to the relation: $p_j \sim m_h P_{bh}^{\phi} \rho^{\theta}$ (where the indices, ϕ and θ are to be determined). Moreover, we obtain the relation, $p_j \sim D^{-2\theta}$, which implies that if we take source observed linear size (D) to be any distance from the central core, then the relation may be interpreted to mean that jet internal pressure falls off with distance from the core. In addition, we obtain a theoretical relation for the projected source linear size. This is given by $D = \left[\left(\frac{kP_{bh}^{\phi}}{p_j}\right)^{\frac{1}{\theta}} \frac{1}{c^3 \Omega \epsilon}\right]^{\frac{1}{2}} P^{-0.5}$; where P is source luminosity, c is speed of light, Ω is jet opening solid angle, ϵ is conversion efficiency of matter into radiation, and k is a constant.

The relation shows that θ may be estimated empirically from $D - P$ plane. Therefore, we carry out linear regression analysis of observed source linear sizes against their individual observed luminosities to find the values of ϕ and θ. Results of the regression shows that linear size relates with luminosity according to the expression, $D \approx 10^{16} P^{-0.6}$. Comparing the indices of the theoretical and empirical relations, we find that while ϕ has positive value, $\theta \approx 0.03$. Therefore, we have jet internal pressure written as $p_j \sim m_h P_{bh}^{\phi} \rho^{0.03}$. This suggestively indicates that the magnitude of jet internal pressure drops as ambient gas density thins out from the core. This shows that jet pressure traces out the source density profile. Therefore, we conclude that jet internal pressure of a compact steep spectrum source has a direct power-law function with its blackhole power and its ambient density according to the relation, $p_j \sim P_{bh}^{\phi} \rho^{\theta}$; where the indices have positive values.

(Keywords: radio jets, luminosity, linear size, radio sources, quasars, blackhole power)

INTRODUCTION

Extragalactic radio jets are collimated (thin and elongated), bipolar (two-sided) outflows shooting out from the central cores of extragalactic radio sources (EGRSs) [1–10]. These jets are believed to serve as conduits through which the lobes are fed with the jet materials [1–10] (Figures 1–2).

Figure (1) delineates the schematics of radio morphological structure of a typical extragalactic radio source on a radio map. The core is the central engine from which the jet is believed to shoot out. The jet traverses immense distances and is brought to a halt at a termination point referred to as the hotspot. Splashes from the hotspot form a radio-emitting cloud which is referred to as the lobe.

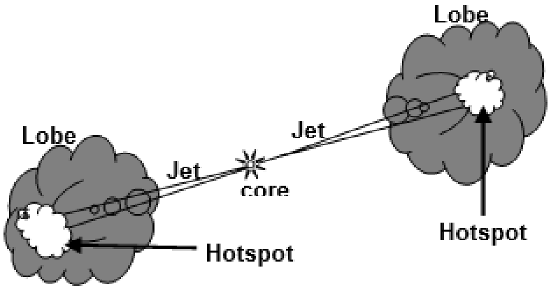

Figure 1: The Schematic Structure of a Typical EGRS. (Source: The author).

Figure 2 is the radio morphological structure of Cygnus A as it appears on the radio map. It shows the structure of a typical extragalactic radio source. The jets are narrow and are observed in a wide variety of EGRSs [11]. Some of these sources are large extended radio sources (e.g., radio galaxies, radio-loud quasars, BL Lacertae objects, etc.) and compact steep-spectrum sources (CSSs).

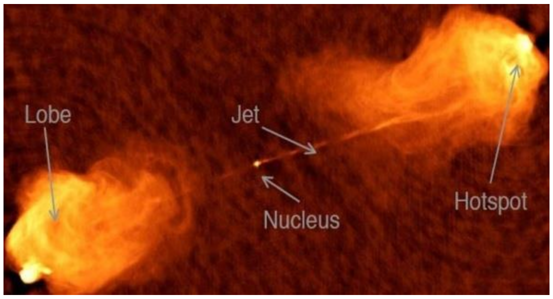

Figure 2: Cygnus A – An EGRS.
(Source: slideplayer.com)

Since jets are believed to serve as conduits through which jet materials propagate, it may be stated that energy and momentum flow through it from the core to the lobe [10–11]. EGRSs are known to show high ratio of radio to optical emission. This ratio is generally defined by the quotient of the two flux densities given by $S_{5\ \mathrm{GHz}}/S_{6\times10^5\mathrm{GHz}} > 10$ [1–4]. The more extended EGRSs have linear sizes, D, given by $D > 30\ \mathrm{Kpc}$ assuming Hubble constant, $H_0 = 75\ \mathrm{kms}^{-1}\mathrm{Mpc}^{-1}$. In all cases, their linear sizes extend into intergalactic media. Their radio luminosities are in excess of 10^{26}Wat$5\ \mathrm{GHz}$ and overall luminosities $(P_{bol} \geq 10^{37}\mathrm{W})$in common with those of the CSSs [1–10].

However, CSS sources are scaled-down versions of the large extended radio sources – their linear sizes are $\leq 20Kpc$. This shows that they are completely encapsulated by their host galaxies. [12–18]. They constitute a remarkable class of radio sources accounting for a substantial fraction of the extragalactic sources selected, especially, at high radio frequencies where the source counts are usually dominated by flat spectrum (spectral index, $\alpha < 0.5, S_\nu \propto \nu^{-\alpha}$; where S_ν is flux density). They are not just cores that show steep spectra, rather they are full-fledged radio galaxies and quasars complete with jets and lobes, but on small scales [12–18]. They have been shown to contain special characteristics that make them be considered as a separate class of objects in addition to lobe- and core-dominated Active Galactic Nuclei (AGNs). They are usually found at high redshifts (generally, they tend to have redshift distribution of $z \leq 4$) and are among high luminosity sources [12–18]. Some authors have wondered on the relationship between CSS sources and the more extended EGRSs. As a result, there are models for the evolution of CSS sources in the literature. These include Youth Scenario (i.e., young evolving sources), Frustration Scenario (i.e., sources confined by ambient dense gases), Relativistic Beaming, and Orientation Effects (i.e., the source sizes are foreshortened by orientation and projection effects) [19–20].

It is generally believed that presence of jets in radio sources simply suggests presence of gaseous ambient media [5-10]. Ezeugo and Ubachukwu (2010) [17] have shown that their observed spectral turnovers simple trace their density profile. They also created a model for evolution of CSS sources and used it to estimate their ambient densities. Furthermore, some hydrodynamic simulations of jet propagations have been carried out by some authors to examine physical states of EGRSs generally [5–7]. These studies show that jet materials have smaller masses than those of the ambient medium.

In this work, we use both analytical and statistical methods to find a relation that connects jet internal pressure, blackhole power, and the ambient medium density of the CSS source. This is important because it will go a long way to explain the propagation of the jet-lobe system through its dense ambient medium. The CSS sources used in this work are CSS quasars obtained from O'Dea (1998) [16]. They include 37 quasars.

JET INTERNAL PRESSURE AND POWER OF BLACKHOLE

The standard beam model for EGRS in general states that jet materials (presumably electrons) are ejected from the central core [7, 21]. They plough their way through the ambient medium until they terminate with strong shocks (i.e., hotspots) which are thermalized to form lobes [7, 21]. Therefore, dynamical expansion of a radio source jet should be expected to depend (in addition to other factors) on the following: (i) power supplied by the core to the jet (or blackhole power), (ii) the source age, and (iii) the nature of the ambient medium through which it propagates.

Hence, we can write:

$$L_j \sim P_{bh}^{\gamma} t^{\mu} \rho^{\sigma} \qquad (1)$$

where L_j = projected length of radio jet
P_{bh} = power of the blackhole residing in the core
ρ = density of externa/ambient medium
t = time.

The superscripts are yet to be determined.

Assuming a uniform medium, jet velocity may be defined as:

$$v_j = \frac{dL_j}{dt} \qquad (2)$$

This gives:

$$t = \int_{t_1}^{t_2} \frac{dL_j}{v_j} \qquad (3)$$

Combining Equations (1) and (3), yields:

$$L_j \sim P_{bh}^{\gamma} \rho^{\sigma} \left(\int_{t_1}^{t_2} \frac{dL_j}{v_j} \right)^{\mu} \qquad (4)$$

For simplicity, we assume ram-pressure balance between the jet and the ambient medium; therefore, we have [15, 21]:

$$p_j \approx \rho m_h v_j^2 \qquad (5)$$

where p_j = jet internal pressure
m_h = hydrogen mass.

Or for jet velocity, we obtain:

$$v_j \approx \sqrt{\frac{p_j}{\rho m_h}} \qquad (6)$$

From Equations (4) and (6), we have:

$$L_j \sim P_{bh}^{\gamma} \rho^{\sigma} \left(\int_{t_1}^{t_2} \sqrt{\frac{\rho m_h}{p_j}} \, dL_j \right)^{\mu} \qquad (7)$$

For the jet internal pressure, the last equation becomes:

$$\sqrt{\frac{\rho m_h}{p_j}} \sim \frac{d\left(\frac{L_j}{P_{bh}^{\gamma} \rho^{\sigma}} \right)^{\frac{1}{\mu}}}{dL_j} \qquad (8)$$

Or, we obtain:

$$p_j \sim \rho m_h \left[\frac{dL_j}{d\left(\frac{L_j}{P_{bh}^{\gamma} \rho^{\sigma}} \right)^{\frac{1}{\mu}}} \right]^{0.5} \qquad (9)$$

Assuming:

$$\frac{d\left(\frac{L_j}{P_{bh}^{\gamma} \rho^{\sigma}} \right)^{-\frac{1}{\mu}}}{dL_j} \approx \left(P_{bh}^{\gamma} \rho^{\sigma} \right)^{-\frac{1}{\mu}} \qquad (10)$$

then, Equations (9) becomes:

$$p_j \sim \rho m_h \left| \left(P_{bh}^{\gamma} \rho^{\sigma} \right)^{-\frac{1}{\mu}} \right|^{0.5} \qquad (11)$$

In simple terms, we have:

$$p_j \sim \rho m_h P_{bh}^{-\frac{\gamma}{2\mu}} \rho^{-\frac{\sigma}{2\mu}} \qquad (12)$$

Or,

$$p_j \sim m_h P_{bh}^{\phi} \rho^{\theta} \qquad (13)$$

where $\phi = -\frac{\gamma}{2\mu}$, and
$\theta = \frac{2\mu - \sigma}{2\mu}$

The last equation can be interpreted to mean that if every other factor is constant, jet internal pressure depends on the source blackhole power and the density of the ambient medium.

JET INTERNAL PRESSURE AND DISTANCE FROM THE CORE

It can be shown (theoretically and empirically) that source luminosity is attenuated by the particles of the medium as distance from the core increases. This is given by:

$$P \approx (m_h c^3 \Omega \epsilon)^{-1} \frac{1}{D^2 \rho} \qquad (14)$$

where $P =$ source luminosity
$c =$ speed of light
$\Omega =$ jet opening solid angle
$D =$ source linear size
$\epsilon =$ conversion efficiency of matter into radiation.

Combining Equations (13) and (14), yields:

$$p_j \sim P_{bh}^{\phi} \left(\frac{1}{c^3 \Omega D^2 \epsilon P} \right)^{\theta} \qquad (15)$$

Let k be an unknown constant; hence, (15) becomes:

$$p_j = k P_{bh}^{\phi} \left(\frac{1}{c^3 \Omega D^2 \epsilon P} \right)^{\theta} \qquad (16)$$

If we take D to be any distance from the central core, then the last equation shows that jet internal pressure falls with distance from the core according to the relation:

$$p_j \sim D^{-2\theta} \qquad (17)$$

Furthermore, solving for source projected linear size, we have:

$$D = \left[\left(\frac{k P_{bh}^{\phi}}{p_j} \right)^{\frac{1}{\theta}} \frac{1}{c^3 \Omega \epsilon P} \right]^{\frac{1}{2}} \qquad (18)$$

Hence, we get:

$$D = \left[\left(\frac{k P_{bh}^{\phi}}{p_j} \right)^{\frac{1}{\theta}} \frac{1}{c^3 \Omega \epsilon} \right]^{\frac{1}{2}} P^{-0.5} \qquad (19)$$

Equation (19) clearly indicates that θ may be estimated from $D - P$ plane.

SIZE/LUMINOSITY RELATIONSHIP

We carry out linear regression analysis of observed source linear sizes against their individual observed luminosities (Figure 3).

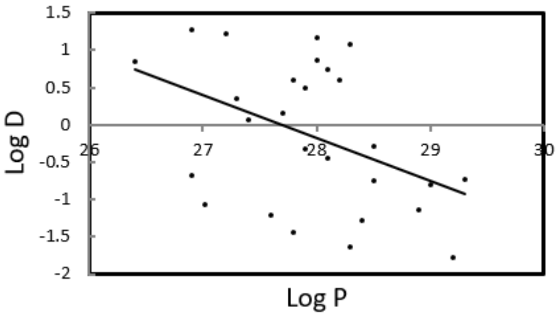

Figure 3: The Scatter Plot of Source Observed Linear Sizes against Observed Luminosities.

Result of the regression shows that D relates with P according to the expression:

$$\text{Log}D = -0.57 \text{Log}\, P + 15.88 \qquad (20)$$

The correlation is appreciable with coefficient, $r = 0.43$; therefore, we may rewrite (20) as:

$$D = 7.59 \times 10^{15} P^{-0.6} \qquad (21)$$

Or to the nearest 10, we have:

$$D \approx 10^{16} P^{-0.6} \qquad (22)$$

Equating the indices of the terms in brackets in (19) and (22), we obtain:

$$\theta \approx 0.03 \qquad (23)$$

while ϕ is a positive number.

Combining this with Equation (13), gives:

$$p_j \sim m_h P_{bh}^{\phi} \rho^{0.03} \qquad (24)$$

This indicates that the magnitude of jet internal pressure reduces as ambient gas density thins out from the core; showing that jet pressure traces out the source density profile.

DISCUSSION AND CONCLUSION

Using analytical methods with some plausible assumptions in the previous sections, we showed from Equations (1), (2), and (5) that jet internal pressure relates with blackhole power and source ambient density according to the relation: $p_j \sim m_h P_{bh}^{\phi} \rho^{\theta}$ (where $\phi = -\frac{\gamma}{2\mu}$, and $\theta = \frac{2\mu - \sigma}{2\mu}$). It suggests that if every other factor is constant, jet internal pressure depends on the source blackhole power and the density of the ambient medium.

Moreover, using Equations (13) and (14), we obtained the relation, $p_j = kP_{bh}^{\phi}\left(\frac{1}{c^3\Omega D^2\epsilon P}\right)^{\theta}$. The relation implies that if we take D to be any distance from the central core, then the equation suggests that jet internal pressure falls with distance from the core according to the relation, $p_j \sim D^{-2\theta}$. Furthermore, we obtained solving for source projected linear size, that $D = \left[\left(\frac{kP_{bh}^{\phi}}{p_j}\right)^{\frac{1}{\theta}}\frac{1}{c^3\Omega\epsilon}\right]^{\frac{1}{2}} P^{-0.5}$; which shows that θ may be estimated from $D - P$ plane.

Therefore, we carried out linear regression analysis of observed source linear sizes against their individual observed luminosities (Figure 3). The correlation is appreciable with coefficient given by $r = 0.43$. Result of the regression shows that linear size relates with luminosity according to the expression, $D \approx 10^{16}P^{-0.6}$. Equating the indices of the terms in brackets in (19) and (22), we obtain $\theta \approx 0.03$. Combining it finally with (13), gives $p_j \sim m_h P_{bh}^{\phi}\rho^{0.03}$. This indicates that the magnitude of jet internal pressure falls off as ambient gas density thins out from the core; showing that jet pressure traces out the source density profile.

In conclusion, we have used both analytical and statistical methods to show that the internal pressure of a compact steep spectrum source has a power-law function with its blackhole power and its ambient density according to the relation, $p_j \sim P_{bh}^{\phi}\rho^{\theta}$; where the indices assume positive values.

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