__ORIGINAL RESEARCH ARTICLE__

ON THE CENTRAL ENGINE OF THE COMPACT STEEP SPECTRUM SOURCE AND SOURCE PHENOMENA

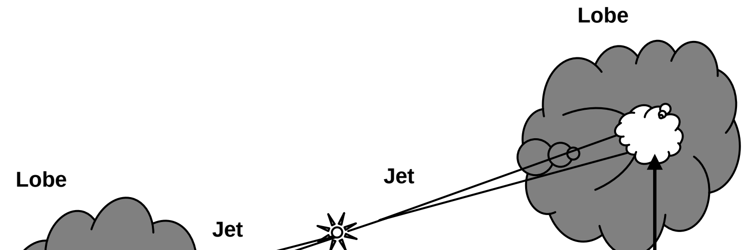
Abstract

In this paper, with some plausible assumptions we use analytical methods and statistical methods to show that the central engine (which presumably houses a super massive blackhole) of a typical compact steep spectrum source fuels the source observed physical phenomena. With analytical methods, we show that the power of the source central engine ($\mathcal{P}_{\mathcal{C}\mathcal{E}}$) relates with some source observable parameters according to the relation, $\mathcal{P}_{\mathcal{C}\mathcal{E}} = \mathrm{Q}\left(\frac{1}{\mathrm{m_h c^3 \Omega \epsilon D^2 P}}\right)^{\beta} \mathrm{p_j^{\psi}}$ (where $\mathrm{m_h}$is mass of hydrogen nucleus, c is speed of light, Ω is jet opening solid angle, ϵ is conversion efficiency of matter into radiation, D is source linear size, P is source luminosity, $\mathrm{p_j}$is jet internal pressure, and Q is a constant). The indices, β and ψ, are to be estimated. In order to semi-empirically obtain estimates of the values of the indices, we carry out linear regression analysis of source linear sizes (D) against their corresponding luminosities (P). Results show that $\beta \approx 0.031$, while $\psi = 32$ is a positive integer. Hence, the aforementioned relation may be re-written as $\mathcal{P}_{\mathcal{C}\mathcal{E}} \sim \left(\frac{1}{\mathrm{m_h c^3 \Omega \epsilon D^2 P}}\right)^{0.031} \mathrm{p_j^{32}}$. This expression may be interpreted to mean that if some external factors are held fixed, the source central engine fuels/powers the observed physical properties/phenomena of the CSS source.

Keywords: central engine, radio jets, luminosity, linear size, radio sources, quasars, steep spectrum

1. 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]. These jets are believed to serve as conduits through which the lobes are fed with the jet materials [1,2,3,4] (see Figures 1–2). Figure (1) shows the schematics of radio morphology 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 distance 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 [1,2,3,4,5,6].



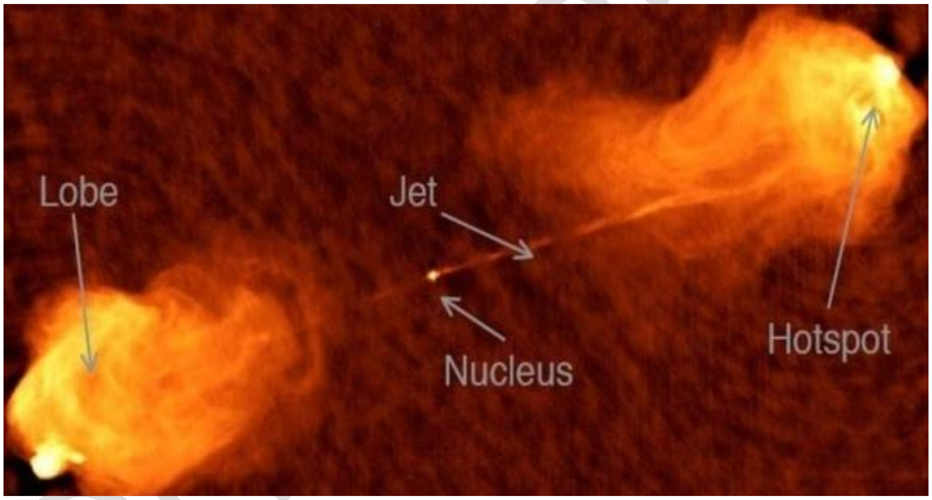


Figure 2: Cygnus A – An EGRS.
Source: slideplayer.com

Figure 2 shows the radio morphology of Cygnus A as it appears on the radio map. It shows the structure of a typical extragalactic radio source. The central engine is the nucleus. The jets are narrow and are observed in a wide variety of EGRSs [1,2,3,4,5,6,7,8,9]. 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) [1,2,3,4].

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 (or central engine / nucleus) to the lobe [1,2,3,4,5,6,7,8,9]. 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 $S_{5\ \mathrm{GHz}}/S_{6\times10^{5}\mathrm{GHz}} > 10$ [1,2,3,4,5,6,7,8,9]. The more extended EGRSs have linear sizes, D, given by $D > 30$ 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}W at 5 GHz and overall luminosities ($P_{bol} \geq 10^{37}$W) in common with those of the CSSs [1,2,3,4,5,6,7,8,9].

However, CSS sources are scaled-down versions of the large extended radio sources – their linear sizes are generally defined to be $\leq 30Kpc$. This shows that they are completely encapsulated by their host galaxies [2,3,10,11,12]. 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 [2,3,10,11,12,13]. 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 [2,3,10,11,12,13,14]. 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) [2,3,10,11,12,13,14,15].

It is generally believed that presence of jets in radio sources simply suggests presence of gaseous ambient media. Studies have shown that their observed spectral turnovers simple trace their density profile [1,2,3,4,5,6,7,8,9,15]. Authors have 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 [6,15]. These studies show that jet materials have smaller masses than those of the ambient medium.

2. Analyses

Here, with some plausible assumptions, we use analytical methods and statistical methods to show that the central engine (which presumably encapsulates a super massive blackhole) of a typical compact steep spectrum source drives the source observed physical phenomena. The CSS sources used in this work are CSS quasars obtained from [12]. They are 37 quasars.

2.1. Power of the Central Engine

The standard beam model for EGRS in general states that jet materials (presumably electrons) are ejected from the central engine [2,3,10,11,12,13,14,15]. They plough their way through the ambient medium until they terminate with strong shocks (i.e. hotspots) which are thermalized to form lobes [2,3,10,11,12,13,14,15,16]. Therefore, dynamical evolution of a radio source should be expected to depend (in addition to other factors) on the following factors: (i) power of the central engine, (ii) time, and (iii) the density of the ambient medium. Hence, we can write

$$D \sim \mathcal{P}_{\mathcal{C}\mathcal{E}}^{\gamma}\mathcal{T}^{\mu}\rho^{\sigma} \qquad (1)$$

where D is projected source linear size, $\mathcal{P}_{\mathcal{C}\mathcal{E}}$ is power of the central engine, ρ is density of ambient medium, $\mathcal{T}$ is time. The indices are not yet known. Assuming a uniform medium, jet velocity, v_j, may be defined as

$$v_j = \frac{dD}{d\mathcal{T}} \qquad (2)$$

So that source age may be expressed as

$$\mathcal{T} = \int_{\mathcal{T}_1}^{\mathcal{T}_2} \frac{dD}{v_j} \qquad (3)$$

where t_1 represents the time jet materials started shooting out from the central engine; while t_2 represents the present epoch. From equations (1) and (3), we obtain

$$D \sim \mathcal{P}_{\mathcal{C}\mathcal{E}}^{\gamma} \rho^{\sigma} \left(\int_{\mathcal{T}_1}^{\mathcal{T}_2} \frac{dD}{v_j} \right)^{\mu} \qquad (4)$$

For simplicity, we assume ram-pressure balance between the jet and the ambient medium; therefore, we have (Ezeugo and Ubachukwu 2010, Fanti *et al.* 1995, O'Dea 1998)

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

where p_j is jet internal pressure, m_h is hydrogen mass.

Or for jet velocity, we obtain

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

Combining equations (4) and (6), we have

$$D \sim \mathcal{P}_{\mathcal{C}\mathcal{E}}^{\gamma} \rho^{\sigma} \left(\int_{\mathcal{T}_1}^{\mathcal{T}_2} \sqrt{\frac{\rho m_h}{p_j}}\, dD \right)^{\mu} \qquad (7)$$

$$\sqrt{\frac{\rho m_h}{p_j}} \sim \frac{d\left(\frac{D}{\mathcal{P}_{\mathcal{C}\mathcal{E}}^{\gamma} \rho^{\sigma}}\right)^{\frac{1}{\mu}}}{dD} \qquad (8)$$

Assuming

$$\frac{d\left(\frac{D}{\mathcal{P}_{\mathcal{C}\mathcal{E}}^{\gamma} \rho^{\sigma}}\right)^{\frac{1}{\mu}}}{dD} \approx \left(\mathcal{P}_{\mathcal{C}\mathcal{E}}^{\gamma} \rho^{\sigma}\right)^{-\frac{1}{\mu}} \qquad (9)$$

then, (8) becomes

$$\sqrt{\frac{\rho m_h}{p_j}} \sim \left(\mathcal{P}_{\mathcal{C}\mathcal{E}}^{\gamma} \rho^{\sigma}\right)^{-\frac{1}{\mu}} \qquad (10)$$

Solving for the power of the central engine, we obtain

$$\mathcal{P}_{\mathcal{C}\mathcal{E}} \sim \rho^{-\frac{\sigma}{\gamma}} \left(\frac{\rho m_h}{p_j}\right)^{-\frac{\mu}{2\gamma}} \qquad (11)$$

Or in simple terms, we may write

$$\mathcal{P}_{\mathcal{C}\mathcal{E}} \sim \rho^{-\left(\frac{2\sigma+\mu}{2\gamma}\right)} p_j^{\frac{\mu}{2\gamma}} \qquad (12)$$

where hydrogen mass, m_h, is a constant. If we let $\beta = -\left(\frac{2\sigma+\mu}{2\gamma}\right)$ and $\psi = \frac{\mu}{2\gamma}$, the last equation becomes

$$\mathcal{P}_{\mathcal{C}\mathcal{E}} \sim \rho^{\beta} p_j^{\psi} \tag{13}$$

Equation (13) may be interpreted to mean that if every other factor is constant, the radio jet derive its power from the central engine; while the magnitude of the power of the central engine depends on the density of the source ambient medium.

2.2. Size/Luminosity Relation (Theory)

We can show semi-empirically that source luminosity is attenuated by the particles of the medium as distance from the central engine increases; this is given by

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

where P is source luminosity, c is speed of light, Ω is jet opening solid angle, D is source linear size, ϵ is conversion efficiency of matter into radiation. Combining (13) and (14), yields

$$\mathcal{P}_{\mathcal{C}\mathcal{E}} \sim \left(\frac{1}{m_h c^3 \Omega \epsilon D^2 P}\right)^{\beta} p_j^{\psi} \tag{15}$$

Equation (15) also shows that the magnitudes of source size and luminosity depend on the power of the central engine. This may be expressed as

$$\mathcal{P}_{\mathcal{C}\mathcal{E}} \sim (D^2 P)^{\beta} \tag{16}$$

where the indices in equations (15) and (16) are to be determined.

Let Q be an unknown constant; therefore, (15) can be rewritten as

$$\mathcal{P}_{\mathcal{C}\mathcal{E}} = Q \left(\frac{1}{m_h c^3 \Omega \epsilon D^2 P}\right)^{\beta} p_j^{\psi} \tag{17}$$

Furthermore, solving for source projected linear size, we have

$$D = \left[\frac{1}{m_h c^3 \Omega \epsilon} \left(\frac{\mathcal{P}_{\mathcal{C}\mathcal{E}}}{Q p_j^{\psi}}\right)^{\frac{1}{\beta}}\right]^{\frac{1}{2}} P^{-0.5} \tag{18}$$

The last equation simply suggests that β may be estimated from $D - P$ data.

2.3. Size/Luminosity Relation (Empirical)

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

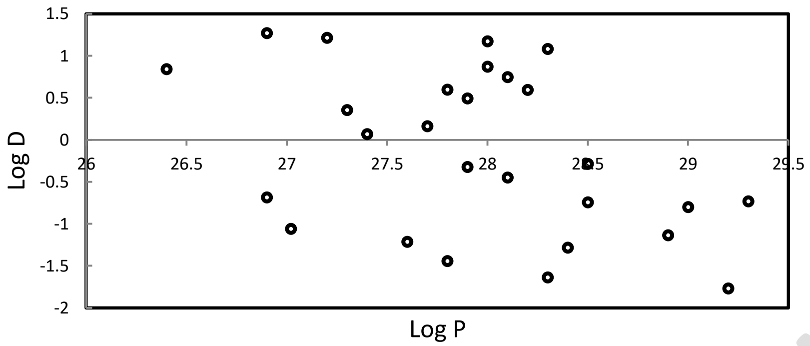


Figure 3: The scatter plot of source observed linear sizes against observed luminosities

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

$$\mathrm{Log}D = -0.57\mathrm{Log}\,P + 15.88 \qquad (19)$$

The correlation is appreciable with coefficient, $r = 0.43$; therefore, we may re-write equation (20) as

$$D = 7.59 \times 10^{15} P^{-0.6} \qquad (20)$$

Or to the nearest 10, we have

$$D \approx 10^{16} P^{-0.6} \qquad (21)$$

Equating the indices of the terms in brackets in (18) and (21), we obtain

$$\beta \approx 0.0313 \qquad (22)$$

while $\psi = 32$ is a positive integer.

Combining this with (17), gives

$$\mathcal{P}_{\mathcal{CE}} = Q\left(\frac{1}{m_h c^3 \Omega \epsilon D^2 P}\right)^{0.031} p_j^{32} \qquad (23)$$

This expression may be interpreted to mean that in absence of external factors, the source central engine fuels the observed physical properties of the CSS source.

2.4. Discussion

Using analytical method with some plausible assumptions in the previous sections, we show from equation (1) to equation (15) that the source central engine relates with some source observable parameters according to the relation (equation (7)), i.e. $\mathcal{P}_{\mathcal{CE}} = Q\left(\frac{1}{m_h c^3 \Omega \epsilon D^2 P}\right)^{\beta} p_j^{\psi}$; where the indices are to be estimated and the symbols have their usual meanings. In order to empirically estimate the values of the indices, β and ψ, we re-write the expression as $D = \left[\frac{1}{m_h c^3 \Omega \epsilon}\left(\frac{\mathcal{P}_{\mathcal{CE}}}{Q p_j^{\psi}}\right)^{\frac{1}{\beta}}\right]^{\frac{1}{2}} P^{-0.5}$. We carry out linear regression analysis of source linear sizes (D) against their correspondence luminosities (P) to obtain equation (21) (i.e. $D \approx 10^{16} P^{-0.6}$). Equating the indices of the terms in brackets in equations (18) and (21), we estimate $\beta \approx 0.031$, while $\psi = 32$ is a positive integer. Combining this with equation (17), gives $\mathcal{P}_{\mathcal{CE}} = Q\left(\frac{1}{m_h c^3 \Omega \epsilon D^2 P}\right)^{0.031} p_j^{32}$. This expression may be interpreted to mean that in absence of external factors, the source central engine fuels the observed physical properties of the CSS source. This is in consonance with the general notion that the central engines of active galaxies house super massive blackholes [2,3,10,11,12,13,14,15].

2.5. Conclusion

In conclusion, we have used both analytical and statistical methods to show that the power of the source central engine relates with some source observed physical properties according to the relation, $\mathcal{P}_{\mathcal{C}\mathcal{E}} \sim \left(\frac{1}{m_h c^3 \Omega \epsilon D^2 P}\right)^{0.031} p_j^{32}$. This relation possibly shows that the central engine produces the power which shows up in the observed physical phenomena. This is expected to be true if some external factors are constant. This supports the presence of blackholes presumed by authors to be present at the central cores/nuclei of active galaxies (see [2,3,10,11,12,13,14,15]).

COMPETING INTERESTS DISCLAIMER:

Authors have declared that no competing interests exist. The products used for this research are commonly and predominantly use products in our area of research and country. There is absolutely no conflict of interest between the authors and producers of the products because we do not intend to use these products as an avenue for any litigation but for the advancement of knowledge. Also, the research was not funded by the producing company rather it was funded by personal efforts of the authors.

References

1. Robson I. (1996) Active Galactic Nuclei, John Wiley and Sons Ltd, England.
2. Ezeugo J.C. (2021a) On the Components of Large Extended Extragalactic Radio Sources, The Pacific Journal of Science and Technology **22** (1), 20–23.
3. Ezeugo J.C. (2021b) On the Intergalactic Media Densities & Dynamical Ages of Some Powerful Radio Sources and Implications, Journal of Physical Sciences and Application **11** (1), 29–34.
4. Readhead A.C. (1995) Evolution of Powerful Extragalactic Radio Sources. In proc. Colloquium on Quasars and Active Galactic Nuclei, ed. Kohen, M., and Kellermann, K. (USA: National Academy of Sciences, Berkman Center, Irvine) **92**, 11447–11450.
5. Jackson J.C. (1999) Radio Source Evolution and Unified Schemes, Publications of Astronomical Society of the Pacific **16**, 124–129.
6. Kawakatu N. and Kino M. (2007) The Velocity of Large-scale Jets in a Declining Density Medium. In Serie de Conferencias. Triggering Relativistic Jets, ed. W.H. Lee and E. Ramirez-Ruiz **27**, 192–197.
7. Mahatma V.H., Hardcastle M.J. and Williams W.L. (2019) LoTSS DR1: Double-double Radio Galaxies in the HETDEX Field, Astronomy and Astrophysics **622**, A13.
8. Mingo B., Croston J.H. and Hardcastle M.J. (2019) Revisiting the Fanaroff-Riley Dichotomy and Radio Galaxy Morphology with the LOFAR Two-Meter Sky Survey (LoTSS), Monthly Notices of the Royal Astronomical Society **488**, 2701-2721.
9. Hardcastle W.L., Williams W.L. and Best P.N. (2019) Radio-loud AGN in the First LoTSS Data Release — The Lifetimes and Environmental Impact of Jet-Driven Sources, Astronomy and Astrophysics **622**, A12.

10. Ezeugo J.C. (2021c) Compact Spectrum Source Size and Cosmological Implication, Journal of Research in Applied Mathematics **7**(2), 1–4.
11. Ezeugo J.C. (2021d) Jet in the More Extended Radio Sources and Unification with Compact Steep Spectrum Sources, The Pacific Journal of Science and Technology **22**, 14 – 19.
12. O'Dea C.P. (1998) The Compact Steep Spectrum and Gigahertz Peaked Spectrum Radio Sources, Publications of the Astronomical Society of the Pacific **110**, 493–532.
13. Fanti C., Fanti R., Dallacasa D., Schillizzi R.T., Spencer R.E. and Stanghellini C. (1995) Are compact steep spectrum sources young, Astronomy and Astrophysics **302**, 317–326.
14. Urry C.M. (2004) AGN Unification: An Update, Astronomical Society of the Pacific conference series 1. No vol.
15. Ezeugo J.C. and Ubachukwu A.A. (2010) The Spectral Turnover–Linear Size Relation and the Dynamical Evolution of Compact Steep Spectrum Sources, Monthly Notices of the Royal Astronomical Society **408**, 2256–2260.
16. Hardcastle W.L., Williams W.L. and Best P.N. (2019) Radio-loud AGN in the First LoTSS Data Release — The Lifetimes and Environmental Impact of Jet-Driven Sources, Astronomy and Astrophysics, **622**, A12.