Physical Science International Journal

25(2): 20-25, 2021; Article no.PSIJ.68307
ISSN: 2348-0130

Extragalactic Radio Sources: Jet/Lobe Internal Pressure and Consequences

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Author's contribution

The sole author designed, analyzed, interpreted and prepared the manuscript.

Article Information

DOI: 10.9734/PSIJ/2021/v25i230241
Editor(s):
(1) Dr. Humaira Yasmin, King Faisal University, Saudi Arabia.
(2) Dr. Thomas F. George, University of Missouri-St. Louis, USA.
Reviewers:
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(2) Sie Long Kek, Universiti Tun Hussein Onn Malaysia, Malaysia.
(3) Lucas Antonio Caritá, Federal Institute of São Paulo, Brazil.
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Complete Peer review History: http://www.sdiarticle4.com/review-history/68307

Original Research Article

Received 18 March 2021
Accepted 22 May 2021
Published 27 May 2021

ABSTRACT

In this work, we use analytical methods to describe expansion of Extragalactic Radio Sources (EGRS). Result shows that source size expansion depends on the following parameters: age of the source, lobe internal pressure, ambient medium density, and angle of observation.

Moreover, from the analyses, we have shown that the obtained results, $\mathcal{D}_n \approx (0.486t)v_j$ and $\mathcal{D}_n \approx t\sqrt{\frac{p_l}{p_j}}v_j$, suggestively implies that $p_l \approx 0.236p_j$ and $v_l \approx 0.486v_j$. This shows that since $\frac{v_l}{v_j} < 1$, jet internal pressure exceeds the lobe's internal pressure. Therefore, for a typical EGRS, this simply indicates that ambient medium density is higher in the jet region than in the region of the lobe. This is expected since the ambient density thins out from the central core to the region where lobe is located. It is in consonance with the notion that for large extended EGRS, lobes are located outside the host galaxies rather than within the host galaxies. Moreover, we can conclude from these results that compact steep spectrum sources have denser ambient medium than their more extended counterparts.

Keywords: Radio sources; ambient density; radio jet; radio lobe; source age; galaxies.

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1. INTRODUCTION

Extragalactic radio sources (EGRS) are located beyond the confines of our home galaxy – the Milky Way. They are known to radiate more copious amount of power in the radio frequencies than in the optical frequencies [1]. This is defined by the ratio of the two flux densities, $S_{5\,\mathrm{GHz}}/S_{6\times10^5\,\mathrm{GHz}} > 10$ [1]. They are made up of radio galaxies, radio-loud quasars, BL Lacertae objects, and compact steep spectrum sources (CSS) [2–4]. Radio morphological structures of these sources usually take the form of two opposite sided relativistic jets that connect the base of the accretion disk to two radio-emitting lobes that straddle the central core, believed to be the central engine [2]. This central core is thought to be more or less coincident with the nucleus of the host galaxy [3,5-7]. In some sources, the lobes contain hotspots believed to be the termination points of the jets [3,5-7].

Moreover, presence of jets in radio sources simply suggests presence of gaseous ambient media [5]. A number of hydrodynamic simulations of jet propagations have been performed to examine their physical state [5–6]. These studies show that jet materials have smaller masses than those of the ambient medium. This simply implies that jet materials are most likely electrons.

Furthermore, Compact steep spectrum sources (CSS) actually are full-fledged, but scale-down versions of larger EGRS. Their properties are as follows [8–9]: their observed linear sizes, $D \leq 20\,\mathrm{kpc}$; they consist of both radio galaxies and radio-loud quasars but on sub-galactic dimensions; they show steep spectra ($\alpha \geq 0.5, S_\nu \sim \nu_p^\alpha$) at high frequencies (e.g. $\geq 0.02\,\mathrm{GHz}$) from the entire radio morphological structures; they have high radio luminosities, $P_{5\,\mathrm{GHz}} \geq 10^{21}$ W; and overall luminosities, $P_{bol} \geq 10^{37}$ W.

In the literature, some authors have discussed on the connection between CSS sources and the more extended EGRS. 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) [8–10].

In this work, we use analytical methods with some plausible assumptions to obtain a mathematical model that may explain the expansion of these radio sources. Moreover, we use observed data for empirical values. The radio sources used in the analyses were obtained from [11]. They are made up of 31 EGRS (radio galaxies) with linear sizes, $D > 30\,\mathrm{kpc}$. These sources are those whose jets have estimated velocities from [12].

2. SOURCE GROWTH

In the standard beam model for EGRS, jets of relativistic plasma are ejected from the parent galaxy which plough their way through the ambient medium until they terminate with strong shocks (hotspots) which are thermalized to form lobes [6]. The evolution of a radio source component is therefore expected to depend (among other factors) on the power supplied by the core to the jet, the source age, and the nature of the ambient medium through which it propagates.

We may write lobe velocity kinematically as

$$v_l dt = d\mathcal{D}_n \qquad (1)$$

where dt is the time frame at which the source grows to the size $d\mathcal{D}_n$ and v_l is lobe velocity. Assuming elastic collision between jet and lobe (and a head-on collision, in which all the velocities lie along the same line; i.e. angular difference between the direction of initial velocity and direction of final velocity is zero), we have from energy conservation principle that

$$m_j v_{j1}^2 + m_l v_{l1}^2 = m_j v_{j2}^2 + m_l v_{l2}^2 \qquad (2)$$

where m_l is mass of lobe, m_j is mass of jet that takes part in the collision with the lobe, v_j is velocity of jet, v_l is velocity of lobe. The subscripts “1” and “2” represent “before” and “after” collisions respectively.

Similarly, from conservation of momentum, we have

$$m_j v_{j1} + m_l v_{l1} = m_j v_{j2} + m_l v_{l2} \qquad (3)$$

For simplicity, let’s assume that the velocity of the lobe before the considered collision is zero. Therefore, equations (2) and (3) yield

$$m_j v_{j1}^2 = m_j v_{j2}^2 + m_l v_{l2}^2 \qquad (4)$$

And

$$m_j v_{j1} = m_j v_{j2} + m_l v_{l2} \qquad (5)$$

respectively. Rearranging equation (4), gives

$$m_l v_{l2}^2 = m_j\left(v_{j1}^2 - v_{j2}^2\right) \tag{6}$$

Also, rearranging equation (5) we obtain

$$m_l v_{l2} = m_j\left(v_{j1} - v_{j2}\right) \tag{7}$$

The quotient of equations (6) and (7) yields

$$v_{l2} = v_{j1} + v_{j2} \tag{8}$$

Combining equations (7) and (8), we have

$$m_l\left(v_{j1} + v_{j2}\right) = m_j\left(v_{j1} - v_{j2}\right) \tag{9}$$

which implies that

$$v_{j2} = \left(\frac{m_j - m_l}{m_j + m_l}\right) v_{j1} \tag{10}$$

Putting this in equation (8), gives

$$v_{l2} = v_{j1} + \left(\frac{m_j - m_l}{m_j + m_l}\right) v_{j1} \tag{11}$$

Or, we obtain

$$v_l = \left(\frac{2m_j}{m_j + m_l}\right) v_j \tag{12}$$

where v_{l2} and v_{j1} have been replaced with v_l and v_j respectively. Simplifying further, we obtain

$$v_l = \mu v_j \tag{13}$$

where $\mu = \frac{2m_j}{m_j+m_l}$

Putting equation (13) in equation (1), we obtain

$$d\mathcal{D}_n = \mu v_j dt \tag{14}$$

Considering the source kinematic age, t, equation (14) becomes

$$\mathcal{D}_n = \mu v_j t \tag{15}$$

It is worthy of notation that jet particles decelerate as they collide with the particles of the lobe [3,5-7]. Therefore Jet velocity is expected to be greater than lobe velocity. Thus, we have

$$\mu < 1 \tag{16}$$

This indicates that mass of jet is less than mass of lobe.

3. SOURCE OBSERVING ANGLE

Here, we want to incorporate the angle of observation; hence, we apply Relativistic Beaming and Orientation Effects. This suggests that the observed linear size ($\mathcal{D}$) of the source should relate with the angle of observation (ϕ) according to the equation,

$$\mathcal{D} = \mathcal{D}_n \sin\phi \tag{17}$$

Therefore combining equations (15) and (17), we obtain

$$\mathcal{D} = \mu v_j t \sin\phi \tag{18}$$

Assuming ram-pressure balance between the lobe and the ambient medium, we have [10,13]

$$p_l \approx \eta m_h v_l^2 \tag{19}$$

where η is particle number density of the source ambient medium, m_h is hydrogen mass, Combining equations (13), (18) and (19), we have

$$\mathcal{D} \approx t\left(\frac{p_l}{\eta m_h}\right)^{0.5} \sin\phi \tag{20}$$

The last equation suggests that the observed source size ($\mathcal{D}$) depends on the source age (t), lobe internal pressure (p_l), ambient particle number density (η), and angle of observation (ϕ).

Furthermore, rewriting equation (19) for the jet we obtain

$$p_j \approx \eta m_h v_j^2 \tag{21}$$

where the parameters have their usual meanings. Combining equations (17) and (20), intrinsic source linear size ($\mathcal{D}_n$) becomes

$$\mathcal{D}_n \approx t\left(\frac{p_l}{\eta m_h}\right)^{0.5} \tag{22}$$

Eliminating η from equations (21) and (22), we have

$$\mathcal{D}_n^2 \approx t^2 \frac{p_l}{p_j} v_j^2 \tag{23}$$

Combining this with equation (1), we obtain

$$v_l^2 p_j \approx v_j^2 p_l \tag{24}$$

The last equation may be interpreted to mean that jet internal pressure exceeds the lobes internal pressure since $\frac{v_l}{v_j} < 1$. This implies that ambient medium density is higher in jet region than in the region of the lobe. This is expected since the ambient density thins out from the central core to the lobe [13]. It supports the idea that lobes in the large extended EGRS are located outside their host galaxies rather than within the host galaxies [10].

Furthermore, from equation (1), we can show that [14]

$$\mathcal{D}_n \approx (0.486t)v_j \tag{25}$$

Moreover, rewriting equation (23), we obtain

$$\mathcal{D}_n \approx t\sqrt{\frac{p_l}{p_j}}v_j \tag{26}$$

Equations (25) and (26) are theoretical relations for source size and jet velocity. Hence, combining them, we have respectively, the ratio of lobe pressure to jet pressure and the ratio of lobe velocity to jet velocity, giving by

$$\frac{p_l}{p_j} \approx 0.236 \tag{27}$$

$$\frac{v_l}{v_j} \approx 0.486 \tag{28}$$

Equations (27) and (28) also show that jet internal pressure exceeds the lobes internal pressure and that $\frac{v_l}{v_j} < 1$ as seen earlier. This also supports that ambient medium density is higher in jet region than in the region of the lobe

Moreover, equations (25) and (26) suggest that we can find these ratios from the linear regression analysis of observed linear sizes of the radio sources and their respective jet velocities. Therefore, we carry out the analysis (Fig. 1) using the aforementioned 31 radio galaxies and obtained

$$\mathrm{Log}\mathcal{D}_n = 0.358\mathrm{Log}v_j + 19.14 \tag{29}$$

The correlation coefficient, $r \approx 0.4$. This is marginal. Rearranging equation (29) yields

$$\mathcal{D}_n \approx (1.51 \times 10^{19})v_j^{0.4} \tag{30}$$

The last relation may be referred to as an empirical value for the $\mathcal{D}_n - V_j$ relationship. The index, 0.4, which is absent in the theoretical relations (i.e. equations (25) and (26)) may have been present as a result of marginality in the correlation ($r = 0.4$) of the data. This marginality might have resulted from inconsideration of the effects from other factors on which the source sizes/jet velocities depend. However, equating the terms in the brackets in equations (25) and (30), age of the radio sources is estimated to be [14] $t \approx 9.88 \times 10^{11}\mathrm{Yr}$

Rearranging equation (30), we obtain

$$\mathcal{D}_n \approx (1.51 \times 10^{19})v_j^{-0.6}v_j \tag{31}$$

Taking $v_j = 3c$ [15], where c is light speed, and substituting for v_j in $v_j^{-0.6}$, equation (31) becomes

$$\mathcal{D}_n \approx (1.24 \times 10^{14})v_j \tag{32}$$

Combining equations (26) and (32), with the estimated value of t substituted, we obtain

$$\frac{p_l}{p_j} \approx 2.34 \times 10^{14} \tag{33}$$

This result is in dissention with equations (27) and (28)! This disagreement between the theoretical result and the empirical result (as suggested earlier) may be attributable to the dependability of the source size on other factors in addition to jet speed and time.

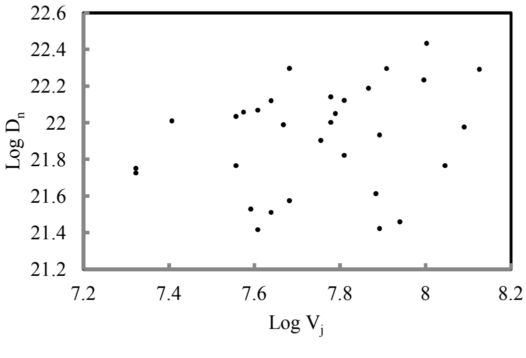

Fig. 1. The scatter plot of linear size against jet velocity

4. DISCUSSION AND CONCLUSION

In the last section, we have used analytical methods to obtain a relation, $\mathcal{D} \approx t\left(\frac{p_l}{\eta m_h}\right)^{0.5} \sin\phi$, that may describe expansion of EGRS components through their ambient dense media. The relation suggests that observed linear size $(\mathcal{D})$ of a typical EGRS depends on lobe internal pressure (p_l), time or age of the radio source (t), source ambient media number density (η), and angle of observation ϕ.

Moreover, from the analyses, we have shown that the obtained relations, $\mathcal{D}_n \approx (0.486t)v_j$ and $\mathcal{D}_n \approx t\sqrt{\frac{p_l}{p_j}}v_j$, suggestively implies that $p_l \approx 0.236p_j$ and $v_l \approx 0.486v_j$. Which shows that since $\frac{v_l}{v_j} < 1$, jet internal pressure exceeds the lobe's internal pressure. However, for this to be satisfied, ambient medium density must be higher in jet region than in the region of the lobe. This is expected since the ambient density thins out from the central core to the region where lobe is located [16]. This supports the idea that for larger EGRS, lobes are located outside the host galaxies rather than within the host galaxies. In conclusion, these results suggestively indicate that, compact steep spectrum sources have denser ambient medium than their more extended counterparts.

Note that we have dropped our empirical result $\left(\frac{p_l}{p_j} \approx 2.34 \times 10^{14}\right)$ because it is not consistent with the theoretical results. This outrageous result might have resulted from inconsideration of the effects from other factors on which the source sizes/jet velocities depend.

COMPETING INTERESTS

Author has declared that no competing interests exist.

REFERENCES

1. Urry CM. AGN Unification: An Update". Astronomical Society of the Pacific conference series. 2004;1.
2. Robson I. Active Galactic Nuclei, John Wiley and Sons Ltd, England; 1996.
3. Readhead AC. Evolution of Powerful Extragalactic Radio Sources". In proc. Colloquium on Quasars and Active Galactic Nuclei, ed. Kohen M, Kellermann, *K*. (USA: National Academy of Sciences, Berkman Center, Irvine). 1995;92:11447–11450.
4. Weber P. The Density in the Accretion Disk of the Active Galactic Nucleus. Friedrich-Alexander-University Erlangen-Nurnberg; 2017.
5. Jackson JC. Radio Source Evolution and Unified Schemes". Publications of Astronomical Society of the Pacific. 1999;16:124–129.
6. Kawakatu N, Kino M. 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. 2007;27:192–197.
7. Fanti C, Fanti R, Dallacasa D, Schillizzi RT, Spencer RE, Stanghellini C. "Are Compact Steep Spectrum Sources Young"? Astronomy and Astrophysics. 1995;302:317–326.
8. O'Dea CP. The Compact Steep Spectrum and Gigahertz peaked Spectrum Radio Sources". Publications of the Astronomical Society of the Pacific. 1998;110: 493–532.
9. Fanti C, Pozzi F, Dallacasa D, Fanti R, Gregorini L, Stanghellini C, Vigotti M. Multi-frequency VLA Observations of a New Sample of CSS/GPS Radio Sources". Astronomy and Astrophysics. 2001; 369:380–420.
10. Ezeugo JC, Ubachukwu AA. The Spectral Turnover–Linear Size Relation and the Dynamical Evolution of Compact Steep Spectrum Sources". Monthly Notices of the Royal Astronomical Society. 2010;408: 2256–2260.
11. Nilsson K. "Kinematical Models of Double Radio Sources and Unified Scheme Monthly Notices of the Royal Astronomical Society. 1988;132:31–37.
12. O'Dea CP, Daly RA, Kharb P, Freeman KA, Baum SA. Physical Properties of Very Powerful FR II Radio Galaxies". Astronomy and Astrophysics. 2009;336: 69–79.
13. Cavalho JC. The Evolution of GHz-peaked Spectrum Radio Sources. Astronomy and Astrophysics. 1998;329: 845–852.
14. Ezeugo JC. Intergalactic Media Densities of Extragalactic Radio Sources and Source Ages". American Journal of Astronomy and Astrophysics. 2021;9(2): 13–17.
15. Koide S, Shibata K, Kudoh T. "Relativistic Jet formation from Blackhole Magnetized

Accretion Disks". The Astrophysics Journal. 1999;522:727–752.

16. Ezeugo JC. On Jet Opening Angle and Dynamical Evolution of Some Powerful Extragalactic Radio Sources". American Journal of Astronomy and Astrophysics. 2015;3(3):40 – 43.

Peer-review history:
The peer review history for this paper can be accessed here:
http://www.sdiarticle4.com/review-history/68307