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Relativistic Jet Propagation: Its Evolution and Linear Size Cosmic Dilation

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Authors' contributions

This work was carried out in collaboration between both authors. Both authors read and approved the final manuscript.

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ABSTRACT

Relativistic jets are ubiquitous in astrophysical systems that contain central cores. They transport large amounts of energy to large distances from the source and their interaction with the ambient medium has a crucial effect on the evolution of the system. Furthermore, the radio luminosity exhibited by these jets are merely an indirect measure of the energy transported through the jets from the central engine which is not easily interpretable. The mechanism(s) responsible for these jet phenomena is still a subject of debate. In this work, we use both statistical and analytical methods to obtain a mathematical relation that may explain the observed physical processes in the evolution of astrophysical jets. We first obtain measured observable parameters characterizing these jets, and then carry out linear regressions of these parameters against each other to obtain a statistical relation. We also use analytical method to obtain a relation which in conjunction with the statistical relation yields a new relation that may explain how these jets interact with the ambient medium through which they propagate. Result shows that radio jet velocity (V_j) depends on the radio source energy density (u) and ambient particle number density (n_e) according to the relation, $V_j \sim \left(U/n_e\right)^{1/2}$.

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This relation suggestively indicates that jet velocity has a direct power-law relationship with the source energy density and an inverse power-law relationship with the ambient particle number density.

Keywords: Relativistic jets; quasars; galaxies; redshift; linear size; cosmic dilation/evolution; ambient density; jet velocity.

1. INTRODUCTION

Astrophysical jets are narrow collimated, bipolar outflows ejected within the vicinities of a massive rotating object that propagate for large distances compared to the size of the launching region [1]. These narrow radio jets are observed in a wide variety of extragalactic sources with active galactic nuclei (AGN). These sources include: radio galaxies, radio loud quasars, compact steep spectrum sources etc. These jets are very powerful with an initial jet radius comparable to the gravitational radius of a black hole which is about one billion initial radii [2]. The typical power of these jets ranges from 10^{35}–10^{40}W with velocities close to the speed of light [1] and they can be traced up to distances of hundreds of kiloparsecs. This remarkable apparent stability of cosmic jets has attracted a lot of attention from both theorists and researchers resulting in a very long list of analytical, statistical and numerical studies.

Jets are believed to be channels along which energy and momentum flow out from the nucleus of the parent galaxy and into the surrounding medium [3]. Also, there is evidence that astrophysical jets interact with their environment by transferring momentum to the surrounding gas, and this interaction may have significant effects upon their evolution [4]. Consequently, relativistic jets transport large amounts of energy to large distances from the source and their interaction with the ambient medium has a crucial effect on the evolution of the system [5]. The propagation of the jet is characterized by the formation of a shocked “head” at the front of the jet which dissipates the jet’s energy and a cocoon that surrounds the jet and potentially collimates it. The critical parameter that determines the properties of the jet–cocoon system is the dimensionless ratio between the jet’s energy density and the rest-mass energy density of the ambient medium. This parameter, together with the jet’s injection angle, also determines whether the jet is collimated by the cocoon or not [5].

Jet interaction with the external medium has been studied extensively in many different scales, using analytical and numerical methods [5]. Initially, it was studied in the context of radio-loud AGNs [6, 7]. They showed that the propagation of the jet generates a double bow-shock structure at the head of the jet. The question of how a jet of material propagating through an ambient medium interacts with that medium begs the following questions. First, what mechanisms work to deposit energy in the ambient medium as the jet propagates through it and how does the jet maintain its coherence as it propagates through such remarkable distances? Also, one ought to ask what the jet is made of and whether or not there are different modes of interaction with the ambient medium through which it propagates [8]. Credible analysis based on hydrodynamic simulations has demonstrated a number of interesting effects originating from ram pressure and the consequent turbulent acceleration of the ambient medium [9, 10]. However, in this paper, we will use statistical methods to first determine the cosmic linear size evolution of astrophysical jet sources and then with the aid of the results obtained employ analytical methods to determine how the jet’s propagating velocity evolves with time as the jet propagates through the ambient space.

2. METHODOLOGY

2.1 Variation of Linear Size (D) with Redshift (Z) For Quasars and Radio Galaxies

The analyses are based on combined samples of Radio sources from Nilsson 1998 sample [11]. It includes 235 quasars and 411 radio galaxies.

The linear regression analysis for these relationships for quasars and radio galaxies respectively are

$$\log_{10} D = 2.47 - 0.09 \ \log_{10}(\mathrm{Z}+) \qquad (1a)$$

$$\log_{10} \mathrm{D} = 2.49 - 0.07 \ \log_{10}(\mathrm{Z}+1) \qquad (1b)$$

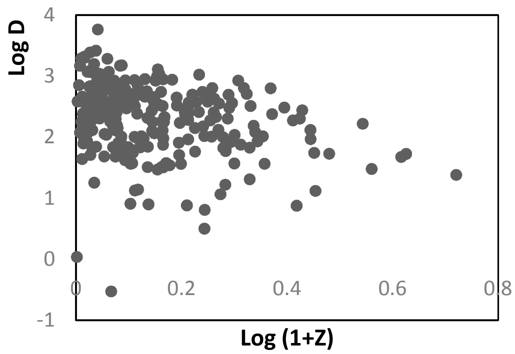

Fig. 1. Scatter plot of D vs Z for Quasars

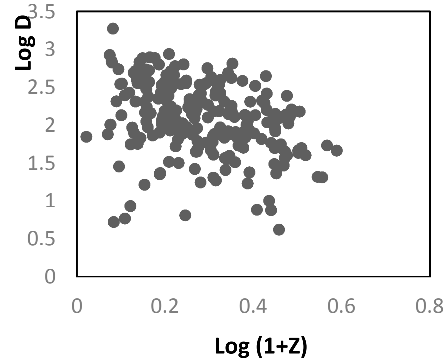

Fig. 2. Scatter plot of D vs Z for Radio Galaxies

Rearranging the above, equation 1a yields

$$\therefore D = K(1+Z)^{-0.09} \quad 2$$

Also from equation 1b we obtain

$$\therefore D = K(1+Z)^{-0.07} \quad 3$$

From the Kinematics of expansion [12], we have

$$a^{-1} = (1+Z) \quad 4$$

Where a is the scale factor of the universe.

Hence, we can write a general equation for equations 2 and 3 as thus,

$$D = Ka^{n} \quad 5$$

Thus,

$$D \sim a^{n} \quad 6$$

Where n is a variable dependent on the density parameter Ω_0 [13]

Hence equation (6) shows that the linear size of a radio source has a power-law function with the scale factor of the universe.

Also, from 'Relativistic Beaming and Orientation Effects' which relates observed linear size, D and angular size, θ [14-16]

$$D = D_o \sin\theta \quad 7$$

D = observed linear size of the radio source
D_o = Intrinsic linear size

Hence equating equations (6) and (7), we have

$$Ka^{n} = D_o \sin\theta \quad 8$$

This yield

$$D_o = \frac{Ka^{n}}{\sin\theta} \quad 9$$

2.2 Jet Interaction with Ambient Environment

We consider an expanding volume, V of sphere within which the jet is propagating

$$V = \frac{4\pi r^3}{3} \quad 10$$

Here r is the radius of the sphere at time, t.

According to [12], the expansion of any small spherical shell with radius r(t) is given by

$$r(t) = r_0 a(t) \quad 11$$

Here a is the scale factor of the universe

Therefore,

$$V = \frac{4\pi a^3 r_0^3}{3} \quad 12$$

The rate at which this volume changes with the scale factor is given by

$$\frac{dv}{da} = 4\pi a^2 r_0^3 \quad 13$$

But from equation (11)

$$r_0 = \frac{r}{a} \quad 14$$

Therefore,

$$\frac{dv}{da} = \frac{4\pi r^3}{a} \qquad 15$$

Since a is a function of time, we have

$$\frac{da}{dt} = \dot{a} \qquad 16$$

The rate at which the expanding volume varies with time is given by

$$\frac{dv}{dt} = \frac{dv}{da} \cdot \frac{da}{dt} \qquad 17$$

This yields

$$\frac{dv}{dt} = \frac{4\pi r^3}{a} \cdot \dot{a} = 4\pi r^3 H \qquad 18$$

Here, H is the Hubble parameter

From the discussions in [15, 17], the jet kinetic power can be expressed as

$$P_j \approx m_H c n_e \Omega D_0^2 V_j^2 \qquad 19$$

Here P_j = jet kinetic power, $m_H = \text{mass of proton}, n_e = \text{ambient number particle density}$, $\Omega =$ jet opening solid angle, c is speed of light and other parameters have their usual meanings.

Therefore,

$$\frac{dE}{dt} \approx m_H c n_e \Omega D_0^2 V_j^2 \qquad 20$$

Where E is energy: We note that the jet kinetic power is the same as the jet energy deposition rate within the ambient medium (according to energy conservation). Thus, the interaction between the jet and the medium can be determined by the interacting source energy density, U within the medium.

Thus,

$$U = \frac{dE}{dV} = \frac{dE}{dt} / \frac{dV}{dt} \qquad 21$$

The above yields

$$U \approx \frac{m_H c n_e \Omega D_0^2 V_j^2}{4\pi r^3 H} \qquad 22$$

Making V_j the subject of the formula we obtain

$$V_j \approx \frac{2}{D_0} \left(\frac{\pi r^3 H U}{m_H c n_e \Omega} \right)^{\frac{1}{2}} \qquad 23$$

Substituting for D_0 in equation (9) we have,

$$V_j \approx \frac{2 \sin\theta}{K a^n} \left(\frac{\pi r^3 H U}{m_H c n_e \Omega} \right)^{\frac{1}{2}} \qquad 24$$

The above equation (24) shows that the propagation velocity of the jet is approximately directly proportional to the square-root of the source energy density of the ambient medium and approximately inversely proportional to the square-root of the particle number density of the ambient medium.

Assuming a constant θ, a, r and Ω; equation (24) can be written as

$$V_j \sim \left(U / n_e \right)^{1/2} \qquad 25$$

This relation suggestively indicates that jet velocity has a direct power-law relationship with the source energy density and an inverse power-law relationship with the ambient density. This result is in consonance with results obtainable in the literature [18].

3. RESULTS AND DISCUSSIONS

From the regression analysis of the linear size (D) against Redshift (Z), we can see that the two classes of radio objects do not differ remarkably in their cosmic evolution. This result is in line with the works of Kapahi and Kulkarni [19, 20] and supports the quasar / radio galaxy unification scheme. However, Singal in [21, 22] claimed that the super luminous sources like the steep spectrum radio loud quasars have a different regressional result; categorically, a reversal trend of what is experienced in radio galaxies. He claimed that in this group of quasars, the more luminous radio loud quasars appear to be smaller in size. The work of Singal [21, 22] goes in line with discussions [23, 24, 25] where the authors first pointed out that Steep spectrum quasars at high redshift appear to be of smaller physical sizes.

However, it must be noted that this departure from cosmic size evolution was only observed for an aspect of quasars known as the steep spectrum quasars. Thus it appears understandable that Singal [21, 22] made this observation by doing his studies based on redshift bins. This explains why such observations can easily evade a researcher that based his research on general consideration of radio sources, since the number of such steep spectrum sources will be very minimal compared to the large number of radio sources under consideration. Hence, we do not seek to justify the discussions in [19, 20] as that is in line with the result obtained here but to point out that the tendency observed in steep spectrum sources might be an indication of a turning point between the effect of cosmic force and gravitational force upon a radio source. Therefore, the discussions in [21, 22] do not necessarily negate the unification scheme of radio galaxies and quasars but might be an indication of a new trend in the evolutionary process. Moreover, since our concern is on the contribution of this cosmic dilation to the evolution of jet propagation, we have considered a wide range of redshift in order to obtain a general relationship for the linear size cosmic dilation.

When we apply the result of the linear regression analysis of linear size (D) vs Redshift (Z) to the evolution of jet propagation through the interstellar space, it can be shown that the propagating velocity of the radio jet depends on the following according to equation 29 above:

I. The source energy density of the ambient medium, U.
II. The jet solid angle (i.e.Ω)
III. The scale factor of the universe (i.e. a)
IV. The angular size of the source, θ.
V. The density parameter, Ω_0 (since it determines the value of the index, n).
VI. The ambient gas particle number density, n_e.

Further analysis on equation 24 (i.e. assuming a constant θ, a, r and Ω) yields the relation $V_j \sim \left(U/n_e\right)^{1/2}$. This relation suggestively indicates that jet velocity has a direct power-law relationship with the source energy density and an inverse power-law relationship with the ambient density. This result is in total consonance with results obtainable in the literature [18].

4. CONCLUSION

In this paper, we have been able to show that despite the discrepancies associated with cosmic linear size dilation between quasars and radio galaxies in the literature, the discrepancies evolved as a result of a particular group of radio loud quasars known as Steep spectrum quasars whose number within the observable universe is very few compared to the vast number of ordinary quasars available for analyses. We also pointed out that this discrepancy might be an indication of a turning point in the evolutionary process of radio quasars. Also, using analytical methods, we have been able to show that the ambient medium density through which radio jet propagates contributes immensely to the evolution of jet propagation according to the relation, $V_j \sim \left(U/n_e\right)^{1/2}$.

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To my brother,Chizoba Ubah. I say, thank you for being there for your brother.

COMPETING INTERESTS

Authors have declared that no competing interests exist.

REFERENCES

1. Vila GS. Astrophysical jets. Instituto Argentino de Radioastronomía (IAR - CONICET) CC. N◦5 Villa Elisa, Buenos Aires, Argentina; 1894.
2. Blandford RD, Znajek RL. Electromagnetic extraction of ener from Kerr black holes. Monthly Notices of the Royal Astronomical Society. 1977:179:433 – 456.
3. Blandford RD, Payne DG. Hydromagnetic flows from accretion discs and the production of radio jets. Mon. Not. R. astr. Soc. 1982;199:883-903
4. De Young DS. Mass entertainment in Astrophysical jets. American astronomical society. The astrophysical Journal. 1986;307:62-72
5. Bromberg O, Nakar E, Piran T, Sariet R (2011). The propagation of relativistic jets in external media, The Astrophysical Journal. 2011;740:100 (12).
6. Blanford RD, Rees MJ. A twin exhaust model for double radio sources. Monthly Notices of the Royal Astronomical Society. 1974:169(3):395 – 415.
7. Scheuer. Models of extragalactic radio sources with continous energy supply from a central object. Monthly Notices of the Royal Astronomical Society. 1974;166(3):: 513– 528.
8. Beall JH John Guillory DV. Rose, Sabine Schindler and S. Colafrancesco (2006). Energetics of Jet interaction with intracluster medium. Chin. J. Astron. Astrophys. 2006;6:Suppl.1:283–291.

9. Basson JF, Alexander P. the long term eefect of radio sources on the intracluster medium.Monthly Notices of the Roral Astronomical Society. 2003:339(2):353 – 359.
10. Krause M, Camenzind M. parameters for very light jets of cD galaxies. New Astronomy reviews. 2003;47(6-7):573-576.
11. Nilson K. Kinematical models of double radio sources and the unified scheme, Monthly notices of Royal Astronomical Society. 1998;132:31-37.
12. Condon JJ, Matthews AM. Cosmology for Astronomers. Astronomical Society of the Pacific. 2018;130: 073001
13. Ubachukwu AA, Ogwo JN. Luminosity selection effects and linear size evolution in the Quasar/Galaxy unification scheme, Australian Journal of Physics. 1998;51:143 – 51.
14. Ubachukwu AA, Ogwo JN. Redshift and luminosity dependence of linear size of compact steep spectrum sources and the quasar/galaxy unification scheme. Australian Journal of Physics. 1999;52: 141-146.
15. Ezeugo JC, Ubachukwu AA. The spectral turnover linear size relation and the dynamical evolution of compact steep spectrum sources. Monthly Notices of the Roral Astronomical Society. 2010;408(4): 2256 – 2260.
16. Ubachukwu AA, Chukwude AE. On the relativistic beaming and Orientation effects in core dominant quasars. Journal of Astrophysics and Astronomy. 2002;23; 235.
17. Cavalho JC. The evolution of GHz peaked spectrum radio sources. Astronomy and Astrophysics. 1998;329:845-852.
18. Dipanjan Mukherjee, Geoffrey V. Bicknell, Ralph Sutherland and Alex Wagner. Relativistic jet feedback in high-redshift galaxies. MNRAS. 2016;461:967–983.
19. Kapahi VK. The angular size-redshift relation as a cosmological tool. In Hans HA; 1987. Available:https://doi.org/10.1007/978-94.009. - 3853-3_23
20. Gopal-Krishina, Kulkarni VK. The unification of radio galaxies and quasars and their linear size evolution. Astronomy and Astrophysics. 1992;257:11 – 16.
21. Singal AK. Cosmic evolution of the physical sizes of extragalactic radio sources and their luminosity-size correlation. Monthly Notices of the Royal Astronomical Society. 1988;233(1):87 – 113.
22. Singal AK. Evidence against the unified scheme for powerful radio galaxies and quasars. Monthly Notices of the Royal Astronomical Society. 1993;262(1):L27 – L30.
23. Miley GK. Variation of the angular sizes of quasars with redshift. Nature. 1968;218: 933 – 934.
24. Miley GK. The radio structure of quasars, a statistical investigation. Monthly Notices of the Royal Astronomical Society. 1971; 152(4):477– 490.
25. Legg TH. Redshift and the size of double radio sources. Nature. 1970;266(5240): 65- 67.

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