

Compact Steep-Spectrum Radio Sources and Ambient Medium Density

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Abstract: Analytical and statistical methods, with some plausible assumptions, have been used in this work to show presence of dense medium around compact steep-spectrum sources in our sample. This is done by carrying out regression analyses using our estimated jet's internal densities (n_j) and some other source parameters for possible deductions. Results indicate that $n_j - D$ and $n_j - n_e$ data (where D and n_e are respectively, observed source linear size and ambient medium density) show strong correlations and yield power-law relations of the forms, $n_j \sim D^{-3.54 \pm 0.02}$ and $n_j \sim n_e^{1.68 \pm 0.08}$. A comparison with obtained theoretical relations suggestively indicates presence of dense gases around these sources. In addition, a simple linear regression analysis of $\nu_p - n_j$ data shows that jet's particles may be responsible (in addition to the ambient gases) for the observed spectral turnover characteristic of compact steep spectrum sources.

Keywords: Spectral Turnover, Steep-Spectrum, Astrophysical Jet, Ambient Density, Active Galaxies

1. Introduction

Compact steep spectrum sources (CSSs) contain special characteristics that make them be considered as a separate class of objects in addition to the conventional radio sources which consist mainly of radio galaxies and radio loud quasars [1,2,3,4,5]. Similarly, CSS sources are made up of radio galaxies and radio loud quasars but on sub-galactic dimensions. Their projected linear sizes, D , range as follows: $D \leq 20\text{kpc}$ assuming Hubble constant, $H_0 = 75\text{km}^{-\text{s}}\text{Mpc}^{-1}$, and deceleration parameter, $q_0 = 0.0$. Their radio luminosity, P , at 5GHz is greater than $10^{25.5}\text{WHz}^{-1}$ [2,3,6,7]. They show double, triple and core-jet morphologies on radio maps [3]. They have steep high frequency spectrum of spectral index, $\alpha \geq 0.5 (S_\nu \sim \nu^{-\alpha})$; where S_ν is flux density and ν is observing frequency). Their spectral turnover is believed to be due to synchrotron self-absorption in a compact component with a large magnetic field. Generally, they have very low polarization at both radio and optical bands, usually, less than one percent [2,3,8,9]. Their proportion is high; from about 15% to 30%, depending on the selection frequency, among distant ($z > 0.2$) radio sources of high luminosity [2,3].

Usually, the structure of a typical extragalactic radio source takes the form of a central core (which, more or less, coincides

with the nucleus of the host galaxy) straddled by two-sided jets. At the end of each jet is located a radio-emitting lobe. The jet is believed to serve as a conduit through which jet's materials feed the lobe. However, it is believed that from accretion disks much of the energy powering the jets is derived [4,10]. Gravitational field of a supermassive black hole, believed to reside at the central core of a radio source, attracts gas clouds in its vicinity [11]. This causes the gas clouds to accelerate toward the black hole from a range of directions and collide with each other as they approach their orbital trajectory, and finally form an accretion disk. This accretion disk is believed to be the source of jet's materials [4,10,11], but the process by which this occurs is not yet fully understood. However, one of the factors that appear to affect the propagation of a jet is jet's internal density (or ratio of jet's internal density to ambient medium density) [12].

Therefore, the purpose of this work is to derive a mathematical relation for estimating internal densities of magnetically driven jets; and use the estimates, through simple regression analyses, to find how they correlate with some other source parameters for possible deductions. The regression analyses are based on the list of 61 CSS sources (with observed linear sizes, $D \leq 20\text{kpc}$) compiled by [3] from the 3CR and source samples from [8].

2. Magnetic Force on Particles of Constant Velocity

As pointed out by [10], one of the most promising models for jet's formation in AGN is the magnetic acceleration model [13,14]. Moreover, according to the study of magnetically driven jets [10], the terminal velocity of a jet is comparable to the rotational velocity of the disk at the foot of the jet. The implication is that a relativistic jet is produced at a position very close to the event horizon of a black hole.

Assuming particles moving with a constant velocity, V_j , in a constant magnetic field, B_j , then the magnetic force, F_B , acting on such an ensemble of particles to produce a jet at the core of a typical radio source may be given by

$$F_B \approx neV_j B_j \quad (1)$$

where n is number of particles. Approximating it to a tangential force (whose result is the usual straightness of jets), (1) may be written as

$$M_j a_j \approx neV_j B_j \quad (2)$$

where M_j is mass of jet, a_j is acceleration of jet, and V_j now represents jet's terminal velocity.

By definition, power, P_{cj} , over the source dynamical age, T , may be given by

$$P_{cj} = \frac{M_j a_j D}{T} \quad (3)$$

where D is taken to be the source linear size. Combining (2) and (3), B_j becomes

$$B_j \approx \frac{P_{cj} T}{neV_j D} \quad (4)$$

3. Jet's Internal Density

However, it is believed that the observed radio emission from jets and lobes, as well as, their confinement emanate from their interactions with the ambient media through ram pressure [2,15,16,17]. Therefore, we assume lobe confinement by ram-pressure balance with the external medium, and have [2,15,16]:

$$P_i \approx n_e m_H V_L^2 \quad (5)$$

where P_i is lobe's internal pressure, n_e is external (or ambient) medium density, m_H is proton mass and V_L is lobe velocity. Using the last equation, it can be shown that power, P_{cj} , delivered to the jet can be expressed according to the following relation [16,18]:

$$P_{cj} = m_H c n_e \Omega D^2 V_j^2 \quad (6)$$

where Ω is jet's opening solid angle. Putting it in (4), we obtain

$$B_j \approx \frac{m_H c n_e \Omega D V_j T}{ne} \quad (7)$$

Furthermore, assuming a jet of constant radius, R_j , the number, n , of particles in a jet can be expressed in relation to the number density, n_j , of the jet's particles as

$$n \approx n_j \pi R_j^2 D \quad (8)$$

However, [19] has pointed out that the correlations between spectral turnover (ν_p), flux density (S_ν), and source angular size (θ) imply a linear correlation between the lobes and source sizes; thereby, indicating that during the evolution of young radio sources, the ratio of the size of the lobes to the distance between the two lobes is constant. This implies that lobe's size increases as the linear size, D , of an extragalactic radio source increases. Similarly, assuming that source linear size and jet's width maintain a constant ratio, then jet's radius may appreciate with distance from the central core according to the relation,

$$R_j \approx 0.004D \quad (9)$$

This is estimated by taking the ratio of the distance between the ends of the two hotspots and jet's width of 3C 405 (Cygnus A). Generalizing this for radio sources and combining (8) and (9) yields

$$n \approx (1.6 \times 10^{-5}) n_j \pi D^3 \quad (10)$$

Putting it in (7), B_j becomes

$$B_j \approx \frac{m_H c n_e \Omega V_j T}{(1.6 \times 10^{-5}) \pi n_j e D^2} \quad (11)$$

Hence, jet's internal density becomes

$$n_j \approx \frac{m_H c n_e \Omega V_j T}{(1.6 \times 10^{-5}) \pi B_j e D^2} \quad (12)$$

The last equation shows that

$$n_j \sim D^{-2} \quad (13)$$

implying that n_j falls off as D^{-2} from the central core of a radio source for constant jet's velocity and magnetic field.

Applying synchrotron-self absorption theory [12,19], source magnetic field, B_s , can be written as follows [12]:

$$B_s = \frac{\pi^3 \theta^4 m_e^3 \nu^5}{18 S_\nu^2 e} \quad (14)$$

m_e is mass of an electron, ν is observing frequency, θ is source's angular size, and ν is flux density. For the purpose of estimating jet's internal density, we assume $B_j \approx B_s$. Therefore, combining (12) and (14), we obtain

$$n_j \approx 1.125 \times 10^6 \left(\frac{m_H c \Omega V_j}{\pi^4 m_e^3} \right) \left(\frac{n_e T S_\nu^2}{D^2 \theta^4 \nu^5} \right) \quad (15)$$

4. Analyses and Result

Taking typical values of the following quantities: $m_H = 1.67 \times 10^{-27} \text{ kg}$, $c = 3 \times 10^8 \text{ ms}^{-1}$, $\Omega = 3.6 \times 10^{-5} \text{ sr}$, $V_j \approx 0.3c$ [10], and $m_e = 9.109 \times 10^{-31} \text{ kg}$, (15) becomes

$$n_j \approx 2.476 \times 10^{79} \left(\frac{n_e T S_v^2}{D^2 \theta^4 v^5} \right) \quad (16)$$

We notice that the parameters at the right-hand side of the last equation are either observed or estimable. The source ages (T) used in our analyses are estimated by dividing the individual source's observed linear size by lobe's velocity ($0.251c$) of the CSS source, 0710+439, observed by [19]. Since the estimated ages which range from 10^2 Yr to 10^5 Yr are consistent with those in the literature [9,15,21], we assume this lobe's velocity for all the CSS sources in our sample.

Therefore, using the observed parameters (i.e. θ [where 1 arc second = 4.85×10^{-6} rad], v , D [where 1pc = 3.086×10^{16} m], and S_v [where 1Jy = 10^{-26} Wm $^{-2}$ Hz $^{-1}$]) from [3], the estimated source ages and ambient density n_e obtained from [18], we estimate jet's density for each source.

Using these estimates, we plot $n_j - D$ data as shown in Fig. 1.

A simple linear regression analysis of the plot gives

$$\text{Log} n_j = (-24.6 \pm 0.2) - (3.54 \pm 0.02) \text{Log} D \quad (17)$$

with correlation coefficient, $r \approx 0.7$.

Also, we carry out a simple linear regression analysis of $n_j - n_e$ plot as shown in Fig. 2; where values of n_e for the sources are obtained from [18]. Result gives

$$\text{Log} n_j = (-23.0 \pm 0.2) + (1.68 \pm 0.08) \text{Log} n_e \quad (18)$$

with $r \approx 0.8$.

Finally, we carry out a linear regression analysis of spectral turnover (ν_p) and jet's density (Fig. 4). This yields

$$\text{Log} \nu_p = (4.8 \pm 0.2) + (0.09 \pm 0.01) \text{Log} n_j \quad (19)$$

with correlation coefficient, $r \approx 0.6$.

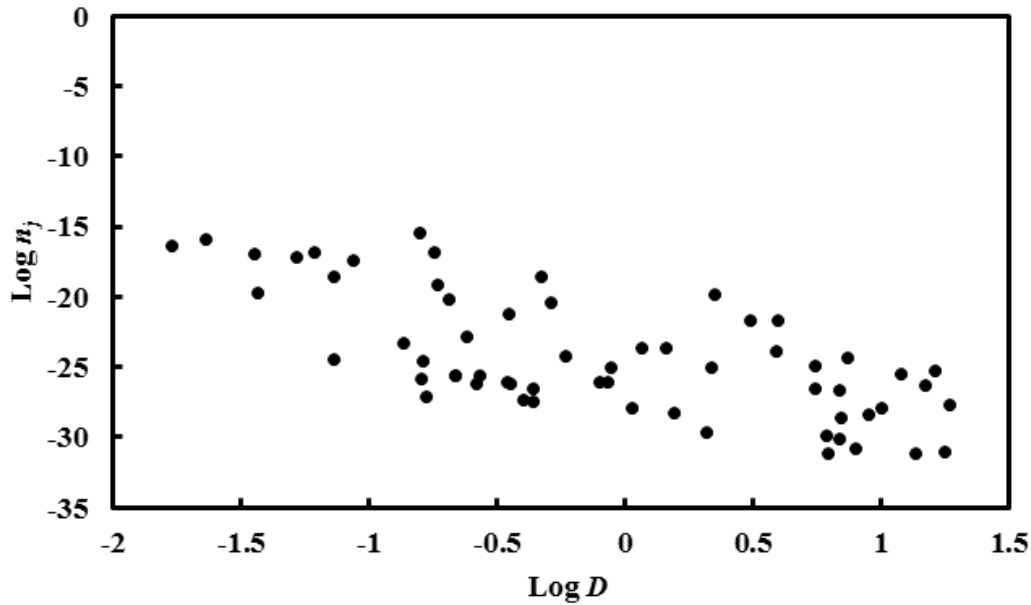


Figure 1. The scatter plot of jet's density against linear size.

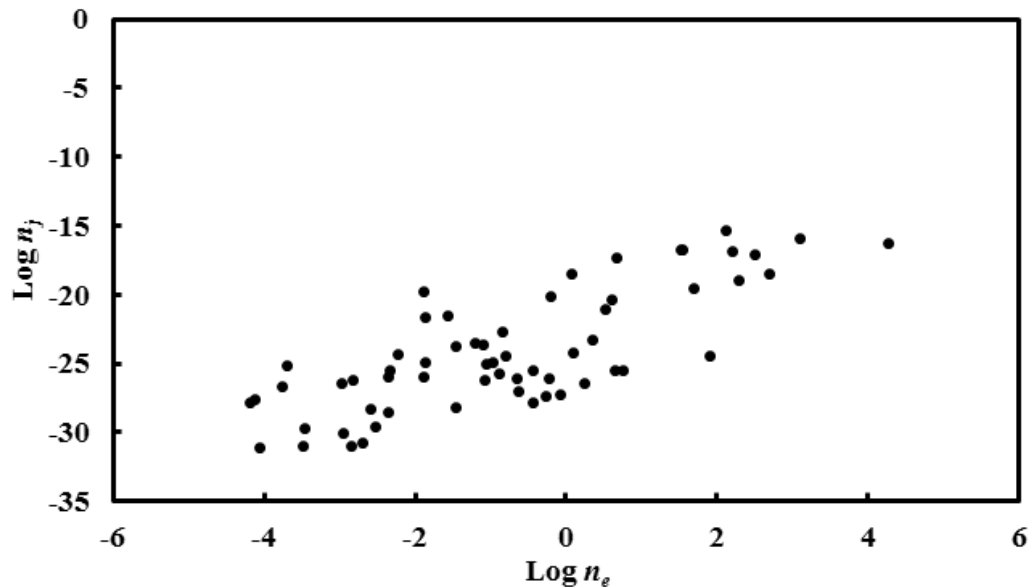


Figure 2. The scatter plot of jet's density against ambient density.

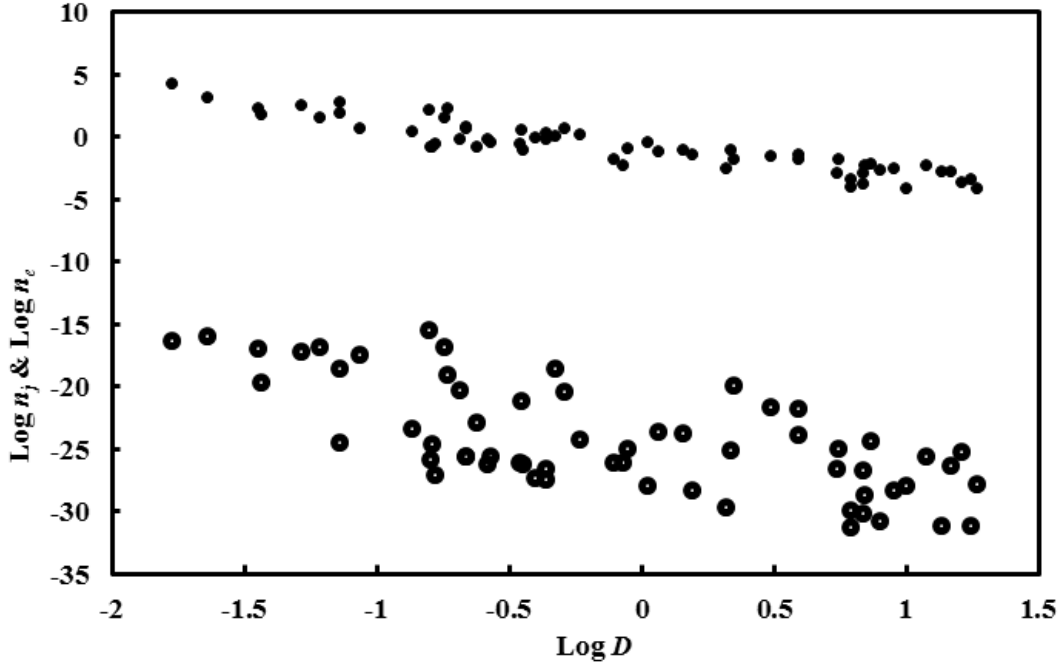


Figure 3. The scatter plot of n_j (open circles) & $\text{Log } n_e$ (filled circles) against D .

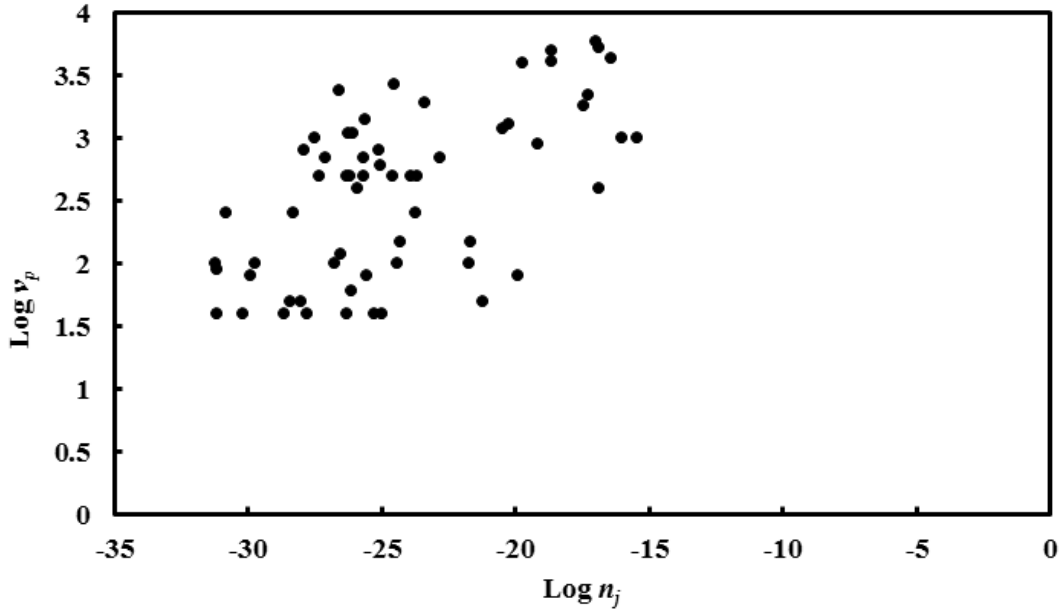


Figure 4. The scatter plot of spectral turnover against jet's density.

5. Discussion

In the previous sections, we find from theory (12) that for a source with constant magnetic force and constant particle's velocity (V_j), jet's density (n_j) is expected to decline with distance (D) from the central core of an extragalactic radio source according to the relation, $n_j \sim D^{-\zeta_1}$ ($\zeta_1 = 2.0$). This implies that as distance from the core increases, some particles of jet fizzle out. If an ambient medium of low (or negligible) density is considered, the energy lost by jet's particles would be mainly outside interactions with particles of ambient medium; and hence, must be due to interactions with fields

surrounding the source. However, in absence of any other radiation whose mechanism of production may not be in consonance with the foregoing, synchrotron radiation which can only result from particles' interactions with magnetic field appears to fit in. This is supported observationally, indicating that the radio continuum emission from jet shows spectra characteristic of synchrotron radiation [3,9,19]. Furthermore, if some jet's particles fizzle out as a result of energy losses due to synchrotron radiation, then jet's luminosity is also expected to drop with distance (see also [3,22]).

On the other hand, [18] has pointed out that the relation, $v_p \sim n_e^{0.35}$, between spectral turnover (v_p) and ambient medium density (n_e) suggests that the spectral turnover

constitutes a characteristic signature of dense gases around CSS sources. Moreover, considering their estimated age range, $10^2\text{Yr} - 10^5\text{Yr}$ (Table 1) (see also [15,21]), the relation implies that CSS sources might be young radio sources growing in dense ambient media. Therefore, if we assume a dense medium around a CSS source, then more jet's particles would fizzle out due to their appreciable interactions with particles of ambient medium (see [16,18,23,24,25]; and hence, the index (ζ_1) is expected to increase. This implies that a simple regression analysis of $n_j - D$ data should yield a slope (say, ζ_2) ≥ 2.0 .

Just as expected, $n_j - D$ data (Fig. 1) show a strong correlation (with $r \approx 0.7$), and yield $n_j \sim D^{-\zeta_2}$ (see equation (17)); where $\zeta_2 (= 3.54 \pm 0.02)$ is greater than $\zeta_1 (= 2.0)$. This implies that greater number of jet's particles than predicted in the theory fizzle out; and hence, suggests the presence of dense ambient media around CSS sources.

Moreover, (15) shows a theoretical relationship ($n_j \sim n_e^{\psi_1}$, where $\psi_1 = 1.0$) between jet's density (n_j) and ambient medium density (n_e); and predicts that both densities decline from the core. However, the result of the regression analysis (18) of $n_j - n_e$ data (Fig. 2) shows, with strong correlation ($r \approx 0.8$), that $n_j \sim n_e^{\psi_2}$; where $\psi_2 \approx 1.68 \pm 0.08$. Though, it indicates a direct relationship between the two densities which is consistent with (15), the disparity in the two indices $\psi_1 < \psi_2$ shows that n_j declines faster than n_e ; and hence, supports the suggestion that dense gases exist around CSS sources.

Fig. 3 shows $n_e - D$ (filled circles) and $n_j - D$ (open circles) plots on the same axes, indicating variations of the two densities over distances. The plot shows that as ambient medium density (n_e) declines according to the relation, $n_e \sim D^{-2.2}$ [18,23,25], jet's density declines according to the relation, $n_j \sim D^{-3.5}$. Hence, n_j declines faster than n_e . This may result from the interactions of jet's particles with ambient gases; therefore, indicating presence of dense ambient media around CSS sources.

Finally, Fig. 4 shows a plot between spectral turnover (ν_p) and jet's density (n_j) with a power-law relation of the form,

$$\nu_p \sim n_j^\delta \quad (20)$$

where $\delta = 0.09 \pm 0.01$ and $r \approx 0.6$. This is indicative that jet's particles (in addition to ambient gases as pointed out by [18]) may be responsible for the observed spectral turnover characteristic of compact steep spectrum sources.

6. Conclusion

We have shown a theoretical relation that may connect jet's internal density (n_j) and observed linear size (D), as well as, between n_j and ambient medium density (n_e). We have also shown that strong correlation exists between n_j and D (Fig. 1), as well as, between n_j and n_e (Fig. 2). The departures of the results of regression analyses of $n_j - D$ and $n_j - n_e$ data from their respectively obtained theoretical values, suggest the presence of dense gases around Compact Steep Spectrum

sources. Moreover, we have seen from a simple linear regression analyses of spectral turnover (ν_p) and n_j that the good correlation (with $r \approx 0.6$) suggestively indicates that jet's particles (in addition to the ambient gases; see [18]) causes spectral turnover which characterizes CSS sources.

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