Original Research Article

Extragalactic Radio Quasars: Consequences of the Luminosity/Redshift Relationship

Abstract: We have used both analytical and statistical methods to show some plausible consequences of the luminosity/redshift relationships for compact steep spectrum (CSS) quasars and the more extended extragalactic radio (EGR) quasars. From the analytical methods (or theory), we find that luminosity shows an inverse dependence on the redshift; while from the statistical (empirical) the converse is the case for both CSS quasars and their extended counterparts. We know that luminosity selection effects may play some role in the empirical results. However, we find that the magnitudes of departure of the two empirical results from the theoretical result are staggering – the difference for the extended EGR quasars far outweighs that of the CSS quasars. We may state categorically that this discrepancy may simply be a sign of a factor in the intergalactic medium (IGM) that appears to cause the anomaly in the extended EGR quasars. This is because sources with similar powers are expected to produce similar luminosities; and besides, central engines of the more extended EGR quasars have roughly similar powers with the CSS central engines. However, our results show great difference between their radiated powers (luminosities). A likely explanation of this is that the irregularity may be a signature of dark/vacuum energy. It simply indicates that among other factors, dark energy may constitute a factor which influences luminosities of the more extended EGR quasars. The components (jets and lobes) of the more extended EGR quasars lie in the intergalactic medium (IGM). This medium is more of a vacuum than the interstellar medium (ISM) in which the components of the CSS sources are located. Therefore, dark energy is expected to show more effect in the IGM than in the ISM. Besides, we estimate percentage influence caused by luminosity selection effect and that caused by the presumed dark/vacuum energy. The estimates are respectively, 1.31% and 98.69%. These results show that intrinsically, dark/vacuum energy influences extended EGR quasars' luminosities by about 75 times more than the observational bias caused by luminosity selection effects.

Keywords: dark energy; luminosity; central engine, steep spectrum; linear size; radio sources; quasars; redshifts.

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1. Introduction

A typical galaxy is composed of about 10^{10} stars of different types. Galaxies can be classified as normal and active galaxies [1]. While the former have their radiations originate from their constituent stars, the latter have theirs from a region less than a parsec which is generally referred to as the central engine/core [1]. Active galaxies are known to radiate power in excess of $10^{36}W$ [1-4]. Unlike the normal galaxy whose radiation comes from the constituent stars just as mentioned earlier, an active galaxy emits bountiful amounts of radiation from its three major components. These components include, central engine (believed to harbor a supper massive blackhole), two-sided jets emanating from the central engine, and two-sided lobes believed to be fed by the jets [1-4].

Active galaxies consist of radio-loud sources and radio-quiet sources. The former are commonly referred to as extragalactic radio sources (EGRS). They emit large amount of radio emission. They show high ratio of radio to optical emission which is generally defined by the quotient of the two flux densities given by $S_{5\ \mathrm{GHz}}/S_{6\times10^5\mathrm{GHz}} > 10$ [1–7]. They are made up of radio galaxies, radio-loud quasars and BL Lacertae objects [4–8]. Observationally, radio emission from these EGRS usually assumes the morphology of two opposite sided relativistic jets that connect what one may assume to be the force center of an accretion disk to two radio-emitting lobes straddling the central engine/core believed to be resident in the force center [1–8]. The jet is believed to serve as a channel through which jets materials reach the lobe. In some sources, the lobes contain hotspots considered to be the termination points of the jets [1–8].The jets of these sources are projected into the intergalactic medium (IGM). It is good to note that this medium is almost a perfect vacuum where vacuum energy (or dark energy) is expected to operate most.

Compact steep spectrum (CSS) sources, on the other hand, belong to this very class of active galaxies known as extragalactic radio sources (EGRS) that radiate more in the radio wavelengths [9–14]. What immediately differentiates these two classes of objects, CSS sources and the more extended EGRS, is that while the former are sub-galactic, the latter are of intergalactic in sizes [9–14]. Moreover, irrespective of their small sizes, their radiated powers are still great. They are made up of radio 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 scale [9–14]. 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 $z \le 4$), and are among high luminosity sources [9–14]. Being sub-galactic in dimension implies that their linear sizes are well below 30 Kpc; and their components are buried in the interstellar media (ISM). The more extended EGRSs however have linear sizes, D, given by $D > 30$ Kpc assuming Hubble constant, $H_0 = 75\ \mathrm{kms^{-1}Mpc^{-1}}$. In all cases, their linear sizes (which are defined by the lengths of jets and lobes) extend far into the IGM. Their radio luminosity is in excess of 10^{26}W at 5 GHz; and overall luminosities ($P_{bol} \ge 10^{37}$W) in common with the CSS sources [4–14].

Furthermore, it has been well-known that existence of jets in radio sources simply suggests presence of gaseous ambient media [15–18]. A number of hydrodynamic simulations of jet propagations have been performed to appreciate their phenomena [15–16]. These studies show that jet materials have smaller masses than those of the ambient medium. Besides, Ezeugo and Ubachukwu [13] obtained a model for evolution of CSS sources and used it to estimate their ambient densities. In this work, we use analytical and statistical methods to show some plausible consequences of the luminosity/redshift relationships for compact steep spectrum (CSS) quasars and the more extended extragalactic radio (EGR) quasars.

Meanwhile, dark/vacuum energy is generally taken to be an intrinsic tendency of vacuum (or free space) to increase in volume. It brings more spaces into existence. This energy is anti-gravity, and is believed to be the driving force behind the evolution (expansion) of the universe [19]. Additionally, effects of this dark energy are expected to be observed most in the IGM because that is the most rarefied medium.

The extragalactic radio sources used in our analyses are gotten from [15]. They are made up of 170 extended EGR quasars with observed linear sizes well beyond 30Kpc. The second sample contains 31 CSS radio-loud quasars obtained from [12] – their linear sizes are well below 30kpc.

2. Luminosity and Redshift (Theory)

Assuming lobe confinement by ram-pressure balance with the ambient density, we may have [3,11,20]

$$\mathcal{P}_\ell \approx \eta m_h v_l^2 \quad (1)$$

where $\mathcal{P}_\ell$ is lobe internal pressure, η particle number density of the source ambient medium, and m_h hydrogen mass. It can be shown that jet kinetic power, $\mathcal{P}_{cj}$, may be written as [20]

$$\mathcal{P}_{cj} \approx \eta m_h c v_j^2 \Gamma \mathcal{D}_0^2 \quad (2)$$

Γ is jet opening solid angle, c light speed, and other symbols have their usual meanings. The last equation may be rewritten as

$$\mathcal{D}_0 \approx \left(\frac{\mathcal{P}_{cj}}{\eta m_h c v_j^2 \Gamma}\right)^{\frac{1}{2}} \quad (3)$$

Moreover, $\mathcal{P}_{cj}$ may be defined as [3],

$$\mathcal{P}_{cj} = \frac{m_j a \mathcal{D}_0}{t} \quad (4)$$

where m_j and a are respectively mass and acceleration of jet. Also, accretion rate is given by [1,3],

$$\dot{\mathcal{M}} = \frac{\mathcal{M}_m}{t} \quad (5)$$

$\mathcal{M}_m$ is the mass of accreted matter for a period of the source dynamical age, t. If we assume that the core-jet power, $\mathcal{P}_{cj}$, is a function of accretion rate, $\dot{\mathcal{M}}$; and for simplicity

$$\mathcal{M}_j \approx \mathcal{M}_m(1-e) \quad (6)$$

(where e is defined as conversion efficiency for the kinetic power into radiation, [5]), we may obtain

$$\mathcal{P}_{cj} = \dot{\mathcal{M}}(1-e)\frac{\mathcal{D}_0^2}{t^2} \quad (7)$$

where a has been substituted with $\frac{\mathcal{D}_0}{t^2}$. Therefore equation (3) becomes

$$\eta \approx \left(\frac{\dot{\mathcal{M}}(1-e)}{m_h c v_j^2 t^2 \Gamma}\right)^{\frac{1}{2}} \quad (8)$$

Moreover, it can be shown that accretion rate can be written as [1,3]

$$\dot{\mathcal{M}} = \frac{\mathcal{P}}{ec^2} \quad (9)$$

$\mathcal{P}$ is luminosity. Therefore, eliminating $\dot{\mathcal{M}}$ in equation (8) yields

$$\eta \approx \left(\frac{\mathcal{P}}{c^3 e m_h \mathcal{D}_0^2 \Gamma}\right)^{\frac{1}{2}} \quad (10)$$

Note that $v_j t \equiv \mathcal{D}_0$ by general definition. In terms of source linear size, the last equation becomes

$$\mathcal{D}_0 \approx \left(\frac{\mathcal{P}}{c^3 e m_h \Gamma \eta}\right)^{\frac{1}{2}} \quad (11)$$

The last equation generally signifies dynamical expansion of extragalactic radio sources. With $\mathcal{P}$ as the subject, we have

$$\mathcal{P} \approx c^3 e m_h \Gamma \eta \mathcal{D}_0^2 \quad (12)$$

implying that

$$\mathcal{P} \sim \mathcal{D}_0^2 \quad (13)$$

This relation suggestively indicates that source radiated power is a function of source size.

Moreover, it can be shown in theory that source size shows a power-law dependence on redshift according to the equation [3],

$$\mathcal{D}_0 \sim (1+z)^{-4.5} \quad (14)$$

Therefore, combining the last two equations yields

$$(1+z) \sim \mathcal{P}^{-0.1} \quad (15)$$

The last equation is a theoretical relation that may connect source luminosity and redshift. It plausibly indicates that the luminosity (or generally, radiated power) of an EGRS falls off as $(1+z)^{-9}$. This suggestively implies that sources with lower luminosities are expected to be observed at earlier epochs. This is our theoretical prediction – in the next section, we have our empirical results.

3. Luminosity and Redshift (Empirical)

From luminosity/redshift $\left(\mathcal{P}_{[z(EGRQ)]} - z\right)$ data for EGR quasars (Figure 1), we obtain a relation given by

$$\text{Log}\,\mathcal{P}_{[z(EGRQ)]} = 0.039\text{Log}\,(1+z) + 1.637 \quad (16)$$

(with good correlation coefficient given as $r = 0.8$), which connects the source luminosity, $\mathcal{P}_{[z(EGRQ)]}$, and redshift, z. Transforming the equation, we obtain

$$\mathcal{P}_{[z(EGRQ)]} \sim (1+z)^{0.04} \quad (17)$$

This indicates that observed luminosity shows a direct power-law function with observed redshift.

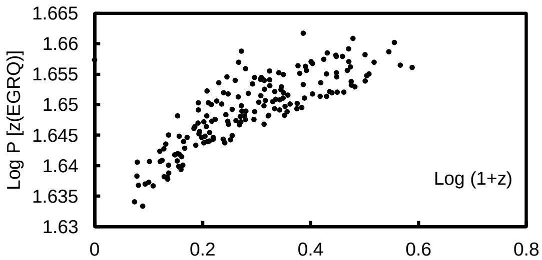

***Figure 1**: The scatter plot of luminosity against redshift for extended quasars*

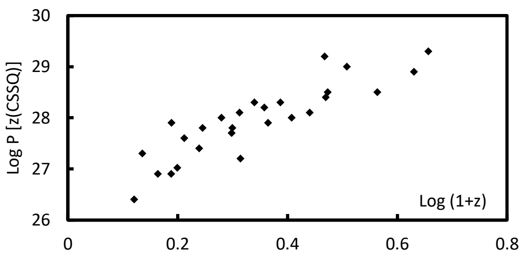

***Figure 2**: The scatter plot of luminosity against redshift for CSS quasars*

In addition to the foregoing, we carry out linear regression of $\mathcal{P}_{[z(CSSQ)]}/z$ data for the CSS quasars (Figure 2), we obtain a relation given by

$$\text{Log}\,\mathcal{P}_{[z(CSSQ)]} = 4.328\text{Log}\,(1+\text{z}) + 26.46 \quad (18)$$

(with good correlation coefficient given by $r = 0.8$). Transforming the equation, we obtain

$$\mathcal{P}_{[z(CSSQ)]} \sim (1+z)^{4.33} \quad (19)$$

This indicates that observed luminosity shows a direct power-law function with observed redshift. Equations (17) and (19) yield respectively

$$(1+z) \sim \mathcal{P}^{25}_{[z(EGRQ)]} \quad (20)$$

and

$$(1+z) \sim \mathcal{P}^{0.23}_{[z(CSSQ)]} P^{0.23} \quad (21)$$

These two empirical results [equations (20 and (21)] are in disharmony with the theoretical result [equation (15)]. What must have caused this disjointedness? There is no doubt, luminosity selection effects [21] (i.e. at higher redshifts, only brighter sources are seen) must have played some role in the empirical relations. However, we are interested in the magnitude of departure of the individual empirical results from the theory. Simply put, why does $\mathcal{P}_{[z(EGRQ)]}$ deviate so much more from the theory than $\mathcal{P}_{[z(CSSQ)]}$ when observed at the same redshift? Figure 3 shows schematically the three results.

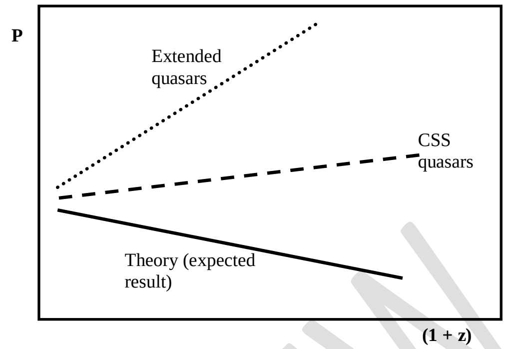

***Figure 3:** Schematics of the deviation among the three results (round dotted line represents extended quasars; dashed line represents CSS quasars; and solid line represents theory)*

The inconsistency may simply indicate that there is something or a factor in the IGM that appears to cause the anomaly in the extended EGR quasars. This is because sources with similar powers are expected to produce similar luminosities, $\mathcal{P}$; and as generally known, central engines of the more extended quasars have roughly similar powers with the CSS central engines; but, as we can see in this work, there is great difference between their radiated powers (luminosities). A plausible explanation to this is that the anomaly may be an effect caused by dark/vacuum energy. It shows that among other factors, dark energy may constitute a factor which affects luminosities of the more extended EGR quasars. The components (jets and lobes) of the more extended EGR quasars lie in the intergalactic medium (IGM). This medium is more of a vacuum than the interstellar medium (ISM) in which the components of the CSS sources lay. Therefore, dark energy is expected to show more effect in the IGM than in the ISM.

Furthermore, from the indices of the three results, we estimate percentage influence caused by luminosity selection effects and that caused by dark/vacuum energy. The estimates are respectively, $\frac{0.33}{25.1} \times 100\% = 1.31\%$ and $\frac{24.77}{25.1} \times 100\% = 98.69\%$. This shows that intrinsically dark/vacuum energy influences extended quasars' luminosities by ≈ 75 times more than the observational bias caused by luminosity selection effects.

4. Discussion and Conclusion

We have used both analytical and statistical methods to show some plausible consequences of luminosity/redshift relationships for CSS quasars and the more extended radio-loud quasars. We assume lobe confinement by ram-pressure balance with the ambient density, we may have [3,11,20], to obtain equation (1); i.e. $\mathcal{P}_\ell \approx \eta m_h v_l^2$, where $\mathcal{P}_\ell$ is lobe internal pressure, η particle number density of the source ambient medium, and m_h hydrogen mass. Moreover, we can show that jet kinetic power, $\mathcal{P}_{cj}$, may be written as [20] $\mathcal{P}_{cj} \approx \eta m_h c v_j^2 \Gamma \mathcal{D}_0^2$ (see equation [2]). Γ is jet opening solid angle, c light speed; while other symbols have their usual meanings. We rewrite equation (15) to obtain $\mathcal{D}_0 \approx \left(\frac{\mathcal{P}_{cj}}{\eta m_h c v_j^2 \Gamma}\right)^{\frac{1}{2}}$; i.e. equation (3).

Moreover, from the definitions of core-jet power ($\mathcal{P}_{cj}$) and accretion rate, we obtained equation (10); i.e. $\eta \approx \left(\frac{\mathcal{P}}{c^3 e m_h \mathcal{D}_0^2 \Gamma}\right)^{\frac{1}{2}}$. The symbols have their usual meanings. In terms of source linear sizes, equation (10) becomes

$\mathcal{D}_0 \approx \left(\frac{\mathcal{P}}{c^3 e m_h \Gamma \eta}\right)^{\frac{1}{2}}$; i.e. equation (11). Equation (11) generally is a statement of dynamical expansion of extragalactic radio sources. In terms of $\mathcal{P}$ it becomes $\mathcal{P} \approx c^3 e m_h \Gamma \eta \mathcal{D}_0^2$ which implies that $\mathcal{P} \sim \mathcal{D}_0^2$. This relation suggestively indicates that source radiated power is a function of size of the source.

Moreover, it can be shown in theory that source size shows a power-law dependence on redshift according to equation (14) [3]; i.e. $\mathcal{D}_0 \sim (1+z)^{-4.5}$. Therefore, from equations (13) and (14) we get equation (15) [i.e. $(1+z) \sim \mathcal{P}^{-0.1}$]. Equation (15) is a theoretical relation that may connect source luminosity and redshift. It plausibly indicates that the luminosity (or generally, radiated power) of an EGRS falls off as $(1+z)^{-9}$. Hence, it states that sources with lower luminosities are observed at earlier epochs.

However, from luminosity/redshift $\left(\mathcal{P}_{[z(EGRQ)]} - z\right)$ data for EGR quasars (see Figure 1), we obtain a relation given by (17); i.e. $\mathcal{P}_{[z(EGRQ)]} \sim (1+z)^{0.04}$. This states that sources with higher luminosities are observed at earlier epochs – this is in contradiction to the theoretical result. In addition, we carry out linear regression of $\mathcal{P}_{[z(CSSQ)]}/z$ data for the CSS quasars (see Figure 2), and obtain a relation given by equation (19); i.e. $\mathcal{P}_{[z(CSSQ)]} \sim (1+z)^{4.33}$. This also implies that sources with higher luminosities are observed at earlier epochs; and is in sharp contrast to the theoretical value. Equations (17) and (19) may be rearranged to obtain respectively equations (20) and (21). These are $(1+z) \sim \mathcal{P}_{[z(EGRQ)]}^{25}$ and $(1+z) \sim \mathcal{P}_{[z(CSSQ)]}^{0.23}$ respectively.

It is easily noticeable that these two empirical results – equations (20) and (21) – are in discord with the theoretical result [see equation (15)]. One may wonder what must have caused this. We know undoubtedly that luminosity selection effects must have played some role in the anomaly [21]. Nevertheless, we are actually interested in the magnitude of departure of the individual empirical results from the theory. We ask, why should $\mathcal{P}_{[z(EGRQ)]}$ deviate so much more from the theory than $\mathcal{P}_{[z(CSSQ)]}$ when both are observed at same redshift? Figure 3 shows schematically the three results.

We may state categorically that this discrepancy may simply be a sign of a factor in the IGM that appears to cause the anomaly in the extended EGR quasars. This is because sources with similar powers are expected to produce similar luminosities, P. As generally known, central engines of the more extended quasars have roughly similar powers with the CSS central engines; nevertheless, as we can see in this work, there is great difference between their radiated powers (luminosities). A likely explanation to this is that the irregularity may be a signature of dark/vacuum energy. It simply indicates that among other factors, dark energy may constitute a factor which affects luminosities of the more extended EGR quasars. The components (jets and lobes) of the more extended EGR quasars lie in the intergalactic medium (IGM). This medium is more of a vacuum (or more rarefied) than the interstellar medium (ISM) in which the components of the CSS sources are housed. Therefore, dark energy is expected to show more effect in the IGM than in the ISM.

Besides, from the indices of the three results, we estimate percentage influence caused by luminosity selection effect and that caused by dark/vacuum energy. The estimates are respectively, $\frac{0.33}{25.1} \times 100\% = 1.31\%$ and $\frac{24.77}{25.1} \times 100\% = 98.69\%$. These results show that intrinsically dark/vacuum energy influences extended quasars' luminosities by roughly 75 times more than the observational bias caused by luminosity selection effects.

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