J. Astrophys. Astr. (2020) 41:9
https://doi.org/10.1007/s12036-020-9626-x

On the unified view of gamma-ray energy distribution of BL Lac objects and flat spectrum radio quasars

F. C. ODO* and B. E. AROH

Department of Physics and Astronomy, University of Nigeria, Nsukka, Nigeria.
*Corresponding author. E-mail: finbarr.odo@unn.edu.ng

MS received 31 August 2019; accepted 12 February 2020

Abstract. We study the distributions of γ-ray properties of a sample of γ-ray loud blazars taken from the third catalogue of blazars detected by Fermi-Large Area Telescope (Fermi-LAT). We compute the γ-ray dominance (D_g) of the sample which includes 415 flat spectrum radio quasars (FSRQs) and 535 BL Lacertae objects (BL Lacs). We find that BL Lacs and FSRQs are highly dominated by γ-ray emission, which is consistent with diffuse high-energy neutrino flux associated with γ-ray loud blazars. The γ-ray dominance fairly scales with γ-ray luminosity ($r \sim +0.5$) in both BL Lacs and FSRQs, but shows little or no correlation ($r \leq 0.2$) with radio luminosity in either sample. BL Lacs and FSRQs occupy separate and parallel regions on the D_g- luminosity plane. There is a fairly significant correlation ($r \sim 0.5$) between γ-ray dominance and frequency at synchrotron peak (ν_{pk}) in BL Lacs, which disappears in FSRQs. On the other hand, there is a tight correlation ($r \geq +0.8$) between γ-ray and radio luminosity with a smooth transition from BL Lacs at low luminosities to FSRQs at high luminosities. Nevertheless, the presence of few BL Lac-like FSRQs is noted. These results suggest that while there may be intrinsic differences between BL Lacs and FSRQs, some form of a unified scheme can also be relevant.

Keywords. Galaxies—active galaxies—blazars – general.

1. Introduction

Blazars are a rare and violent type of active galactic nuclei (AGN) which are characterized by strong, rapid and irregular variability of radiation fluxes, flat radio spectra, optical polarization and frequent superluminal motion (Urry & Padovani 1995; Fan & Xie 1996; Li *et al.* 2017). Based on their optical spectra, blazars have two main subclasses, namely, those with strong, broad emission lines, known as flat spectrum radio quasars (FSRQs), and those with weak or absent emission lines, known as BL Lacertae objects (BL Lacs). According to the unified schemes for radio loud AGN, FSRQs and BL Lacs are said to be beamed counterparts of high- and low-luminosity radio galaxies, respectively with their radio jets forming small angles with the line-of-sight (Urry & Padovani 1995). Blazars emit non-thermal radiation across the whole electromagnetic spectrum. Recent studies show that blazars are strong γ-ray emitters and dominate the high-energy sky (Savolainen *et al.* 2010; Abdo *et al.* 2010; D'Abrusco *et al.* 2019). However, the spectral energy distribution (SED) of blazars gives two peaks in a frequency–luminosity ($\nu - \nu F_\nu$) representation, often attributed to synchrotron process at low (radio to X-ray) energy and inverse Compton process at high (X-ray to γ-ray) energy (e.g. Padovani *et al.* 2003).

The relationship between the two blazar subclasses has been an outstanding problem in blazar research for past few decades and is a subject of intense study (Fossati *et al.* 1998; Padovani *et al.* 2019). Some authors argue that FSRQs evolve into BL Lacs, becoming weak-lined objects by virtue of increased beaming of the continuum (Vagnetti *et al.* 1991); suggested that the jet angle to the line-of-sight could significantly contribute to variations in properties of different subclasses of blazars (Finke 2013). However, the supposition under this context is that BL Lacs represent FSRQs with the most highly boosted continuum is increasingly criticized with the recognition that the amount of relativistic beaming and intrinsic power are lower in some BL Lacs than in FSRQs (Padovani 1992; Ghisellini *et al.* 1993; Chen *et al.* 2016; Odo *et al.* 2017), implying some intrinsic differences. Similarly, since BL Lacs and FSRQs

Published online: 19 March 2020

were observed to occupy separate and approximately parallel regions in the luminosity–redshift plane (Urry & Padovani 1995), it was said that the two subclasses have distinct histories rather than evolutionary connection. However, recent results (Odo *et al.* 2017) seem to provide substantial evidence that FSRQs can evolve into BL Lacs through luminosity evolution. Furthermore, recent analyses of γ-ray data of blazar samples suggest a close connection between γ-ray emission, relativistic beaming and orientation of the blazars (Savolainen *et al.* 2010; Li *et al.* 2017). In fact, the lack of γ-ray bright blazars at large viewing angles has been interpreted to say that relativistic beaming of γ-rays is important in blazars (Savolainen *et al.* 2010). Furthermore, there is a close connection between γ-ray emission and high-energy neutrino flux associated with both FSRQs and BL Lacs (Palladino *et al.* 2019). All these appear to provide evidence that there is a unified scheme for blazars in the γ-ray band.

On the other hand, it is widely argued that FSRQs and BL Lacs are different manifestations of the same physical process that differ only by bolometric luminosity (Fossati *et al.* 1998; Ghisellini *et al.* 1998). This has led to the popular unification of the blazar phenomenon through 'blazar sequence', which appears to dominate discussions on unification of the blazars in recent studies (Fossati *et al.* 1998; Meyer *et al.* 2011; Finke 2013; Mao *et al.* 2016) and suggests that the differences between the blazar subclasses arise from effects connected with the differences in bolometric luminosity. The two-component broad-band SED of blazars has led to a new classification of the blazar family of AGNs into high-synchrotron peaking (HSP), intermediate-synchrotron peaking (ISP) and low-synchrotron peaking (LSP) blazars, depending on the frequency at the peak of synchrotron emission (Ackermann *et al.* 2011; Abdo *et al.* 2010). Analyses of SED of recent blazar samples suggest that while most FSRQs are LSPs, BL Lacs span the entire range from LSPs, through ISPs to HSPs (Abdo *et al.* 2010). A unification of the blazars through the broad-band SED (Fossati *et al.* 1998), on one hand, suggests a sequence in which the frequency at the peak of synchrotron emission ($\nu_{\rm pk}$) is anti-correlated with bolometric luminosity ($L_{\rm bol}$). This sequence has been widely studied earlier and a range of conflicting results have been reported (Fossati *et al.* 1998; Nieppola *et al.* 2006; Padovani *et al.* 2003; Meyer *et al.* 2011; Finke 2013; Odo *et al.* 2014; Nalewajko & Gupta 2017).

An important aspect of the blazar sequence that has gained attention by Finke (2013), Nalewajko & Gupta (2017), is the relationship between low-energy and high-energy components of SED. Fossati *et al.* (1998) introduced a broad-band parameter, namely, γ-ray dominance ($D_{\rm g}$), defined as the ratio of γ-ray luminosity ($L_{\rm g}$) to the luminosity at synchrotron peak ($L_{\rm pk}$) and found strong anti-correlation between the parameter and synchrotron peak frequency ($\nu_{\rm pk}$) for the energetic gamma-ray experiment telescope (EGRET) blazars, which they used to argue for a blazar sequence. $D_{\rm g}$ is expected to show a sequence of increase from HSPs at low-synchrotron luminosity end, through ISPs to LSPs at high-synchrotron luminosity end. This sequence obviously suggests that the SED of FSRQs would be more dominated by γ-ray emission than the BL Lacs, making γ-ray dominance is an important tool for studying blazar sequence. However, this parameter seems to have been somewhat overlooked in earlier studies, partly due to insufficient γ-ray information for majority of blazars in older samples: only 33 blazars were detected in the γ-ray band by the EGRET instrument, which were used by Fossati *et al.* (1998). Thus, several authors adopted some proxy parameters, which depend on $\nu_{\rm pk}$ to study the sequence. Among the proxy parameters that were frequently used, it is the effective broad-band spectral index (α_{1-2}), usually defined between two frequencies (Abdo *et al.* 2010) as

$$\alpha_{1-2} = \frac{\log\left(\frac{F_1}{F_2}\right)}{\log\left(\frac{\nu_1}{\nu_2}\right)}, \quad (1)$$

where F_1 and F_2 are the observed radiation fluxes at the frequencies ν_1 and ν_2 respectively. A major problem against this parameter is that it is somewhat redshift-dependent (Athreya & Kapahi 1998) in the sense that the spectrum is steeper at high redshifts than at low redshifts, which would introduce some ambiguities in the analyses.

Nevertheless, Finke (2013) attempted to break the neglect of γ-ray dominance by deriving a similar parameter, namely, Compton dominance (CD). It is defined as the ratio of luminosity at inverse Compton peak ($L_{\rm IC}$) to luminosity at synchrotron peak ($L_{\rm pk}$) to study the sequence, and which the author argued it to also be redshift independent. However, for many FSRQs, the peak position of the high energy hump is not known such that Finke (2013) estimated CD using empirical relations that are associated with varying degrees of error. The effect is that a distinct L-shape is observed on CD–$\nu_{\rm pk}$ plane, rather than a clear anti-correlation as proposed by Fossati *et al.* (1998) for $D_{\rm g}$. Although $D_{\rm g}$ is known to be related to CD and $\nu_{\rm pk}$: $D_{\rm g} \approx f(\text{CD}; \nu_{\rm pk})$, the nature of the relationship between them over wide $\nu_{\rm pk}$ range is not yet clear (Giommi *et al.* 2013). Moreover, subsequent analyses using CD as alternative parameter to $D_{\rm g}$

(Nalewajko & Gupta 2017) have not found satisfactory results in support of the correlation of D_g with spectral properties as proposed by Fossati *et al.* (1998) and this is partly the motivation for present study.

Although blazar unification appears to have been well studied up to X-ray band by several authors earlier (Nieppola *et al.* 2006), it is still poorly studied in the γ-ray band mainly due to paucity of γ-ray data for a vast majority of the blazars. However, Fermi-Large Area Space Telescope (Fermi-LAT) has enabled the characterization of GeV γ-ray energy component of a large number of blazar AGNs than previously possible. Results convincingly show that a large number of blazars detected by Fermi-LAT are γ-ray loud, the ratio of their integral γ-ray flux exceeds the radio flux by a factor $\geq$ 10 (Dondi & Ghisellini 1995; Böck *et al.* 2016). The distribution of the γ-ray loudness of blazars suggests that while quasars are less γ-ray loud, the BL Lacs cover a broader range with somewhat higher average γ-ray loudness – a sequence that seems to be consistent with shift of peak frequencies in the SEDs (Böck *et al.* 2016). Although, it is now well known that extreme high-energy peaked BL Lacs with inverse Compton peaks up to several TeV energy are emerging from recent observations of Imaging Atmospheric Cherenkov Telescopes (IACTs), but the number of TeV detected BL Lacs is still very limited and the extreme TeV spectra is yet to be unambiguously modelled (Foffano *et al.* 2019). Hence, most of the statistical population properties of γ-ray loud AGNs still rely on the Fermi-LAT data. In this paper, we use the distributions of 1-GeV γ-ray dominance of BL Lacs and FSRQs in a sample of Fermi-LAT blazars to study a unification of BL Lac and FSRQ populations.

2. FSRQ–BL Lac unification

Relativistic beaming and orientation hypothesis – a popular paradigm that explains the difference between various subclasses of active galactic nuclei as similar objects seen at varying orientation angle to the line-of-sight, has been remarkably successful in explaining the variability of SED of blazars. The distinctive characteristic of blazars is a relativistic jet-oriented close to our line-of-sight. Synchrotron radiation of energetic electrons in the jet dominates the low energy end of the blazar SED. This emission is strongly beamed due to relativistic effects which increase the observed flux of a stationary jet (Pei *et al.* 2019). According to this theoretical framework, the dependence of the syspectral flux (F_ν) of a relativistic jet at any frequency (ν) on the viewing angle (ϕ) is directly due to the increased Doppler boosting factor (δ) at low angles in the form (Bai and Lee 2001)

$$\delta = [\Gamma\,(1-\beta\cos\phi)]^{-1} \tag{2}$$

where $\Gamma = \left(1-\beta^2\right)^{-1/2}$ is the bulk Lorentz factor of the jet and β is the speed of the radiating plasma (in units of speed of light). The double peak in SED, often attributed to synchrotron and inverse Compton radiation from the relativistic jet, dominates in blazars due to the alignment of the jet axis close to the line-of-sight (Böttcher 2007). Thus, if BL Lacs and FSRQs differ in orientation, the difference in their spectral energy distributions can also be accommodated in the beaming models. In this sense, blazar sequence posits that misaligned blazars will drop in spectral luminosity according to the decrease in Doppler boosting with increasing viewing angle and synchrotron peak frequency (Meyer *et al.* 2011). However, it was thought that BL Lacs are seen through intervening galaxies, so that microlensing effects lead to higher boosting than in FSRQs (Ostriker & Vietri 1985). The fact that luminosity of FSRQs in the radio band is systematically higher than that of BL Lacs, and it seems to favour a unified scheme via orientation, but somewhat contradictory to the initial supposition that BL Lacs represented FSRQs with the most highly boosted continuum (Vagnetti *et al.* 1991).

Typical SED of different subclasses of blazars from which the blazar sequence scheme was proposed shows that the synchrotron (lower energy) peaks are systematically displaced from low frequency at high luminosity end to high frequency at low luminosity end (Fossati *et al.* 1998; Ghisellini *et al.* 1998; Donato *et al.* 2001), which suggests an anti-correlation between $L_{\rm pk}$ and $\nu_{\rm pk}$, implying a unification scheme for the different subclasses of blazars – the blazar sequence unification scenario. Agreement with the blazar spectral sequence is found by Ghisellini *et al.* (1998); Finke (2013); Odo *et al.* (2014). This sequence also appears to fit in very nicely with a unification of the FR-I and FR-II radio galaxies (Bicknell 1995). However, violations to the sequence are well-known, especially, with the emergence of low radio power FSRQs outside the spectral blazar sequence (Perlman *et al.* 1998; Padovani *et al.* 2003; Raiteri & Capetti 2016).

Analyses of γ-ray data of recent blazar samples (Chen *et al.* 2016) appear to provide evidence that relativistic beaming and orientation can be important in explaining the variation of γ-ray emission from blazars. This is supported by many correlations between the γ-ray flux and radio properties of γ-ray loud samples

(Giommi *et al.* 2013). In particular, the requirement that the γ-ray bright sources have small linear sizes as deduced from the γ-ray variability, suggests that the γ-ray emission originates in the jet and is also relativistically beamed, in the same manner as the low-energy emission (Savolainen *et al.* 2010). Hence, in general, the observed spectral flux (F_ν) depends strongly on the viewing angle (ϕ) and can be expressed in terms of the intrinsic value (F_i) as

$$F_\nu = F_i \delta^{n+\alpha_\nu} \quad (3)$$

where α_ν is the spectral index at the observed frequency ($F_\nu \sim \nu^{-\alpha}$) and n is a jet-model dependent parameter: $n = 2$ for continuous jet model, whereas $n = 3$ for blob jet model (Lind & Blandford 1985). Equations (2) and (3) suggest that a systematic trend in variation of γ-ray flux from FSRQs at high γ-ray flux to BL Lacs at low γ-ray flux would be expected and can represent a sequence of orientation of the jets to the line-of-sight.

The discovery of high-energy neutrino flux associated with a γ-ray loud blazar (TXS 0506 + 056) has opened a new chapter in understanding the underlying physical processes in blazars (IceCube Collaboration 2018). The neutrino flux (F_μ) is found to correlate strongly with γ-ray flux (F_g) in blazars and can be expressed (Palladino *et al.* 2019) as

$$F_\mu \approx \psi F_g \quad (4)$$

where ψ is a parameter that quantifies neutrino production efficiency from accelerated cosmic rays within the jet. Equation (4) provides the framework upon which neutrino emission around blazars is being explained with blazar radiation models (Keivan *et al.* 2018). An obvious implication of this scenario is that neutrino emission from blazars can be accommodated in a beaming model of blazar unified scheme and should also give rise to a sequence across different subclasses of blazars.

3. Analysis and results

The analysis presented here is based on a sample of 1081 blazars taken from the third catalogue of blazars (Acero *et al.* 2015) detected by the Fermi-LAT. The sample consists of 461 FSRQs and 620 BL Lacs. Most objects in current sample have been detected in various earlier studies, which enabled a characterization of their spectral energy distributions using empirical relationships between low- and high-energy flux (Ackermann *et al.* 2011; Acero *et al.* 2015). However, 85 BL Lacs and 46 FSRQs in the sample do not have information on radio luminosity, and hence were excluded from the analysis. For the remaining 950 objects (535 BL Lacs and 415 FSRQs) with complete data, we calculate the γ-ray dominance, which for simplicity; we derive from the available monochromatic 1-GeV γ-ray luminosity and peak synchrotron luminosity data. We note that γ-ray dominance calculated in this way is redshift-independent, given as (Ubachukwu 1998)

$$L_\nu = 4\pi d_\mathrm{L}^2 F_\nu (1+z)^{\alpha_\nu+1} \quad (5)$$

where d_L is the luminosity distanc and z is the redshift. Henceforth, we adopt the modern concordance (Λ CDM) cosmology with $H_0 = 70\,\mathrm{km\,s^{-1}Mpc^{-1}}$ and $\Omega_0 = \Omega_\mathrm{m} + \Omega_\Lambda = 1$ ($\Omega_\mathrm{m} = 0.3$; $\Omega_\Lambda = 0.7$), with the luminosity distance defined as (Ubachukwu 1998)

$$d_L = H_0^{-1} \int_0^z \left[(1+z)^2 (1+\Omega_m z) - z(2+z)\,\Omega_\Lambda\right]^{-1/2} \mathrm{d}z \quad (6)$$

The distribution of the 950 objects in 1-GeV γ-ray luminosity (L_g) is shown in Figure 1. Apparently, the distribution is continuous, with the FSRQs displaced to high γ-ray luminosity and BL Lacs to low γ-ray luminosity, suggestive that FSRQs are stronger γ-ray emitters than BL Lacs. Nevertheless, the distributions yield mean (logarithm) values $\sim$ 44.81 and 46.18 ergs^{-1} for BL Lacs and FSRQs, respectively. Furthermore, statistical test reveals that both BL Lacs and FSRQs are nicely fitted to a log–normal distribution with skewness, $\mu \sim -0.08$ and -0.03, respectively. The observation suggests that similar mechanisms are responsible for the variations in γ-ray luminosity of both classes of objects. Thus, we carried out a two-sample Kolmogorov–Smirnoff (K–S) test between the distributions of these BL Lacs and FSRQs. The result yields almost a zero probability that there is a fundamental difference between the underlying distributions of these objects in γ-ray luminosity.

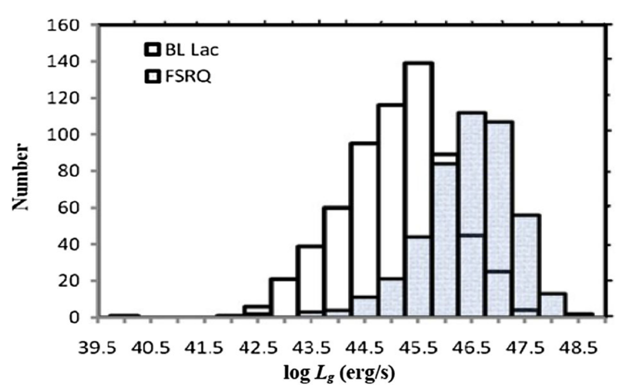

Figure 1. Distribution of FSRQs and BL Lacs in 1-GeV γ-ray luminosity.

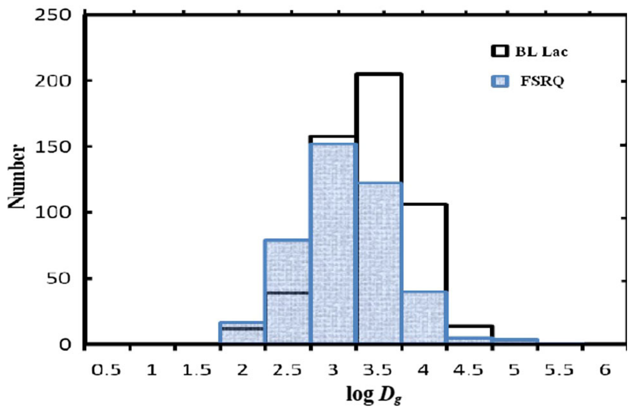

Figure 2. Distributions of FSRQs and BL Lacs in γ-ray dominance.

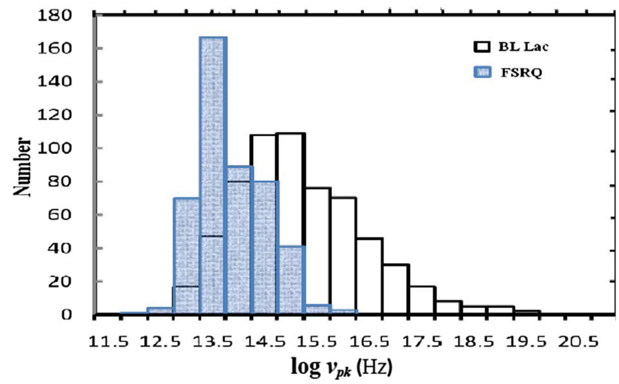

Figure 3. Distributions of the BL Lacs and FSRQs in synchrotron peak frequency.

We show the distribution of the sample in γ-ray dominance (D_g) in Figure 2. Obviously, BL Lacs and FSRQs are indistinguishable in the plot. However, the distribution gives a mean value of 3.25 ± 0.43, on logarithmic scale, for the two sub-samples taken together. This is consistent with γ-ray emission of blazars being up to three orders of magnitude more prominent than radio emission (Abdo *et al.* 2011; Dermer & Giebels 2016; Nalewajko & Gupta 2017), which shows that blazars are strong γ-ray emitters. The mean values for individual sub-samples on logarithmic scales are 3.40 ± 0.30 and 3.01 ± 0.22, respectively for BL Lacs and FSRQs. Thus, BL Lacs are more γ-ray dominant than FSRQs. Although FSRQs are more luminous in the γ-rays, implying that γ-ray luminosity is not the leading driver of γ-ray dominance. Perhaps, γ-ray dominance may be more sensitive to synchrotron activities in the jets, which make it useful as a parameter for studying the blazar sequence. Figures 1 and 2 show the interesting features that can be considered relevant for BL Lac–FSRQ unification: there is continuity in distributions of γ-ray properties of FSRQs and BL Lacs in the figures.

Similarly, the distribution of the sample in synchrotron peak frequency (ν_{pk}) is shown in Figure 3. While all FSRQs are low and intermediate-synchrotron peaking sources log $\nu_{pk} \leq 15.5$, BL Lacs span the entire frequency range, with mean values of log $\nu_{pk} \sim 15.07$ Hz and 13.60 Hz, respectively for BL Lacs and FSRQs.

We study the relationship between low- and high-energy components of the SED of current sample by plotting the scatter of 1.4 GHz radio luminosity against Fermi 1-GeV γ-ray luminosity in Figure 4. There is a tight correlation between γ-ray and radio luminosities with a smooth transition from BL Lacs at low luminosities to FSRQs at high luminosities. Simple regression analysis on the data yields log $L_g = (0.91 \pm 0.08)$ log $L_R + (6.32 \pm 0.11)$ with a correlation coefficient $r \sim +0.85$ for the entire sample taken together, log $L_g = (0.92 \pm 0.08)$ log $L_R + (6.36 \pm 0.10)$ with a correlation coefficient $r \sim +0.86$ for BL Lacs and log $L_g = (0.91 \pm 0.12)$ log $L_R + (6.61 \pm 0.34)$ with $r \sim +0.82$ for FSRQs. All together, the highest luminosity regime is populated mostly by FSRQs and the lowest luminosity regime mostly by BL Lacs, with spectral slope close to unity, which is in good agreement with the original blazar sequence proposed by Fossati *et al.* (1998). However, we observe the presence of a number of FSRQs, which are up to two-orders of magnitude fainter than the vast majority of the FSRQs in radio and γ-ray luminosities.

To study the relative effects of γ-ray dominance on spectral luminosity, the scatter plot of γ-ray dominance against each of γ-ray luminosity and radio luminosity is shown in Figure 5. A form of dichotomy between FSRQs and BL Lacs is well pronounced in each plot. Apparently, while the two populations of sources share the same parameter space in γ-ray dominance, FSRQs are displaced to higher γ-ray and radio luminosities compared to BL Lacs. An interesting feature of Figure 5 is that while the γ-ray dominance appears to increase with increasing γ-ray luminosity in (a), it appears to be decreasing with increasing radio luminosity in (b). Regression analysis of the data show that there is a fairly significant correlation between γ-ray dominance and γ-ray luminosity in Figure 5(a), whereas there is little or no correlation between γ-ray dominance and radio luminosity in Figure 5(b) for both FSRQ and BL Lac subclasses. Results yield $r \sim +0.5$ as the correlation coefficient for each of FSRQs and BL Lacs between γ-ray dominance and γ-ray luminosity. On the other hand, radio data shown in Figure 5(b) yield correlation coefficient $r \sim$ –0.1 and –0.2, respectively for FSRQs and BL Lacs, with chance probability $\rho < 10^{-4}$ in each

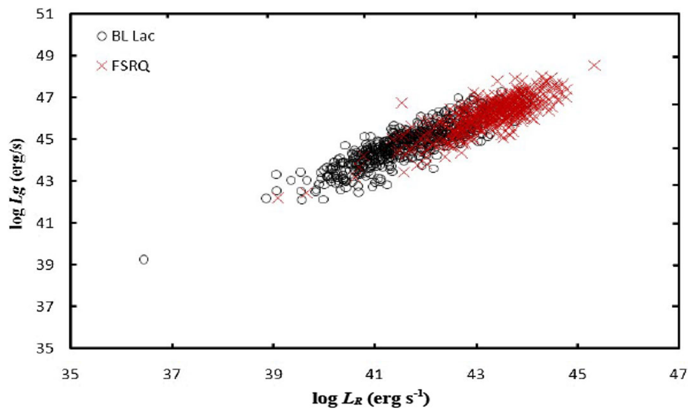

Figure 4. Scatter plot of Fermi γ-ray luminosity against radio luminosity of BL Lacs and FSRQs.

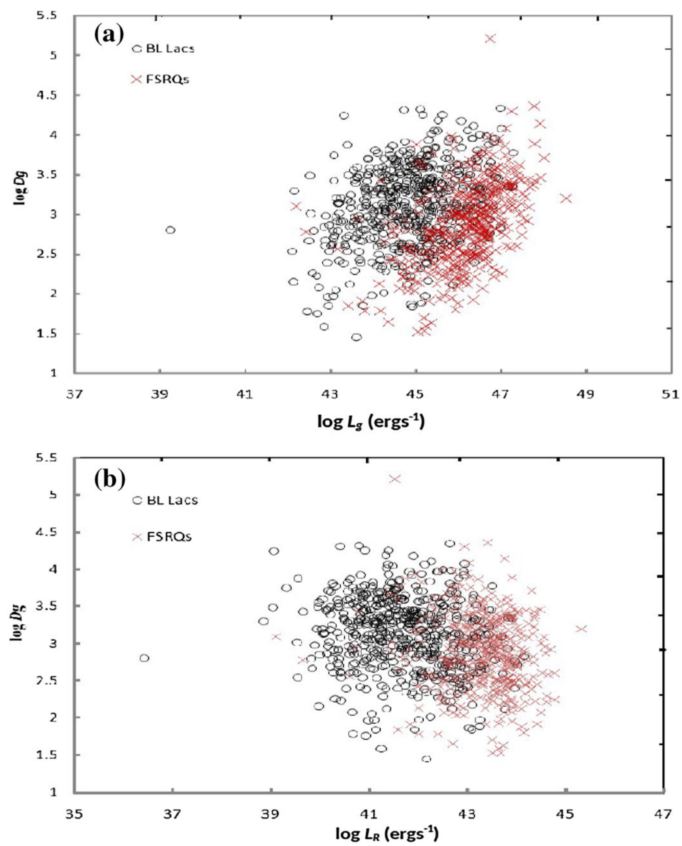

Figure 5. Scatter plot of γ-ray dominance against γ-ray luminosity (a) and radio luminosity (b) for the BL Lacs and FSRQs.

case. Obviously, the variation in γ-ray dominance is driven by intrinsic variations in γ-ray luminosity, rather than radio luminosity, suggestive that radio emission has little effects on the detection of γ-rays around the blazars. We conclude that the observed radio power is not a major driver of the broadband properties of the blazars.

We use the γ-ray dominance to study blazar sequence in the sample. Thus, the scatter plot of the γ-ray dominance against synchrotron peak frequency is shown in Figure 6. It could be observed from the plot that the BL Lac sources span about six orders of magnitude in $\nu_{\rm pk}$ and γ-ray dominance appears to increase linearly with it over the $\nu_{\rm pk}$ range. There is no tendency for high $\nu_{\rm pk}$ BL Lacs to possess low $D_{\rm g}$. Correlation analysis yields a fairly significant correlation ($r \sim +0.5$) between $D_{\rm g}$ and $\nu_{\rm pk}$ for the BL Lacs, with a chance probability $\rho \sim 10^{-3}$, which is not observed in the FSRQs: the scatter increases towards low $\nu_{\rm pk}$ where the FSRQs are concentrated. This suggests that the

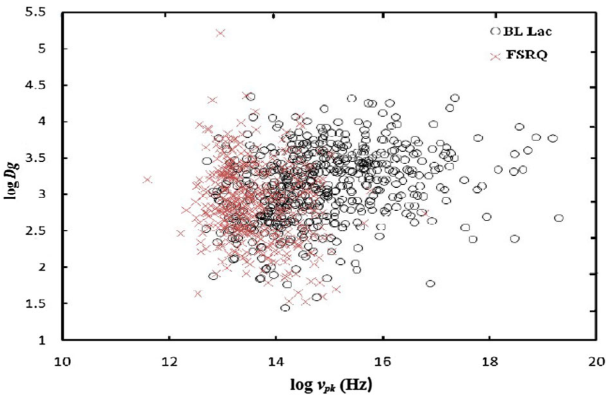

Figure 6. Scatter plot of γ-ray dominance against synchrotron peak frequency for BL Lacs and FSRQs.

mechanisms controlling D_g may be different in the two subclasses. Nevertheless, the correlation seems to persist ($r \sim +0.4$) when BL Lacs and FSRQs are taken together, but there is a chance of probability $\rho \sim 0.2$. Figure 6 appears rather like a mirror image of L-shaped anti-correlation of CD–ν_{pk} data found by Finke (2013) for the second Fermi-LAT blazars or the strong anti-correlation for D_g–ν_{pk} data found by Fossati *et al.* (1998) for the EGRET sample.

4. Discussion and conclusion

We have used 1-GeV γ-ray dominance of Fermi-LAT blazars to study the relationship between BL Lacs and flat spectrum radio quasars, in order to understand the connection between the high energy components of the two major subclasses of blazars. The results have shown that both BL Lacs and FSRQs are sites of very high energy phenomena with γ-ray emission ranging up to three orders of magnitude higher than radio emissions (Dermer & Giebels 2016). This requires a very powerful energy source and supports the hypothesis of highly relativistic jets at small orientation angles to the line-of-sight (Mukherjee *et al.* 1997), with an efficient energy conversion into γ-rays.

Distribution of the objects in γ-ray luminosity shows that FSRQs, on average, are more prominent in the γ-ray band than BL Lacs. FSRQs are high-radio luminosity sources while BL Lacs are low-radio luminosity objects and the trend also persists in γ-ray band. Most FSRQs in the sample have higher radio and γ-ray luminosities than BL Lacs. The high and wide range of γ-ray luminosity detected around the BL Lacs and FSRQs can be understood in terms of a combination of synchrotron self Compton of both leptonic and hadronic processes (Rees 1967) and external Compton process in which there is inverse Compton scattering of photon fields coming from different sources outside the jets (Dermer & Schlickeiser 1993). This is actually in agreement with a recent prediction through Monte Carlo simulation of close connection between γ-ray emission from AGNs and neutrino flux (Palladino *et al.* 2019).

We have observed in the results that there is a tight correlation ($r \geq 0.8$) between the radio and γ-ray luminosities in each of the subsamples. This actually seems to support many strong correlations between γ-ray emission and radio properties of blazars detected in earlier γ-ray loud blazar samples (e.g. Kovalev *et al.* 2005). Obviously, BL Lacs and FSRQs were observed to be continuous in the radio–γ-ray luminosity plane, which can be interpreted to understand that the two subclasses of blazars have similar luminosity histories (Odo *et al.* 2017). Analysis of redshift data of current sample also shows that the BL Lacs and FSRQs match in redshift (see also Ghisellini *et al.* 2017). Since on one hand, the correlation or lack of correlation between source parameters could be due to evolutionary effects generally related to redshift (Alhassan *et al.* 2013), we checked its effect in current analysis by subtracting out the common dependence of both luminosities on redshift using Spearman's partial correlation statistic. The Spearman partial correlation coefficient for $L_g - L_R$ relation independent of redshift (z) is given (Odo & Ubachukwu 2013) by

$$r_{gR,z} = \frac{r_{gR} - r_{gz} r_{Rz}}{\left[\left(1 - r_{gz}^2\right)\left(1 - r_{gz}^2\right)\right]^{\frac{1}{2}}} \tag{7}$$

The result yields $r_{gR,z} = 0.88$. The result shows a strong intrinsic connection between radio and γ-ray emission of blazars, which is frequently used to argue in favour of relativistic beaming and orientation of γ-ray emissions (Liu *et al.* 2016). The observations also seem to suggest a fundamental connection between FSRQs and BL Lacs and are actually in agreement with the radio-based hypothesis that BL Lacs and FSRQs can be unified via luminosity evolution (Odo *et al.* 2017). However, Liu *et al.* (2016) have used the correlation between radio core-dominance and γ-ray luminosity of 80 Fermi detected radio sources to argue that relativistic beaming and orientation effects play a significant role in detection of γ-ray emissions of AGNs (see also Chen *et al.* 2016). Perhaps, the strong γ-ray emission detected around FSRQs and BL Lacs in this study is an indication of strong beaming effect, in which sense, it can be suggested that blazars possess highly boosted

γ-ray continuum. If this is actually the case, then the difference in distributions of γ-ray emission of BL Lacs and FSRQs in current analysis is attributable to beaming effects and can be interpreted to mean that the two subclasses of blazars may differ in orientation (Chen *et al.* 2016; Li *et al.* 2017).

We have consistently shown in the results that there is a close connection between γ-ray energy distributions of FSRQs and BL Lac objects, which can be understood in the framework of blazar sequence. The blazar sequence posits that BL Lacs and FSRQs are different manifestations of the same physical process that differ only by bolometric luminosity (Fossati *et al.* 1998; Ghisellini *et al.* 1998). In this sense, there should be continuity in distributions of spectral properties of BL Lacs and FSRQs. Distributions of the γ-ray luminosity and γ-ray dominance of current sample of blazars are apparently in agreement with the scheme, as there is clear continuity between the subclasses of blazars. However, the distribution of the objects in γ-ray dominance does not evidently show that FSRQs are more γ-ray dominant than BL Lacs. It is an indication that more efficient γ-ray emitters are not the more γ-ray dominant sources. Moreover, where there is a correlation between γ-ray dominance and ν_{pk} for the BL Lacs, there is virtually no correlation for FSRQs, but there appears to be a general trend in variation of γ-ray dominance from FSRQs to BL Lacs. Regression analysis of D_g–L_{pk} data yields a fairly significant anti-correlation ($r \sim -0.5$) for BL Lacs and FSRQs taken together. The results appear to be consistent with blazar sequence. However, the results are not to be in close agreement with a recent result in the radio band (Pei *et al.* 2019) in which both radio core-dominance parameter and spectral indices are quite different for BL Lacs and quasars. Nevertheless, γ-ray luminosity did not yield any significant anti-correlation with ν_{pk} which is not consistent with the blazar sequence.

The distribution of γ-ray dominance as a function of ν_{pk} observed in this study for FSRQs and BL Lacs cannot be due to orientation as there is no continuous trend in the distributions. We interpret this to mean that the mechanisms that control the γ-ray dominance in the two populations are different (Chen *et al.* 2016). For the BL Lacs, it can be argued that γ-ray emission is linked to the wide range of synchrotron activity as earlier suggested by Ghisellini *et al.* (1998).

Another important result of present study is the presence of FSRQs whose properties in the γ-ray band are comparable to the BL Lacs rather than traditional FSRQs. However, their spectral energy distributions are not consistent with FSRQs in the sense that they are LSP or ISP sources. In particular, we have statistically shown that on average, these BL Lac-like sources are over two orders of magnitude fainter than the majority of FSRQs in the sample. This observation has a significant implication for the popular orientation-based unification scheme (OUS) for extragalactic radio sources, in which BL Lacs and FSRQs are the beamed counterparts of FR-I and FR-II radio galaxies, respectively. Although relativistic beaming and orientation effects appear to have provided a plausible explanation for the chameleon nature of the SED of blazars as well as the apparent differences in the observed properties between the two blazar subclasses and their respective parent radio galaxy populations (Urry & Padovani 1995). The presence of these BL Lac-like FSRQs in current analysis appears to break this simple dichotomy between the high luminosity and low luminosity sources. This result appears to be in good agreement with a recent result (Mingo *et al.* 2019) in which a large population of low-luminosity FR-II radio galaxies, extending several orders of magnitude below the traditional FR break has been observed in low-radio frequency array (LOFAR) survey. Nevertheless, several results argued for the presence of high radio power BL Lacs and low power FSRQs in various earlier samples (e.g. Kharb *et al.* 2010; Landt *et al.* 2006; Padovani *et al.* 2003; Perlman *et al.* 1998) such as CLASS blazar sample (Caccianiga & Marchã 2004). In fact, Giommi *et al.* (2013) predicted that up to 75% of Fermi-LAT BL Lacs are actually FSRQs with hidden emission lines. Interestingly, Padovani *et al.* (2019) confirmed one of the intrinsically Fermi-LAT FSRQs masquerading as BL Lacs, with SED properties exceeding that expected from traditional FSRQs by several orders of magnitude. All these are not in agreement with simple OUS and are quite consistent with our results, which can be interpreted to understand that there could be some form of a unified scheme for BL Lacs and FSRQs. Actually, these few FSRQs are observed to occupy regions of our plots in such a manner that favours a unified scheme for BL Lacs and FSRQs.

In conclusion, the results presented in this paper suggest that while there are some fundamental differences between BL Lacs and a vast majority of FSRQs in the Fermi-LAT blazar catalogue, some form of a unified scheme for BL Lacs and FSRQs cannot be ruled out. However, it has been observed from analysis of the third Fermi-LAT catalogue (Ackermann *et al.* 2015) that the Fermi-LAT sources were in flaring state most of the time, which could make their observed γ-ray flux much higher than average at such times. It can thus be argued that the high γ-ray dominance observed among BL Lacs in this study has arisen because they were in flaring state for most of the (4-year) duration. If this is actually the case, these flaring BL Lacs can also be candidates for detection of hard TeV γ-rays as well as high energy neutrinos.

Cosmic ray protons are believed to be accelerated in the relativistic jet of the blazars during a period of flaring activity, which can contribute significantly to high-energy neutrino flux (Palladino *et al.* 2019; Gao *et al.* 2017). Thus, the properties of these BL Lacs as well as the few BL Lac-like FSRQs observed in this analysis need to be further studied.

Acknowledgements

We are grateful to the anonymous referee whose invaluable comments and suggestions helped to improve the manuscript.

References

Abdo A. A., Ackermann M., Ajello M. *et al.* 2010, Astrophys. J., 729, 912
Abdo A. A., Ackermann M., Ajello M. *et al.* 2011, Astrophys. J. Lett., 733, LL26
Acero F., Ackermann M., Ajello M. *et al.* 2015, Astrophys. J. Sup., 218, 23
Ackermann M., Ajello M., Allafort A. *et al.* 2011, Astrophys. J., 743, 171
Ackermann M., Ajello M., Atwood W. *et al.* 2015, Astrophys. J., 810, 14
Alhassan J. A., Ubachukwu A. A., Odo F. C. 2013, J. Astron. Astrophys., 34, 61
Athreya R. M., Kapahi, V. K. 1998, J Astrophys. Astron., 19, 63
Bai J. M., Lee, M. G. 2001, Astrophys. J., 548, 244
Bicknell G. V. 1995, Astrophys. J. Suppl., 101, 29
Böck M., Kadler M., Müller C. *et al.* 2016, Astron. Astrophys., 590, A40
Böttcher M. 2007, Astrophys. Space Sci., 309, 95
Caccianiga A. and Marchã M. J. 2004, Mon. Not. R. Astron. Soc., 348, 937
Chen Y. Y., Zhang X., Xiong D. R., Wang S. J.,Yu X. L. 2016, Res. Astron. Astrophys., 16, 13
D'Abrusco R., Crespo N. A., Massaro F. *et al.* 2019, Astrophys. J. Suppl., 242, 1
Dermer C. D., Giebels B. 2016, Com. Rend. Physique, 17, 594
Dermer C. D., Schlickeiser R. 1993, Astrophys. J., 416, 458
Donato D., Ghisellini G., Tagliaferri G., Fossati G. 2001, Astron. Astrophys., 375, 739
Dondi L., Ghisellini G. 1995, Mon. Not. R. Astron. Soc., 273, 583
Fan J. H., Xie G. Z. 1996, Astron. Astrophys., 306, 55
Finke J. D. 2013, Astrophys. J., 763, 134
Foffano L., Pradini E., Franceschini A., Paiano S. 2019, Proc. Sci., arXiv:1907.13076v1 [astro-ph.HE]
Fossati G., Maraschi L., Celotti A., Comastri A., Ghisellini G. 1998, Mon. Not. R. Astron. Soc., 299, 433
Gao S., Pohl M., Winter W. 2017, Astrophys. J., 843, 109
Ghisellini G., Padovani P., Celotti A., Maraschi L. 1993, Astrophys. J., 407, 67
Ghisellini G., Celotti A., Fossati G., Maraschi L., Comastri, A. 1998, Mon. Not. R. Astron. Soc., 301, 451
Ghisellini G., Righi C., Costamante L., Tavacchio F. 2017, Mon. Not. R. Astron. Soc., 469, 255
Giommi P., Padovani P., Polenta G. 2013, Mon. Not. R. Astron. Soc., 431, 1914
IceCube Collaboration 2018, Science, 361, 147
Kharb P., Lister M. L., Cooper N. J. 2010, Astrophys. J., 710, 764
Keivan A., Murase K., Petropoulou M. *et al.* 2018, Astrophys. J., 864, 84
Kovalev Y. Y., Kellermann K. I., Lister M. L. *et al.* 2005, Astron. J., 130, 2473
Landt H., Padovani P., Perlman E. S. 2006, Astrophys. J., 367, 183
Li Y. T., Fu S. Y., Feng H. J. *et al.* 2017, J. Astrophys. Astron., 38, 22
Lind K. R., Blandford R. D. 1985, ApJ, 295, 358
Liu Z., Wu Z., Gu M. 2016, Res. Astron. Astrophys., 16, 103
Mao P., Urry C. M., Massaro F., Paggi A., Joe C., Sorren R. 2016, Astophys. J. Suppl., 224, 26
Meyer E. T., Fossati G., Georganopoulos M., Lister M. L. 2011, Astrophys. J., 740, 98
Mingo B., Croston J. H., Hardcastle M. J. *et al.* 2019, Mon. Not. R. Astron. Soc., 488, 2701
Mukherjee R., Bertsch D. L, Bloom S. D., Dingus B. L. *et al.* 1997, Astrophys. J., 490, 116
Nalewajko K., Gupta M. 2017, Astron. Astrophys., 606, A44
Nieppola E., Tornikoski M., Valtaoja E. 2006, Astron. Astrophys., 445, A41
Odo, F. C., Ubachukwu, A. A. 2013, Astrophys. Space Sci. 347, 357.
Odo F. C., Chukwude A. E., Ubachukwu A. A. 2014, Astrophys. Space Sci., 349, 939
Odo F. C., Chukwude A. E., Ubachukwu A. A. 2017, Astrophys. Space Sci., 362, 23
Ostriker J. P., Vietri M. 1985, Nature, 318, 446
Padovani P. 1992, Mon. Not. R. Astron. Soc., 257, 404
Padovani P., Perlman E. S., Landt H., Giommi P., Perri M. 2003, Astrophys. J., 588, 128
Padovani P., Oikonomou F., Petropoulou M., Giommi P., Resconi E. 2019, MNRAS Lett., 484, 5, arXiv:1901.06998
Palladino A., Rodrigues X., Gao S., Winter W. 2019, Astrophys. J., 871, 41

Pei Z. Y., Fan J. H., Bastieri D., Sawangwit U., Yang J. H. 2019, Res. Astron. Astrophys., 19, O70

Perlman E., Padovani P., Giommi P. *et al.* 1998, Astron. J., 115, 1253

Raiteri C. M., Capetti A. 2016, Astron. Astrophys., 587, A8

Rees M. J. 1967, Mon. Not. R., Astron. Soc., 135, 345

Savolainen T., Homan D. C., Hovatta T. *et al*. 2010, Astron. Astrophys., 512, A24

Ubachukwu A. A. 1998, Aut. J. Phys., 51, 585

Urry C. M., Padovani P. 1995, Pub. Astron. Soc. Pacific, 107, 715

Vagnetti F., Giallongo E. and Cavaliere A. 1991, Astrophys. J., 368, 366