UNIVERSAL PEAKS RATIO IN THE SPECTRAL ENERGY DENSITY
OF DOUBLE HUMP BLAZARS, GAMMA RAY BURSTS, AND MICROQUASARS?

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ABSTRACT

The peak frequencies of the two broad humps evident in the spectral energy density of blazars (SED) are time dependent and vary a lot between different blazars. However, their ratio in most blazars, appears to be almost universal and equal to \(\frac{m_e c^2}{4(1+z)\epsilon_p}\) to a good approximation, where \(m_e\) is the electron mass, \(\epsilon_p\) is the peak energy of the cosmic microwave background radiation, and \(z\) is the redshift of the blazar. We discuss a possible origin of such a universal ratio in blazars, gamma ray bursts (GRBs). We point out a possible connection between the knee in the energy spectrum of cosmic ray electrons and the maximal peak energies of the two broad humps in the SED of high-energy peaked blazars and GRBs. We also point out that a universal peaks ratio in double hump blazars which belong to different classes in the BL Lac sequence, may simply reflect different viewing angles of otherwise similar blazars.

Keywords: Blazars, Microquasars, Gamma Ray Bursts, Inverse Compton Scattering
1. INTRODUCTION

Blazars form a subclass of active galactic nuclei (AGN) where the mass accreting central massive black hole fires a highly relativistic jet of plasmoids in a direction very close to that of Earth (Blandford & Rees 1978; Urry & Padovani 1995; Ulrich et al. 1997). As such, blazars are very luminous and violently variable over a large range of frequencies $\nu$ from radio to TeV gamma rays. A two hump structure in the broad band spectral energy density (SED) $\nu F_\nu$ of blazars is evident when it is plotted as a function of $\log \nu$ (Fossati et al. 1998). The low energy hump has a peak value anywhere in the radio to X-ray band, while the high energy hump has a peak in the MeV - TeV gamma ray band. Although the origin of these two humps has not been established beyond doubt, it is widely believed that the first hump is synchrotron radiation emitted by energetic electrons within the jet (Konigl 1981; Urry & Mushotzky 1982) while the second hump is produced by inverse Compton scattering (ICS) of synchrotron radiation by the relativistic electrons in the jet - the so-called Synchrotron Self-Compton (SSC) mechanism (Jones et al. 1974a,b) or external photons from the accretion disk, and/or a dusty torus, and/or a broad line region, and/or galactic and extragalactic background radiations, the so-called External Compton (EC) mechanisms (e.g., Marscher & Gear 1985; Dermer et al. 1992; Dermer and Schlickeiser 1993; Sikora et al. 1994; Ghisellini & Madau 1996); Hartman et al. 2001; Krawczynski et al. 2001; Sikora et al. 2001; Sokolov & Marsh 2005; Albert et al. 2008; Abdo et al. 2014; Yang et al. 2017a,b). Both the SSC and EC models of high energy emission had considerable success in fitting the observed broad band SED of many blazars. They have been used also to explain the recent discoveries of TeV gamma ray emission from the gamma ray burst (GRB) 190114C (Acciari et al. 2019a, Ajello et al. 2020) and from the terminal lobes of the bipolar jet of the Galactic microquasar SS 433 (Abeysekara et al. 2018; Xing et al. 2019). However, the claimed success of both the SSC and EC models was based on posteriori fits to observational data, which involved many adjustable parameters and free choices, rather than on falsifiable predictions.

In this letter we show that although the peak frequencies of the two broad humps evident in the broad band SED of blazars vary between and within the different blazar classes, and depend on viewing angle and epoch, their ratio appears to be almost universal. We demonstrate that for a selected sample of blazars with simultaneous, well sampled broadband SED between radio and TeV energies. These blazars include both flat spectrum radio quasars (FSRQs) with a low $\nu_{p1}$ (below $10^{14}$ Hz), and the so-called BL Lac sequence: LBL, IBL, HBL, and EHBL, with $\nu_{p1}$ values, low ($<10^{14}$ Hz), intermediate (between $10^{14}$ and $10^{15}$ Hz), high (between $10^{15}$ and $10^{17}$ Hz), and extremely high (above $10^{17}$ Hz), respectively (Acciari et al. 2019b, and references therein). To a good approximation, this universal ratio satisfies

$$(1+z)\nu_{p2}/\nu_{p1} = m_e c^2/4\epsilon_p(CMB) \approx 1.88 \times 10^6,$$

where $m_e c^2/2$ is the photon energy in the electron rest frame around which inverse Compton scattering changes from the Thomson regime to the Klein Nishina regime, and ($1+z)\epsilon_p = (1+z)0.68 \times 10^{-3}$ eV is the peak energy of the cosmic microwave background (CMB) radiation (Fixsen 2009) at the observed redshift $z$ of the blazar.

We also show that the above universal ratio is expected if both humps are produced by ICS of isotropic distribution of external photons. The low energy hump is produced by ICS of CMB photons in the Thomson regime by the inert electrons in the jet of plasmoids ("cannonballs") which are ejected with a high relativistic bulk motion in mass accretion episodes onto the central compact object. The high energy hump by ICS in the Klein-Nishina regime of harder radiation fields encountered along the jet trajectory, by the ambient electrons of the surrounding medium which are scattered by the plasmoids to cosmic ray (CR) energies. The seed photons can be blazar radiations such as UV light and x rays from the accretion disk, and gamma rays from hadronic interaction in the broad line region of flat spectrum radio quasars (Dar and Laor 1997), but more likely, photons of the nearly isotropic galactic and extragalactic background radiations along the jet trajectory, or synchrotron radiation emitted by Fermi accelerated electrons within the plasmoids of blazar jets (e.g., Longair 2011 and references therein).

Finally, for completeness, we examine whether the discoveries of TeV gamma rays from GRB 190114C (Acciari et al. 2019a, Ajello et al. 2020) and the Galactic microquasar SS 433 (Abeysekara et al. 2018; Xing et al. 2019) suggest a double hump broad band SED of GRBs (Dado & Dar 2005) and microquasars with the nearly universal peak ratio observed in blazars.

2. ORIGIN OF BLAZAR’S DOUBLE HUMPS SED

Mass accretion episodes onto the central massive black hole in blazars launch highly relativistic jets of plasmoids of ordinary matter with an initial bulk motion Lorentz factor $\gamma(0) \gg 1$. These highly relativistic plasmoids (cannonballs) slow down mainly by gathering and scattering of the ionized nuclei and free electrons in front of them (e.g., Dar & De Rújula 2008). Consequently, initially the highly relativistic plasmoids contain two populations of electrons: the inert electrons of the plasmoids,
and the external electrons which were swept in with a Lorentz factor $\gamma$ in the plasmoids rest frame and scattered within them by internal magnetic fields.

When a jet of plasmoids with a large bulk motion Lorentz factor $\gamma \gg 1$ propagates through a radiation field, they produce, through ICS of ambient photons, a narrow beam of photons along the jet direction of motion. As long as the initial energy of the incident photons in the electron rest frame is much smaller than $m_e c^2$ (the Thomson regime), the maximal energy that ambient photons acquire in head-on collisions in which they are scattered backward, i.e., in the direction of motion of the plasmoid, is

$$E_{\text{p1}} \approx 2h\nu_{p1} \approx \gamma \delta \epsilon_p(CMB),$$

where $\delta = 1/\gamma(1 - \beta \cos \theta)$ is the Doppler factor, and $\epsilon_p(CMB)$ is the peak energy of the CMB photons. Note that $E_{\text{p1}}$ is independent of the blazar redshift. This is because the blue shift of the CMB temperature at the blazar emission time is equal to the redshift of the emitted radiation on its way to Earth.

The interstellar medium (ISM) electrons which are scattered forward by the jet of plasmoids have a Lorentz factor $\gamma_e \approx 2 \gamma^2$ in the blazar rest frame. Their maximal energy probably is similar to the observed knee energy of Galactic cosmic ray electrons (Dar and De Rújula 2008; De Rújula 2019). This beam of high energy CR electrons, while propagating in the blazar halo and beyond, up-scatter x rays and gamma ray photons -whose origin is the blazar accretion disk and broad line region (Dar and Laor 1997), respectively- up to TeV energies through ICS in the Klein Nishina regime. These ICS photons have energies which extend effectively up to

$$h\nu_{\text{max}} \approx 2\gamma^2 m_e c^2,$$

in the jet direction of motion, and up to $\gamma^2 m_e c^2$ for a typical viewing angle $\theta \sim 1/\gamma$ relative to the jet direction of motion, yielding

$$E_{\text{p2}} = h\nu_{p2} \approx \gamma^2 m_e c^2/2.$$  

3. UNIVERSAL PEAKS RATIO IN BLAZARS SED

ICS of photons in the Klein Nishina regime by CR electrons, which were accelerated by blazar jets, are very narrowly beamed along the direction of motion of the CR electrons. Consequently, the scattered photons in the Thomson and Klein Nishina regimes share the same beaming cone. Hence, the ratio of the locally observed peak energies of the ICS of photons of the blazar x-ray/$\gamma$-ray halo (eq.3) and the peak energies of the ICS of CMB photons at the blazar redshift (eq.5), are expected to satisfy

$$(1+z)\nu_{p2}/\nu_{p1} \approx m_e c^2/4\epsilon_p(CMB) \approx 1.88 \times 10^8.$$  

Note that although the broad band SED of double humped blazars, vary between blazars, and depends on their viewing angle, and on time due to blazar activity and deceleration of blazar jets in the blazar’s surrounding medium, Eq.6 implies that all these effects, cancel out to a good approximation in the double humps peaks ratio. This is demonstrated first in Figures 1,2 for the best studied blazar, Mrk 421. Its peaks ratio during the $\sim$ 13-day flaring event of Mrk 421 in March 2010 (Aleksic et al. 2015) and its weighted average value $R=8.23$ ($\chi^2/dof = 0.78$).
and coincided within errors with its long term average value during the multi-frequency campaign from January 19 to June 1, 2009 (Abdo et al. 2011b). Moreover, Figure 2 shows that, within errors, this peaks ratio remained the same during the steady states, outburst, and flares of Mrk 421 in the 4.5 years period from August 2008 to February 2013 (Bartoli et al. 2016). The peak values of the broad humps in the SED of a representative sample of 12 double hump blazars with a known redshift and well measured peak frequencies of both humps obtained from multi-wavelength campaigns are listed in Table I. The \( \nu p_2 \) values have been extracted from published spectra which were corrected for absorption by extragalactic background light according to the model of Franceschini et al. (2008). In Figure 3, \( \log((1+z)\nu p_2) \) is plotted as a function of \( \log(\nu p_1) \) for a representative sample of 12 double hump blazars with a known redshift and well determined peak frequencies of both humps obtained from multi-wavelength campaigns. The line is the best fit line \( \log((1+z)\nu p_2) = a \log(\nu p_1) + b \), where \( a = 1.0 \), \( b = 8.38 \), \( (\chi^2/dof = 0.16) \).

The detection of GeV photons following prompt emission pulses in GRBs by EGRET (Hurley et al. 1994) led to the suggestion (Dado & Dar 2005) that the SED of GRBs has a double hump structure similar to that observed in blazars. Recently multi-frequency observations of the ultrabright GRB 190114C at redshift \( z = 0.425 \) (Selsing et al. 2019; Castro-Tirado, et al. 2019) and its afterglow emission across 17 orders of magnitude in energy, from \( 5 \times 10^{-6} \) to \( 10^{12} \) eV, found that its broad band SED, was double-peaked. Its high energy hump which was observed with the MAGIC telescope (Acciari et al. 2019a) peaked around TeV (after correcting for absorption by extragalactic background light), while the Fermi and Swift observations of GRB 190114C (Ajello et al. 2020) indicated a broad SED hump which peaked around 5.2 keV. The observed peaks ratio, \( (1+z)E_{\text{p,2}}/E_{\text{p,1}} \approx 2.74 \times 10^5 \), is consistent with that observed in blazars (eq. 6). This ratio in GRB 190114C is also indicated in Figure 1.

5. DOUBLE HUMP SED OF MICROQUSARS?

The Galactic microquasar SS 433 (e.g., Mirabel & Rodríguez 1999 for a review of Galactic microquasars) is a binary system containing a compact object (either a stellar mass black hole or a neutron star) accreting matter from a supergiant star, which is overflowing its Roche
lobe. Bipolar jet of plasmoids (cannonballs) which are ejected with a bulk velocity $\approx 0.26c$, extend from the binary perpendicular to the sightline and terminate in lobes $25$ pc away, emit GeV-TeV gamma rays (Xing et al. 2019), then ICS of CMB photons by such electrons in the plasmoid rest frame) and $\approx 3$ TeV (Ambrosi et al. 2017; De Rújula 2019). Such a CRe knee was predicted by the cannonball (CB) model of cosmic ray electrons (CRe) in our Galaxy has a knee around $\approx 2.3\pm0.7$ TeV (Ambrosi et al. 2017; De Rújula 2019), then ICS of CMB photons by such electrons inside/outside the lobes of SS 433 yields high energy photons with a peak energy around $E_p \approx [E_{knee}(e)/m_e]^2 \epsilon_p(CMB) \approx 14(+10, -4)$ GeV. (7)

However, the hard x-ray continuum emission from SS 433 which peaks around $\approx 22$ keV, is consistent with being bremsstrahlung emission by the ambient electrons of the interstellar matter which enter the plasmoids of SS 433 with $\beta \approx 0.29$, (in the plasmoid rest frame) and decelerates there. This observed speed of the plasmoids implies a kinetic energy release $m_ec^2(\sqrt{1+\beta^2}-1) \approx 41$ keV within the plasmoids by swept in electron. This energy release may explain the hard x-ray emission observed by Suzaku (Kubota et al. 2010), INTEGRAL (Cherepashchuk et al. 2013), and NuSTAR (Middleton et al. 2019) X-ray satellites. Hence the ratio of the broad band peaks of the SED of the microquasar SS 433 may have coincided by chance with the universal ratio observed in blazars.

6. CONCLUSIONS AND IMPLICATIONS

The peak energies of the double humps of broad band spectral energy density of different blazars/GRBs are spread over a wide range and are time dependent. However, their observed ratio (after correcting for photon absorption along their sightline) appears to satisfy, within observational errors, $(1+z)E_{p2}/E_{p1} \approx m_ec^2/4\epsilon_p$. Such a universal ratio is obtained if both humps are produced by inverse Compton scattering (ICS); the lower hump by ICS of cosmic microwave background (CMB) photons in the Thomson regime, the high energy hump by ICS of x-rays and gamma rays in the Klein Nishina regime.

Universal peaks ratio in blazars belonging to different classes in the BL Lac sequence, may reflect mainly different viewing angles and initial Lorentz factors of their jetted plasmoids, $\gamma(0)2\beta^2 \leq 1$ of EHBL and HBL blazars and $\gamma(0)^2\beta^2 \gg 1$ of IBL and LBL blazars of otherwise quite similar blazars.

The energy spectrum of the cosmic ray electrons (CRe) in our Galaxy has a knee around $\approx 2.3$ TeV (Ambrosi et al. 2017; De Rújula 2019). Such a CRe knee was predicted by the cannonball (CB) model of cosmic ray acceleration. In the CB model, the acceleration of ISM nuclei and electrons to high energies by highly relativistic plasmoids ejected by blazars and gamma ray bursters yields energy spectra with a knee proportional to their mass (Dar & De Rújula 2008), i.e., $E_{knee}(CRe) \approx (m_e/m_A)E_{knee}(m_A)$. If the knee energy of CRe is universal, that is, common to our Milky Way, external galaxies, and blazars, then the maximal peak energy of the observed humps in high-energy peaked blazars satisfy (after correcting for photon absorption) and the maximal peak energy of their low energy hump satisfy,

$$\max E_{p1} \approx 2(E_{knee}(CRe)/m_ec^2)\epsilon_p \approx 6 \text{ keV},$$

### Table 1. SED peak ratio in representative sample of double hump blazars

| Blazar         | $z$   | $\log[(1+z)\nu_{p2}/\nu_{p1}]$ | MJD-Data Summary |
|----------------|-------|---------------------------------|------------------|
| 1ES 0229+200   | 0.1396| $\approx 8.40$                 | 55118-           |
| J0733.5+1513   | 0.065 | $\approx 8.38$                 | 58141-           |
| Mrk 501        | 0.0336| $\approx 8.34$                 | 56087-           |
| Mrk 421        | 0.0300| $\approx 8.23$                 | 54850-           |
| 1ES 1741+196   | 0.084 | $\approx 8.05$                 | 54940-           |
| 1ES 1959+650   | 0.048 | $\approx 8.20$                 | 57547-           |
| H 2356-309     | 0.165 | $\approx 8.30$                 | 53534-           |
| 1ES 2344+54    | 0.044 | $\approx 8.30$                 | 57611-           |
| 3C 66A         | 0.340 | $\approx 8.30$                 | 54734-           |
| 1ES 1215+303   | 0.135 | $\approx 8.40$                 | 54682-           |
| TXS 0506+056   | 0.5573| $\approx 8.22$                 | 58020-           |
| 3C 279         | 0.5362| $\approx 8.30$                 | 56741-           |
max \( E_{p2} \approx E_{knee}(CRe) \approx 2.3/(1+z) \) TeV, \hspace{1cm} (9)

Such limits are consistent with the observed peak energies (after correcting for photon absorption along the sightline) of EHBL blazars.

The Lorentz factors of the plasmoids comprising the jets of blazars and GRBs have been estimated from measurements of their apparent superluminal velocity (Rees 1967) long time after ejection (in the blazar/GRB rest frame), assuming that \( \gamma(t) \), the Lorentz factor of the jet, and its viewing angle satisfy \( \gamma \approx 1 \). Typically, such estimates have yielded \( \gamma(t) < 100 \), far below \( \gamma(0) \approx 1500 \) needed to explain the knee energies of cosmic ray nuclei and electrons (Dar & De Rújula 2008; De Rújula 2019). However, the observations of superluminal velocities of plasmoids launched by blazars/GRBs were carried out at relatively late times after launch (in the blazar/GRB rest frame), when the plasmoids have already decelerated considerably in the ISM of the host galaxy and satisfy \( \gamma(0) 
\) and \( \theta \), the apparent superluminal velocity of plasmoids satisfies

\[
V_{sl} = \left( \frac{\beta \sin \theta c}{1 - \beta \cos \theta} \right) \approx \frac{\gamma^2 \theta^2}{1 + \gamma^2 \theta^2} \frac{2c}{\theta}.
\] \hspace{1cm} (10)

The assumption \( \gamma \theta \approx 1 \) yields \( \gamma \approx V_{sl}/c \). However, highly relativistic plasmoids decelerate very fast with increasing time \( t \) in the observer frame due to time abberation \( (dt = (1+z)dt'/\gamma) \), yielding \( \gamma \theta^2 \ll 1 \) shortly after launch. Consequently, as can be seen from eq.(10), most measurements of the superluminal velocity of ejected plasmoids with \( \gamma(0) \theta \approx 1 \) yield \( V_{sl}(t) \ll V_{sl}(0) \approx \gamma(0)c \).

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**REFERENCES**

Aarsten, M. G., Ackerman, M., Adams, J., et al., 2018, Science 361, 1378 [arXiv:1807.08816]

Abdo, A. A., Ackerman, M., Ajello, M., et al., 2011a, ApJ, 726, 43 [arXiv:1011.1054]

Abdo, A. A., Ackerman, M., Ajello, M., et al., 2011b, ApJ, 736, 131 [arXiv:1106.1348]

Abdo, A. A., Abeysekara, A. U., Allen, B. T., et al., 2014, ApJ, 797, 110 [arXiv:1403.2161]

Abeysekara, A. U., Archambault, S., Archer, A., et al., 2016, MNRAS, 459, 2550 [arXiv:1603.07286]

Abeysekara, A. U., Albert, A., Alfaro, R., et al., 2018, Nature, 562, 82 [arXiv:1810.01892]

Acciari, V. A., Ansoldi, S., Antonelli, L. A., et al., 2019a, Nature 575, 459 [arXiv:2006.07251]

Acciari, V. A., Ansoldi, S., Antonelli, L. A., et al., 2019b, MNRAS, 490, 2284 [arXiv:1909.11621]

Aharonian, F., Akhperjanian, A. G., Bazer-Bachi, A. R., et al., 2000, A&A, 355 [arXiv:astro-ph/0007569]

Albert, J., Aliu, E., Anderhub, H., et al., 2008, Sci, 320, 1752

Ahnen, M. L., Ansoldi, S., Antonelli, L. A., et al., 2018, A&A, 620, A181 [arXiv:1808.04300]

Ajello, M., Arimoto, M., Axelsson, M., et al., 2020, ApJ, 890, 9 [arXiv:1909.10605]

Alison, E., Archambault, S., Arlen, T., et al., 2014, ApJ, 782, 13A [arXiv:1312.6592]

Ambrosi, G., An, Q., Asfandiyarov, R., et al., 2017, Nature, 552, 63 [arXiv:1711.10981]

Bartoli, F., Bernardini, P., Bi, X. J., et al., 2016, ApJS, 222, 6 [arXiv:1511.06851]

Blandford, R. D., & Rees, M. J., 1978, in Pittsburgh Conference on BL Lac Objects, ed. A. M. Wolfe (Pittsburgh, PA: Univ. Pittsburgh Press), 328

Bottacini, E., Boettcher, M., Pian, E., Collmar, W., 2016, ApJ, 832, 17 [arXiv:1610.01617]

Castro-Tirado, A. J., Hu, Y., Fernandez-Garcia, E., et al., 2019, GCN 23708

Cheeck, C. M., Muskhotzky, R. F., Kondo, Y., Hackney, K. R., Hackney, K. R. L., 1982,ApJ, 261, 12

Urry, C. M., Padovani, P., 1995, PASP, 107, 803

Valverde, J., Horan, D., Bernard, D. et al., 2020, ApJ, 891, 170 [arXiv:2002.04119]

Xing, Y., Wang, Z., Zhang, X., Chen, Y., Jithvesh, V. 2019, ApJ, 872, 25 [arXiv:1811.09495]

Yang, J. H., Fan, J. H., Liu, Y., et al., 2017, ApJ, 836, 22

Yang, J. H., Fan, J. H., Liu, Y., et al., 2017, ApJ, 836, 219