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Using the SED to locate the γ -ray emission site of powerful blazars

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The location of the Gamma-ray emission of powerful blazars is a matter of active debate. Is the location within the UV emitting sub-pc scale broad line region, or farther out at pc scales where the molecular torus IR emission dominates? We present a diagnostic that connects three observables, the synchrotron and external Compton peak frequencies and the Compton dominance (the ratio of Compton to synchrotron luminosity) to the seed photon energy and energy density. We discuss encouraging preliminary results and discuss how to use our diagnostic to understand the location of the Gamma-ray emission as a function of source power through the use of multiwavelength observations.

I. INTRODUCTION

A central question that is been debated in the *Fermi* era regards the location of the blazar γ -ray emission site: is the γ -ray emission of powerful blazars produced inside the sub-pc size broad line region (BLR) or further out at scales of ~ 1 - few pc (fig. 1) where the IR photon field of the dusty molecular torus (MT) dominates over that of the UV field of the BLR? In the first case the γ -ray emission is most probably external Compton (EC) scattering of the ~ 10 eV BLR photons [28], while in the second the seed photons for the EC emission are the ~ 0.1 eV photons emitted by the dust [9] in the MT [8]. The issue of the energy dissipation location is connected to the jet formation and collimation process [24, 34] and, as we propose, can be approached through a SED diagnostic we introduce.

A. The near camp: Few hour GeV variability puts the blazar inside the BLR.

Fermi has detected flares with decay time down to ~ 3 hours, comparable to the telescope sky scanning period. Such variations have been seen in 3C 454.3 [6, 33], PKS 1454-354 [1], 3C 273 [3], PKS 1502+106 [2], PKS B1222+216 [12]. The short variability timescale has been used to argue that the emission is produced within the BLR (e.g. [33]): For a jet with $\Gamma = \delta = 10$, where Γ is the bulk Lorentz factor of the flow and δ the corresponding Doppler factor, variability times of $t_{var} = 10^4$ s (~ 3 hours), correspond to a maximum source size of $r = ct_{var}\delta = 3 \times 10^{15}$ cm. Assuming a jet half-angle $\theta_{jet} = 0.17/\Gamma$ [17], an upper limit on the distance of the blazar from the central engine is $R = r/\theta_{jet} = r\Gamma/0.17 = 3.5 \times 10^{17}$ cm. This distance is comparable to the BLR size $R_{BLR} \approx 1-3 \times 10^{17}$ cm [19] and, therefore, it is plausible that the GeV emission is produced inside the BLR. Essentially this argument is based on the assumption that the entire cross section of the jet is emitting. If

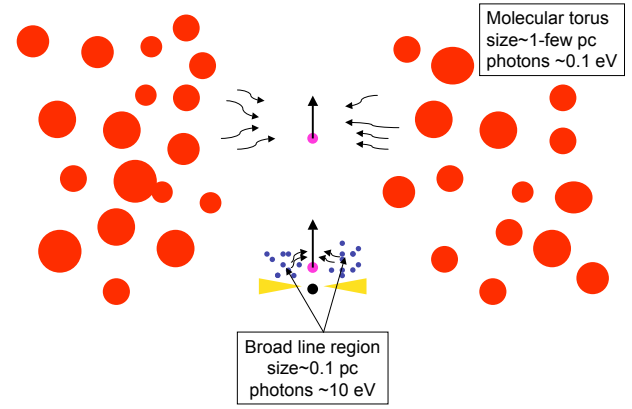


FIG. 1: Is the blazar GeV emission produced inside the sub-pc broad line region or further out at distances ~ 1 - few pc, comparable to the size of the molecular torus? This is an ongoing debate with strong cases presented by both camps. Here we introduce a diagnostic based on the spectral energy distribution (SED) and we show how it can be used to locate the blazar emission site.

however one allows smaller parts of the jet to produce the γ -ray emission (e.g. [14]) such short variations can take place further out.

B. The far camp: Optical/VLBI polarization and GeV/X-ray data put the blazar few pc from the central engine.

The sub-pc scale energy dissipation is challenged by observations that put the emission at few pc distance from the black hole (e.g. [4, 5, 18, 24, 25]). In several cases, optical polarimetry during an optical - γ -ray flare showed a polarization behavior similar to that observed in simultaneous high frequency VLBI coming from the 43 GHz core, several pc away from the central engine. Because of the similar optical and

VLBI polarization behavior, the optical emission is constrained to emerge from the VLBI core and because the optical and γ -ray variations are seen to be simultaneous, the γ -ray emission is also constrained to emerge from the VLBI core at a distance of few to several pc from the black hole. Additional arguments placing some of the γ -ray flares at ~ 10 pc have been advanced for 3C 454.3 [29, 30]. These arguments are based on the similar behavior of optical and millimeter light curves and explain the GeV emission as EC scattering of photons emitted from the dust of the MT. Although at distances of ~ 10 pc from the central engine variability events are expected to be of the order of ~ 10 days, significantly shorter variations (day long or even down to a few hours) are seen (e.g. PKS 1510-089 [25]). These can be explained if the observed variations come from a fraction of the jet cross section.

Recently, a diagnostic has been proposed [11] for the location of the blazar GeV emission that is based on the energy dependence of Fermi flux variations. This diagnostic makes use of the fact that if the blazar emission takes place inside the BRL the cooling is done on the ~ 10 eV BLR photons, while if it takes place outside the BLR, the most abundant seed photons are IR photons (~ 0.1 eV of the MT. In the first case cooling takes place at the onset of the Klein-Nishina cross section and GeV variability is achromatic, while in the second case cooling takes place in the Thomson regime and variability is faster at higher energies. Although this is a powerful diagnostic, it can only be applied to a small number of bright *Fermi* flares.

II. AN SED-BASED γ -RAY LOCATION DIAGNOSTIC AND ITS APPLICATION

In powerful blazars, the emission consists of two spectral components. The low frequency one peaks at $\nu_s \sim 10^{13}$ Hz [16] and is attributed to synchrotron radiation; the high frequency one peaks at $\nu_c \sim 10^{22}$ Hz [16] and is usually attributed to inverse Compton emission from external photons that are produced in the broad line region or in the MT.

If Γ is the bulk Lorentz factor and δ the usual Doppler factor of the jet flow, and γ_b is the Lorentz factor of the electrons responsible for the synchrotron and EC SED peaks, then,

$$\epsilon_s = \frac{B}{B_{cr}} \gamma_b^2 \delta, \quad (1)$$

$$\epsilon_c = \frac{4}{3} \epsilon_0 \gamma_b^2 \delta^2, \quad (2)$$

where ϵ_s is the synchrotron peak energy, ϵ_c is the EC peak energy, ϵ_0 is the characteristic energy of the external photon field, all in units of the electron rest mass, B is the magnetic field permeating the emission

region and $B_{cr} = (m_e^2 c^3)/(e\hbar) = 4.4 \times 10^{13}$ G is the critical magnetic field. Note that equation (2) is valid only if the scattering of electrons with Lorentz factor γ_b takes place in the Thomson regime. The condition for this, $\epsilon_0 \gamma_b \delta \lesssim 1$ can be written with the help of equation (2) as $(\epsilon_c \epsilon_0)^{1/2} \lesssim 1$. The highest possible energy external seed photons are UV line photons with $\epsilon_0 \approx 10^{-4}$, which means that the scattering is indeed in the Thomson regime as long as $\epsilon_c \lesssim \epsilon_0^{-1} \approx 10^4$. This corresponds to an energy of ≈ 5 GeV or $\nu_c \approx 10^{24}$ Hz. Given that in most cases powerful blazars peak at lower ν_c , with $\langle \nu_c \rangle \approx 10^{22}$ Hz [16], the scattering of the electrons producing the EC peak is well within the Thomson regime. Taking the ratio of the two peak energies we obtain:

$$\frac{B}{\delta} = \frac{4\epsilon_0 \epsilon_s B_{cr}}{3\epsilon_c} \quad (3)$$

The same ratio B/δ can be obtained from the expression for the Compton dominance k , the ratio L_c/L_s of EC to synchrotron luminosity:

$$k = \frac{L_c}{L_s} = \frac{U'_0 (\delta^6 / \Gamma^2)}{U_B \delta^4} = \frac{32\pi \delta^2 U_0}{3B^2}, \quad (4)$$

where U_0 is the external photon field energy density in the galaxy frame, $U'_0 = (4/3)U_0\Gamma^2$ is the external photon field energy density in the jet comoving frame and $U_B = B^2/(8\pi)$ is the magnetic field energy density [10, 13]. Solving equation (4) for B/δ and equating to equation (3), we obtain our final expression

$$\frac{U_0^{1/2}}{\epsilon_0} = \sqrt{\frac{k B_{cr}^2}{6\pi}} \frac{\epsilon_s}{\epsilon_c} = 3.2 \times 10^4 \frac{k_1^{1/2} \nu_{s,13}}{\nu_{c,22}} \text{ G} \quad (5)$$

where k_1 is the Compton dominance in units of 10, $\nu_{c,22}$ is ν_c in units of 10^{22} Hz, and $\nu_{s,13}$ is ν_s in units of 10^{13} Hz. *Note that the RHS contains only observables. It is the RHS that informs us about the ratio of the square root of the energy density over the peak energy of the seed photons (seed factor, SF, in Gauss) available at the location of the γ -ray emission. It is this information that we can use for understanding where the emission comes from.*

A. The SF in the BLR and in the MT.

Reverberation mapping finds that $R_{BLR} \approx 1 - 3 \times 10^{17} L_{d,45}^{1/2}$ cm where $L_{d,45}$ is the accretion disk luminosity L_d in units of 10^{45} erg s $^{-1}$, and that a fraction $\xi \sim 0.1$ of L_d is reprocessed by the BLR [7, 19]. The energy density for the BLR is then $U_0 = \xi L_d / (4\pi R^2 c) \approx 0.29 - 2.6 \times 10^{-2}$ erg cm $^{-3}$ [15]. Because $R \propto L_d^{1/2}$, U_0 is the same for sources of different luminosities. The BLR SED in the galaxy frame can be approximated by a blackbody peaking

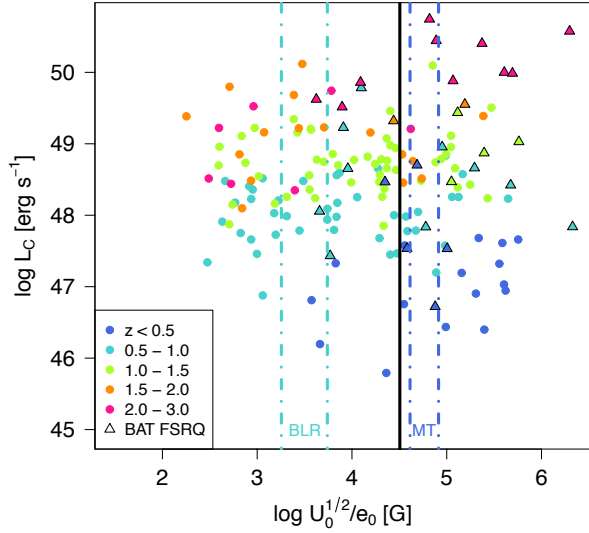


FIG. 2: L_c as a function of the SF for a number of sources, color-coded for redshift, for which ν_s , ν_c and k are found from their SEDs. The solid line is the average from [16], the areas marked by dotted lines correspond to the γ -ray emission site being inside the BLR (left) or the MT (right).

at $\nu_0 = 1.5\nu_{\text{Ly}\alpha}$ ($\epsilon_0 \approx 3 \times 10^{-5}$, [32]). Using these we obtain $SF \sim 1.8 - 5.5 \times 10^3$ G.

Because of the larger distance of the MT from the central engine, reverberation mapping has only been performed for Seyferts (e.g. [31]), lower luminosity and therefore smaller MT size sources. These studies, along with IR interferometric studies (e.g. [20]) are also in agreement with an $R \propto L_d^{1/2}$ scaling, suggesting that U_0 is the same for sources of different luminosities. Adopting the results of [23] for the blazar 4C 21.35, a blackbody of temperature $T = 1200$ K ($\epsilon_0 = 5.7 \times 10^{-7}$) and $L = 7.9 \times 10^{45}$ erg s $^{-1}$ emitted from a radius of $\sim 1 - 2$ pc, we obtain $U_0 = 0.5 - 2.2 \times 10^{-3}$ ergs cm $^{-3}$. With these we obtain $SF \sim 4.1 - 8.2 \times 10^4$ G. A comparison of these indicative ranges is shown in Figures 2 and 3.

B. Can SSC be dominant?

In the previous discussion we considered only external photons. Here we briefly discuss under what conditions synchrotron photons would be the dominant seed photons. A lower limit for the synchrotron photon density U_s in the comoving frame (assuming $\delta = \Gamma$ is

$$U_s = \frac{L_s}{4\pi c^3 t_{var}^2 \Gamma^6}, \quad (6)$$

where t_{var} is the observed variability timescale and L_s the luminosity of the synchrotron component. For this

to dominate over $U_0 \Gamma^2$, the comoving external photon field energy density, we require

$$\Gamma < \left(\frac{L_s}{4\pi c^3 t_{var}^2 U_0} \right)^{\frac{1}{8}} = 12.6 \left(\frac{L_{s,47}}{t_{var,6h} U_{0,-4}} \right)^{\frac{1}{8}}. \quad (7)$$

For our adopted BLR range, $U_0 \approx 0.29 - 2.6 \times 10^{-2}$ erg cm $^{-3}$, this is equivalent to $\Gamma < 8.4 - 11.0 L_{s,47}^{1/8} t_{var,6h}^{-1/8}$. Similarly for our adopted MT range, $U_0 = 0.5 - 2.2 \times 10^{-3}$ erg cm $^{-3}$ this is equivalent to $\Gamma < 11.4 - 13.7 L_{s,47}^{1/8} t_{var,6h}^{-1/8}$. VLBI studies of superluminal speeds in FSRQs [e.g. see figure 24 of 17] show that for most FSRQs, $\Gamma \gtrsim 10$, with values reaching up to ~ 40 . This raises the possibility that our diagnostic is relevant for sources that have relatively high Γ , and that for the slower sources SSC may dominate.

III. PRELIMINARY RESULTS.

Some preliminary results using the sample of [26] with detections in the 2FGL or BAT are shown in Figures 2 and 3. The average values of $k \sim \text{few}$, $\nu_s = 10^{13}$ Hz, and $\nu_c = 10^{22}$ found for powerful blazars [16] correspond to a SF (solid line) that is closer to the MT range than that of the BLR. The fact that the two bands corresponding to the SF we estimated for the BLR and the MT occupy the central part of the observed SF range is encouraging and indicates that FSRQs experience a seed photon environment that is within the range of what is expected from our simple BLR and MT considerations. We note that estimating ν_s and ν_c requires good multi-wavelength coverage, and errors of a factor up to ~ 10 are possible, particularly in the current estimates of ν_c . This suggests that the actual range of SF is significantly more narrow than the current data suggest, likely giving closer agreement with the range denoted by the bands in Figures 2 and 3 once we have completed our SED analysis on very well sampled sources.

In future work, we plan to use all available data, including archival data from sources like NED with newer catalogues from WISE, Planck, SWIFT, BAT, LAT to produce SEDs with simultaneous or contemporaneous data for as many sources as possible and derive their ν_s , ν_c and k following [26], along with error estimates for these quantities. We anticipate that this work will significantly expand the sample in [26] which was restricted to coverage of the synchrotron component only.

To estimate the actual range of the SF in the BLR and the MT, we need to know how the quantity $U_0^{1/2}/\epsilon_0$ is expected to vary radially. This requires information on the BLR and the MT stratification, something that is not yet well constrained [7, 19, 22]) yet. For the modeling component of the project, we plan to explore how the SF range widens if one considers the stratification of different line photons in the

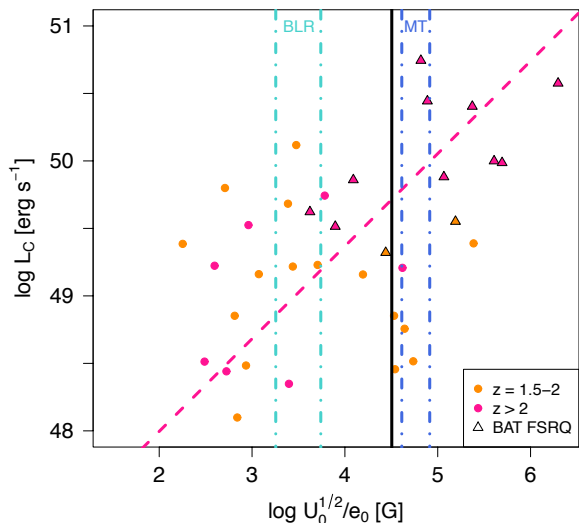


FIG. 3: Same as Figure 2, but for sources with $z > 2$. There is a clear correlation between the total IC power and the seed factor SF , moving from values consistent with the BLR to the MT at highest energies.

BLR (e.g. [27] and the fact that powerful IR components with T down to ~ 300 K have been detected in radio-loud AGN [22].

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