Modelling emissions from secondary electron-positron pairs created by absorption of gamma-rays in the broad-line region of blazars and their contribution to the broadband SED

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The Problem / Motivation of Study

Spectral Energy Distributions (SEDs) of some FSRQs show signs of γ-ray absorption in the $\sim$ 10 to few 100 GeV range.

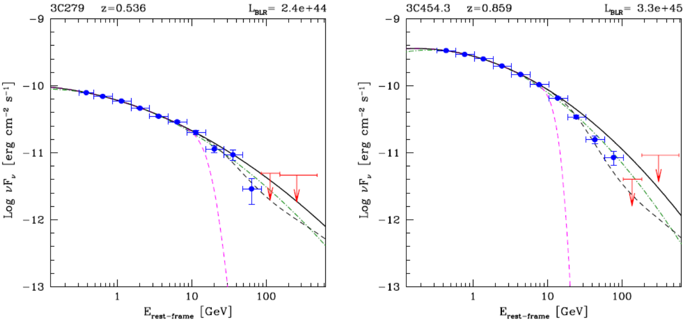


Figure 1: Snapshot of SEDs from the works of Costamante et al., 2018.

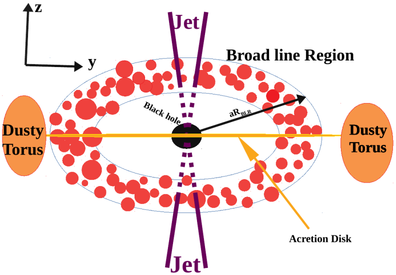
Suggested cause for dips

Gamma-gamma Pair Production

$\sim 10 - 100$ GeV gamma-rays absorbed by the broad-line region (BLR).
Secondary electron-positron ($e^{\pm}$) pairs are produced in this process.

Our Proposal
Study effect of $e^{\pm}$ on SED by calculating its emission (SSC).

Effect of γ-ray absorption and emission by $e^{\pm}$ pairs



AGN side-view

$0 < a < 1$

- "a" is fraction of R_{BLR}, where gamma-ray absorption takes place. Gives indication about production zone of γ - rays.
- We explore SSC emission from secondary e$^{\pm}$ pairs to see if it can compensate for the absorbed γ-ray flux.

Application to 3C 279

A well-known bright FSRQ: 3C 279

- Redshift $z = 0.536$.
- $RA_{J2000} = 12^h 56^m 11.1^s$, $Dec_{J2000} = -05^d 47^m 22^s$

Analysis Tools: R_{BLR} Scaling

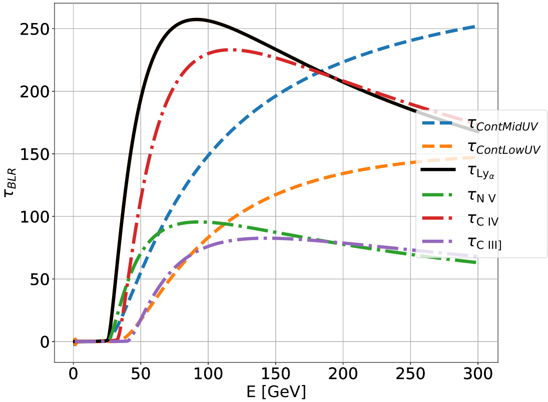
R_{BLR} scales with disc luminosity with power-law index of 0.5[1].

$$R_{BLR} \propto \sqrt{\frac{L_{disk}}{10^{45}\mathrm{erg/s}}}\ \mathrm{pc} \approx 1.7 \times 10^{17}\ \mathrm{cm}. \tag{1}$$

where $L_{disk} = 3 \times 10^{45}$ erg/s for 3C 279[2].

[1] Ghisellini & Tavecchio, 2009.
[2] H.E.S.S. Collaboration, 2019.

RESULTS: Opacity, 3C 279



Opacity curves correspond to individual **emission lines** and **continuum** of BLR.

Up to 180 GeV consistent with SED absorption, Ly_α line dominates the BLR opacity.

Analysis Tools: Gamma-Ray Spectrum Model

To fit the intrinsic *Fermi* γ - ray spectrum (F_{intr}) we use Log-parabola (LP). Without absorption.

$$F_{intr}(E) = LP(E) = F_0 \left(\frac{E}{E_0} \right)^{-(\alpha + \beta \log \frac{E}{E_0})} \tag{2}$$

With absorption (F_{absorb}),

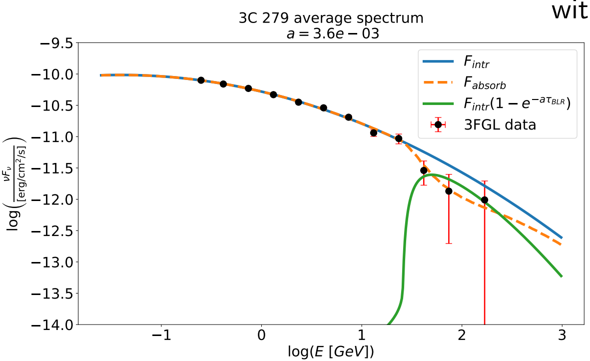
$$F_{absorb}(E) = LP(E) e^{-a \tau_{BLR}(E)} \tag{3}$$

where $\tau_{BLR}(E) = R_{BLR} \frac{d\tau_{BLR}(E)}{dx}$
and $0 < a < 1$ is a Free Parameter.

Fit Gamma-Ray Spectrum with LP: 3C 279[3]

$a = 0.0036$

γ-rays travel a distance of $aR_{BLR} = 6.12 \times 10^{14}$ cm within the BLR.



$F_{intr}(1 - e^{-a\tau_{BLR}})$ are absorbed γ-rays that are converted into $e^{\pm}$ pairs

[3] 3C 279 Gamma-ray data obtained from Costamante et al., 2018.

Analysis Tools: Injected $e^{\pm}$ Spectrum

Differential Pair Spectrum[4]

$$\frac{dn(\gamma)}{dVdtd\gamma} = \frac{3}{32} c\sigma_T \int_{\gamma}^{\infty} d\epsilon_1 \frac{n_{SED}(\epsilon_1)}{\epsilon_1^3} \int_{\frac{\epsilon_1}{4\gamma(\epsilon_1-\gamma)}}^{\infty} d\epsilon_2 \frac{n_{BLR}(\epsilon_2)}{\epsilon^2} g(\epsilon_2, \epsilon_1, \gamma) \tag{4}$$

where

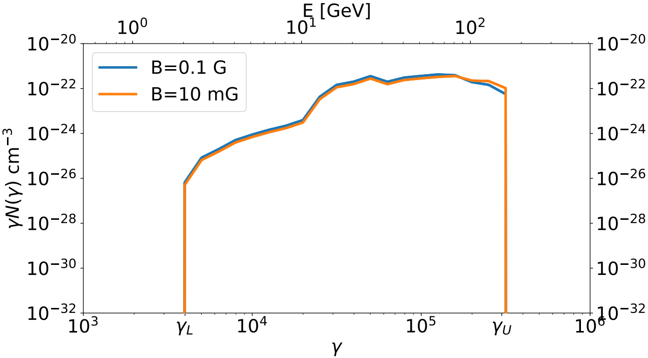
$$g(\epsilon_2, \epsilon_1, \gamma) = \frac{4\epsilon_1^2}{\gamma(\epsilon_1-\gamma)} \ln \frac{4\epsilon_2\gamma(\epsilon_1-\gamma)}{\epsilon_1} - 8\epsilon_1\epsilon_2 + \frac{2\epsilon_1^2(2\epsilon_1\epsilon_2-1)}{\gamma(\epsilon_1-\gamma)} - \left(1-\frac{1}{\epsilon_1\epsilon_2}\right)\frac{\epsilon_1^4}{\gamma^2(\epsilon_1-\gamma)^2}$$

[4] Used in this work is Aharonian et al., 1983 approximation of $e^{\pm}$ pair spectrum. This approximation is very nearly equal to exact analytical expression derived by Böttcher and Schlickeiser, 1997.

RESULTS: Electron-Positron Pair Spectrum of 3C 279

Use Log-Parabola (γ-ray) and Breit-Wigner (BLR photon) profiles as inputs for $n_{SED}(\epsilon_1), n_{BLR}(\epsilon_2)$, respectively. Then multiply Eq (4) by time

$$t(\gamma, B) = \min\left[t_{inj}, t_{cool}(\gamma, B)\right].$$



$\gamma_L < \gamma < \gamma_U$

where

$\gamma_L = 4 \times 10^3$

$\gamma_U = 3 \times 10^5$

where $t_{inj} = 0.1 R_{BLR}/c$,

$t_{cool}(\gamma, B) = \frac{3 m_e c^2}{4\sigma_T c \gamma (U_B + U_{BLR})}$; $U_B/U_{BLR} << 1$.

Analysis Tools: SSC Model

Adapt SSC Model for Blazars developed by Chiaberge and Ghisellini, 1999.

Where $I_{S/C}(\nu)$ is **intensity** of synchrotron or inverse-Compton radiation resulting from cooling of $e^{\pm}$ pairs.

$$I_S(\nu) = \frac{R_{BLR}}{4\pi} \int_{\gamma_{min}}^{\gamma_{max}} d\gamma \frac{dn(\gamma)}{dVdtd\gamma} t(\gamma, B) P_S(\nu, \gamma) \quad (5)$$

$$I_C(\nu_1) = R_{BLR} \frac{\sigma_T}{4} \int_{\nu_0^{min}}^{\nu_0^{max}} \frac{d\nu_0}{\nu_0} \int_{\gamma_1}^{\gamma_2} \frac{d\gamma}{\gamma^2 \beta^2} \frac{dn(\gamma)}{dVd\gamma} f(\nu_0, \nu_1) \frac{\nu_1}{\nu_0} I_S(\nu_0) \quad (6)$$

Analysis Tools: SSC Model

where

$\gamma, c\beta$ - Lorentz factor and speed of electron, respectively.

$I_{S,C}(\nu)$ - synchrotron, Compton intensity, respectively.

$P_S(\nu, \gamma)$ - single electron synchrotron emissivity averaged over an isotropic distribution of pitch angles.

$f(\nu_0, \nu_1)$ - single electron scattering spectrum of monochromatic photons of frequency ν_0.

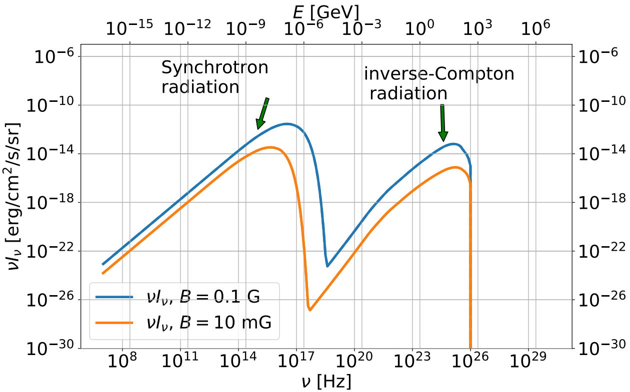
$t(\gamma, B) = \min\left[t_{inj}, t_{cool}(\gamma, B)\right]$

$\frac{dn}{dVdtd\gamma}$ is pair spectrum (Eq (4)).

$\frac{dn}{dVd\gamma} = \frac{dn}{dVdtd\gamma} t(\gamma, B)$

SSC Emission from $e^{\pm}$ Pairs

SSC for different magnetic fields in the jet.

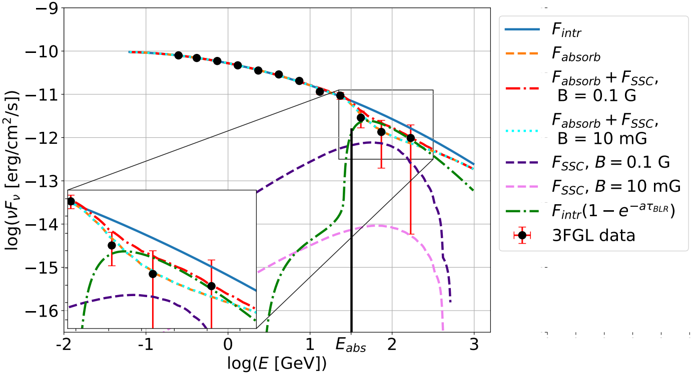


External Compton scattering of BLR photons is not significant as the energy density of BLR photons is significantly less than the energy density of synchrotron emitted photons.

RECONSTRUCT THE GAMMA-RAY SPECTRUM

$$F_{intr}(E) \geq F(E) = F_{absorb}(E) + F_{SSC}(E)$$

For $B > 10$ mG, SSC emission by $e^{\pm}$ starts compensating for lost γ-ray flux.



Fits consistent with *Fermi*-LAT (3FGL) data.

$F_{SSC} \leq F_{intr}(1 - e^{-a\tau_{BLR}})$

$E > E_{abs} \approx 31$ GeV.

Discussion and Conclusion

1. **If** the jet $B < 0.1$ G
   then the SSC contribution from $e^{\pm}$ to the SED is not significant and the dip may occur as a result of γ-rays being absorbed in the BLR.
2. **If** $B \gtrsim 0.1$ G,
   then the SSC emission becomes significant and can compensate for the absorbed γ-rays within the BLR.
3. $B = 0.1$ G is consistent with magnetic fields used in some models of multiwavelength SEDs of blazars, (e.g. Abdalla et al., 2019 use 0.65 G in their model of 3C 279 multiwavelength SED).

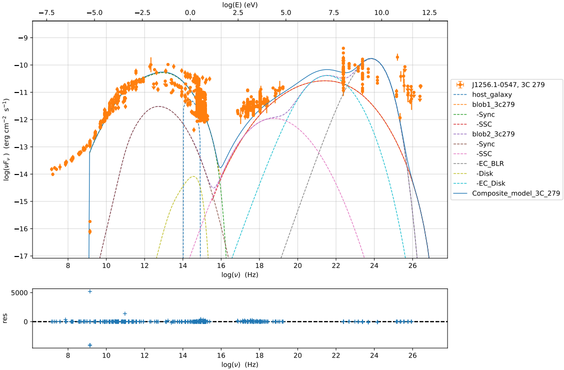
Future work

Upper limit on jet magnetic field

Use JetSet software[5] to perform fits to broadband spectral energy distribution of 3C 279.
Preliminary result:
2-jet blob model best describes broadband SED of 3C 279. Fits could improve by including external Compton by BLR, Accretion disc or Dusty Torus

[5] Tramacere, 2020; Tramacere et al. 2011; Tramacere et al., 2009; Massaro et al., 2006.

Future work



- In 2-jet model, blobs have magnetic fields 6.3 μ G and 0.5 G.
- It appears magnetic field should $\lesssim 1$ G.
- Further investigation to be done.

End

Thank you!

Appendix

BACK-UP SLIDES

Analysis Tools: BLR Model (3C 279)

Build BLR model using the Power Law (PL), Breit-Wigner (BW)[6] and Gaussian (Ga) functions.

$$
\begin{aligned}
PL(\epsilon) &= F_0 \left(\frac{\epsilon}{\epsilon_0}\right)^{-\alpha} && (7) \\
BW(\epsilon) &= \frac{n_i w_i}{2\pi} \left[(\epsilon - \epsilon_i)^2 + (w_i/2)^2\right]^{-1} && (8) \\
Ga(\epsilon) &= \frac{n_i}{\epsilon_i} \exp\left[-\frac{(\epsilon - \epsilon_i)^2}{2w_i^2}\right] && (9)
\end{aligned}
$$

Here w_i is the equivalent width, n_i is the photon number density of emission line i given by

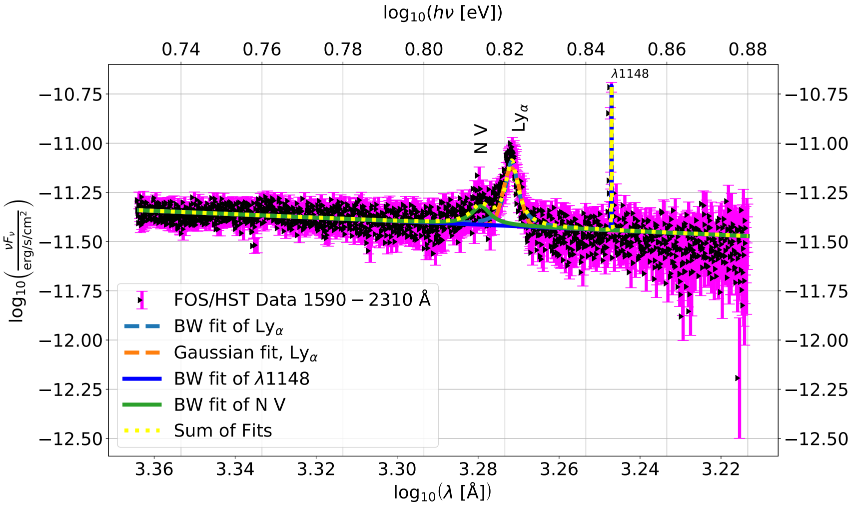
$$
n_i = 1.66 \times 10^{11} \mathrm{cm}^{-3} \left(\frac{L_i}{10^{45} \mathrm{erg/s}}\right) \left(\frac{\epsilon_i}{\mathrm{eV}}\right)^{-1} \left(\frac{R_{BLR}}{10^{17} \mathrm{cm}}\right)^{-2} \quad (10)
$$

[6] Britto, Razzaque & Lott, 2015.

RESULTS: Broad-Line Region, 3C 279[7]

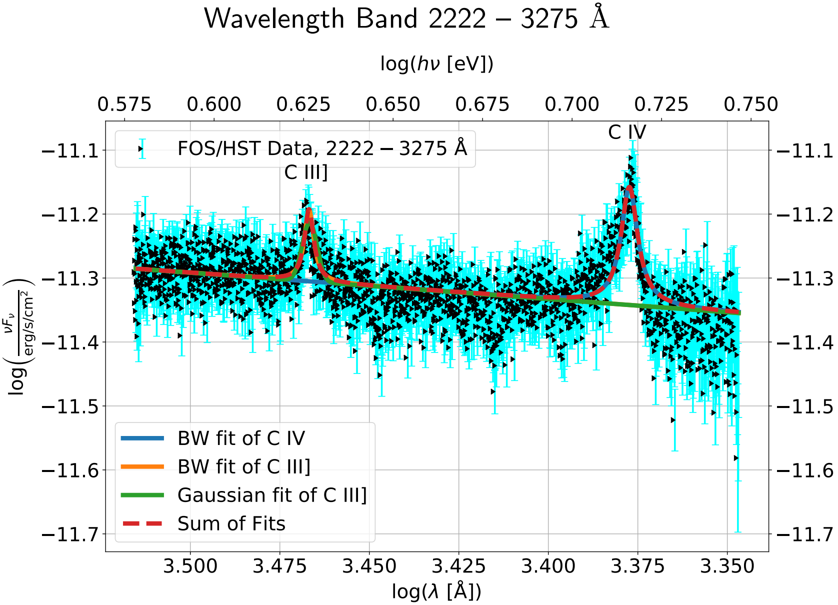
Emission lines fit with Breit-Wigner (BW) and Gaussian (Ga)

Wavelength band: 1590 – 2310 Å



[7] Ref. Bechtold et al., 2002.

RESULTS: Broad-Line Region, 3C 279



Gamma-gamma Opacity

Absorption per unit length from PL and BW respectively are[8]

$$\frac{d\tau_{PL}(E)}{dx} = \frac{\pi r_e^2 L_0}{4\pi c R_{BLR}^2 \epsilon_0^4} \left(\frac{m_e^2 c^4}{E(1+z)} \right)^2 \int_{\frac{m_e^2 c^4}{E(1+z)}}^{\infty} d\epsilon \bar{\phi}[s_0(\epsilon)] \left(\frac{\epsilon}{\epsilon_0} \right)^{-(\alpha+2)} \quad (11)$$

$$\frac{d\tau_{BW,i}(E)}{dx} = \frac{r_e^2}{2} \left(\frac{m_e^2 c^4}{E(1+z)} \right)^2 n_i w_i \int_{\frac{m_e^2 c^4}{E(1+z)}}^{\infty} \frac{d\epsilon}{\epsilon^2} \frac{\bar{\phi}[s_0(\epsilon)]}{(\epsilon - \epsilon_i)^2 + (w_i/2)^2} \quad (12)$$

The delta function approximation opacity of the i^{th} line is given by,

$$\tau_i = \frac{L_i}{4\pi c R_{BLR} \epsilon_i} \frac{\sigma_T}{5}$$

where n_i is number density of a line
w_i is equivalent width of the line
L_i is luminosity of the line,
ϵ_i is peak energy of the line.

[8] Equations adapted from Gould and Schréder, 1966.