The Evolution of Spectral Curvature of Fermi Bright Blazars

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Abstract

We study the evolution of spectral curvature of emitting electron energy distribution (EED) against its peak energy in a combined stochastic acceleration and cooling scenario by inverse Compton (IC) modeling of spectral energy distributions (SEDs) of Fermi bright blazars. **The blazar sample shows the theoretical blazar sequence between jet power and peak energy, and another sequence between jet power and curvature, suggesting that spectral curvature might be an important parameter of blazar sequence.** Curvature evolves differently in blazars depending on the source conditions. **We find that the curvature anti-correlates with peak energy in BL Lac objects (BL Lacs), that is a signature of pure hard-sphere stochastic acceleration. The curvature of FSRQs rather evolves in a transition cooling regime, where curvature either correlates positively with the peak energy or remains steady.**

Introduction & Background

The broadband spectral energy distribution (SED) of a blazar is significantly curved. The curvature of observed SED is related to an intrinsic curvature of source electron energy distribution (EED). The curvature in source EED can be explained either due to radiative cooling or a stochastic acceleration mechanism.

In a pure **cooling scenario**, an accelerated power-law EED $N(\gamma) = K\gamma^{-p}$ injected into the jet will be broken at an energy γ_b and the spectral index at high energy tail steepens to p_1. Now $\Delta p = |p_1 - p| \simeq 1$ roughly measures the curvature of EED. Since the spectral index $\alpha = (p-1)/2$ for optically thin non-thermal spectra, an EED curvature $\Delta p \simeq 1$ leads to curvature $\Delta\alpha = |\alpha_1 - \alpha| \simeq 0.5$. Thus a cooing scenario leads to a constant curvature $\Delta\alpha \simeq 0.5$.

A **stochastic acceleration mechanism** in which the probability of acceleration decays with particle energy (Massaro et al. 2004) or the gain is random (Tramacere et al. 2011) leads to a curved EED, approximated by a log-parabolic law as given by

$$N(\gamma) = N_0 \left(\frac{\gamma}{\gamma_0}\right)^{-a-b\log(\gamma/\gamma_0)},$$

where a is spectral index at reference energy γ_0 and b is curvature parameter. The peak energy of EED becomes

$$\log\gamma_p = \log\gamma_0 + \frac{3-a}{2b}.$$

This shows that in a purely acceleration scenario, the curvature b is inversely related to peak energy γ_p. The spectra of blazars are curved even in a single X-ray energy band as shown in Figure 1.

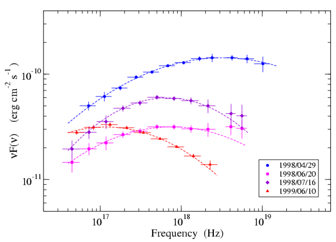

Figure 1:The keV X-ray spectra of high synchrotron peak blazar Mrk 501 (Massaro et al. 2004).

The synchrotron radiation spectra of log-parabolic EED follow similar shape. The keV photon spectra are fitted by a log-parabolic model

$$F(E) = K\left(\frac{E}{E_0}\right)^{-\alpha+\beta\log(E/E_0)} \quad (\mathrm{ph.cm^{-2}s^{-1}keV^{-1}}),$$

where photon curvature $\beta \approx b/5$ (Massaro et al. 2006).

The Stochastic Acceleration: Statistical Description

The log-parabolic SED in the νF_ν form is described as

$$\log(\nu F_\nu) = \log(\nu_p F_{\nu_p}) - \beta\log\left(\frac{\nu}{\nu_p}\right)$$

The stochastic acceleration suggests a linear relationship between SED peak frequency ν_p and curvature parameter β (Chen 2014) as

$$\frac{1}{\beta} = A\cdot\log\nu_p + B,$$

Where slope $A = 5/2$ for **energy dependent** and $10/3$ for **random gain** mechanism.
Chen (2014) found that slope A is nearly consistent with energy dependent acceleration.

The Motivation

The correlation between ν_p and β does not correspond to an intrinsic correlation between γ_p and b, since $\nu_p \propto \gamma_p^2 B\delta$ also depends on B and δ. Thus the intrinsic signature of stochastic acceleration has not been found previously. Furthermore, the evolution of intrinsic EED curvature b in a combined cooling and acceleration scenario has not been studied in observed blazars.

The Sample

We obtain the SEDs of 48 Fermi-LAT blazars from **LAT Bright AGN Sample (LBAS)** from Abdo et al. (2010). The SEDs include quasi-simultaneous Fermi-LAT and SWIFT-XRT and -UVOT.

- 23 FSRQs
- 9 low synchrotron peak BL Lacs (LBLs).
- 8 intermediate synchrotron peak BL Lacs (IBLs).
- 8 high synchrotron peak BL Lacs (HBLs).

The Model

We assume a **one-zone inverse Comton (IC) model** assuming a log-parabolic EED, that is produced in a stochastic acceleration.

EED: $N(\gamma) = N_0(\gamma/\gamma_p)^{-3}\, 10^{-b\log\left(\gamma/\gamma_p\right)^2}$

Peak energy: $\gamma_p = \sqrt{\nu_c/\nu_s}$

Emission coefficient: $j(\nu) = \frac{1}{4\pi}\int N(\gamma)P(\nu,\gamma)d\gamma$

Average synchrotron power: $P_s(\gamma) = \frac{4}{3}\sigma_T c\gamma^2 U_B$

Magnetic energy density: $U_B = B^2/8\pi$

Average IC power: $P_c(\gamma) = \frac{4}{3}\sigma_T c\gamma^2 U_{rad}$

Radiation energy density: $U_{rad} = L/4\pi R^2 c$

For SSC: $U_{ssc}(\nu) = (9/4)L_s(\nu)/(4\pi R^2 c)$

For EC: $U_{ec} = \frac{17\Gamma^2}{12}\frac{\eta L_{disk}}{4\pi R^2 c}$

We assume $\Gamma = \delta$.
The SED is described as

$$L(\nu') = 2\pi^2 R^3 j(\nu')\frac{2\tau^2 - 1 + (2\tau+1)e^{-2\tau}}{\tau^3}.$$

We use synchrotron self-absorption and a full Klein-Nishina cross-section to calculate Compton losses. We constrain physical jet parameters $B, \gamma_p, R, \delta, N_0$ from SED observable quantities.

Results: IC Modeling

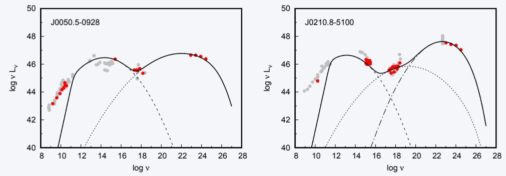

Figure 2:The SSC (left) and EC (right) model fit on blazar SEDs (Anjum et al. 2020).

- The SSC model successfully fits the Fermi γ-rays of HBLs.
- The EC component is necessarily important in LBLs and FSRQs.
- The γ-ray location might be at the edge of BLR.

Results: Curvature and Blazar Sequence

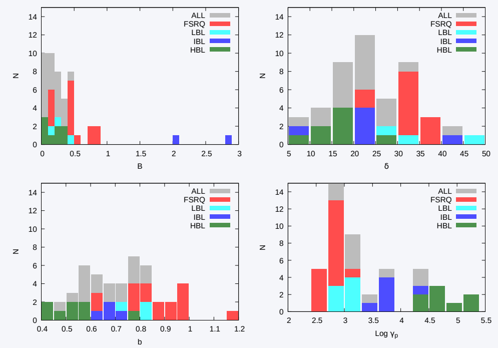

Figure 3:Distributions of physical jet parameters of the blazar sample (Anjum et al. 2020).

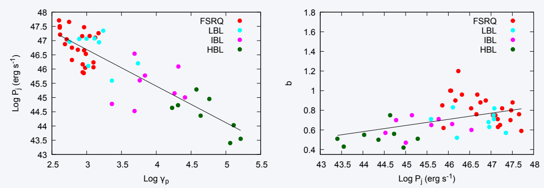

Figure 4:The relation of jet power P_j with peak energy γ_p (left) and curvature b (right).

- The different blazar classes show a systematic trend of source parameters.
- Jet power is negatively correlated to peak energy γ_p (blazar sequence).
- Jet power shows positive relation against curvature b.
- Spectral curvature might be an important parameter of blazar sequence in addition to ν_p and $\nu_p L_{\nu_p}$.

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Results: Stochastic Acceleration

We study the relationship between electron peak energy γ_p and curvature b as constrained by SED modeling.

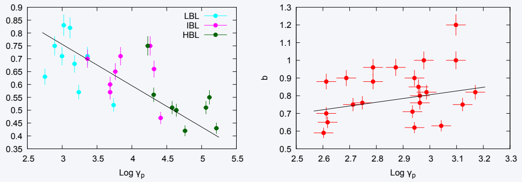

Figure 5:Relationship between peak energy γ_p and b for BL Lacs (left) and FSRQs (right). The solid lines represent best linear fits.

- BL Lacs show the signature anti-correlation expected in stochastic acceleration.
- FSRQs show a mild positive relationship opposite to BL Lacs.
- Cooling might be irrelevant in BL Lacs but important in FSRQs due to additional EC component.

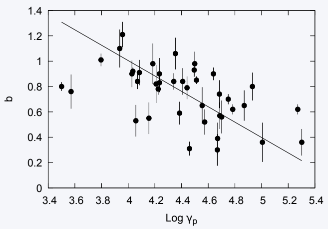

Figure 6:Relationship between peak energy γ_p and b for TeV BL Lacs based on Ding et al. (2017).

- Based on modeling of TeV BL Lacs by Ding et al. (2017), we find results similar to our BL Lac sample.

Stochastic Acceleration & Cooling Scenario

Diffusive shock acceleration is a stochastic process.

The time evolution of electron spectrum in a cooling and diffusive shock is described by

$$\frac{\partial N(\gamma,t)}{\partial t} = \frac{\partial}{\partial \gamma}\left[\{C(\gamma,t)-A(\gamma,t)\}N(\gamma,t)+D(\gamma,t)\frac{\partial N(\gamma,t)}{\partial\gamma}\right] - E(\gamma,t) - Q(\gamma,t)$$

Injection term: $Q(\gamma,t)$

Escape term: $E(\gamma,t) = N(\gamma,t)/t_{esc}$

Escape time: $t_{esc} = R/c$

Diffusion coefficient: $D(\gamma,t)$

Diffusive gain term: $A(\gamma,t)$

Cooling term: $C(\gamma,t) = \frac{4\sigma_t}{3m_e c}\gamma^2[U_B(t)+U_{rad}(\gamma,t)]$

A magnetic turbulence accelerate the particles via resonant interactions of particle and MHD modes of turbulence (Stawarz & Petrosian 2008).

The turbulence spectra is given by $W(k) = \frac{\delta B(k)^2}{8\pi}\left(\frac{k}{k_0}\right)^{-q}, \quad k = 2\pi/\lambda$

$q = 1$ for Bohm diffusion, $q = 2$ for hard-sphere spectrum, $q = 5/3$ for Kolmogorov spectrum, and $q = 3/2$ for Kraichnan spectrum.

Diffusion coefficient: $D(\gamma) \simeq \beta_A^2 \left(\frac{\delta B}{B}\right)^2 \left(\frac{\rho_g}{\lambda_{\max}}\right)^{q-1} \frac{\gamma^2 c^2}{\rho_g c}$

Alfven speed:$\beta_A = v_A/c$

Larmor radius: $\rho_g = \gamma c/eB$

Turblence parameter= $\partial B^2/B^2$

Acceleration time: $t_{acc} \simeq \frac{\gamma^2}{D(\gamma)} = \frac{\rho_g(\gamma_0)}{c\beta_A^2}\left(\frac{B^2}{\delta B^2}\right)\left(\frac{\gamma}{\gamma_0}\right)^{2-q}$

Spatial diffusion: $D_x \approx p^2\beta_A^2/D(\gamma)$

Escape time: $t_{esc} \simeq \frac{R^2}{D_x} \approx \frac{R^2}{(c\beta_A)^2 t_{acc}}$

The diffusion and gain timescales are do not depend on particle energy for hard-sphere (q=2) acceleration (Tramacere et al. 2011).

Evolution of Curvature

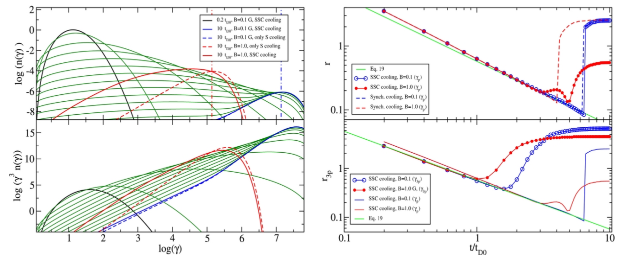

Figure 7:The evolution of EED (left) and curvature r (right) in a combined scenario for hard-sphere $q = 2$ for impulsive injection and no escape, with turbelnce level $\partial B/B = 0.1$, $\beta_A = 0.5$ and jet size $R = 10^{15}$ cm (Tramacere et al. 2011).

Tramacere et al. (2011) showed that curvature decreases continuously as the γ_p grows initially. When cooling compensate the acceleration, the curvature increases with energy in the cooling dominated regime leading to a steady state where curvature remains remains constant with energy.

Conclusions & Summary

- The curvature might be an important parameter of blazar sequence.
- The curvature in BL Lacs evolves in the acceleration dominated phase showing the signature anti-correlation between curvature and γ_p.
- The curvature in FSRQs evolves in a cooling dominated regime.
- The nature of underlying turbulence in blazar jets should be hard-sphere.

References

Anjum et al. 2011, ApJ, 898, 48; Chen 2014, ApJ, 788, 179; Ding et al. 2017, MNRAS, 464, 599; Massaro et al. 2004, A&A, 422, 103; Massaro et al. 2006, A&A, 448, 861; Tramacere et al. 2011, ApJ, 739, 66

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