Signatures of energy dependent diffusion in X-ray spectra of HBL Mkn 421

Pranjupriya Goswami[1] ; Sunder Sahayanathan[2] ; Atreyee Sinha[3] ; Rupjyoti Gogoi[1]

[1]Tezpur University, Assam, India. [2] Bhabha Atomic Research Centre, Mumbai, India. [3]Laboratoire Univers et Particules de Montpellier, CNRS, France.

Abstract

We present a phenomenological approach to model and interpret the observed X-ray spectral curvature of the HBL Mkn 421 under the simplistic assumptions of shock acceleration theory. The curved spectrum can be alternatively described as an outcome of energy-dependent electron diffusion in the acceleration region (EDD model). The model parameters determine the intrinsic curvature in terms of energy dependence electron escape timescale and the spectral index at a given electron energy. For the observational study, we utilize simultaneous Swift-XRT and NuSTAR data of Mkn 421 during 2012-2017 including flaring/quiescent flux states. While the model is capable of explaining various flux state spectra satisfactorily, the best-fit parameters show a strong linear correlation. The observed linear correlation enables us to determine an expression for the product of source magnetic field (B) and jet Doppler factor (δ) in terms of synchrotron and Compton peak energies. Through the underlying assumption of energy-dependent diffusion, we probe the magnetohydrodynamic turbulence in the jet and show a possible shift in the turbulence from Kolmogorov/ Kraichnan type to Bohm limit during high flux states.

Contact

Pranjupriya Goswami
Email: pranjupriya.g@gmail.com

Website: https://www.researchgate.net/profile/Pranjupriya-Goswami-2

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Objective

- The X-ray spectra in high energy peaked blazars are known to exhibit strong/mild curvature and hence, the underlying particle distribution significantly deviates from a power-law.
- A curved spectrum can be interpreted as an outcome of the energy-dependent diffusion from the acceleration region.
- In this work, we develop a synchrotron spectrum model to investigate the origin of spectral curvature and provide its physical interpretation

Model Description

A steady state two-zone model under leptonic scenario:

AR: $$\frac{\partial N_a(E)}{\partial t} + \frac{\partial}{\partial E}\left[\left(\frac{E}{t_{\rm acc}} - \beta_s E^2\right) N_a(E,t)\right] = Q_0\delta(E - E_{\rm inj}) - \frac{N_a(E,t)}{t_{\rm esc}}$$

CR: $$-\frac{d}{d\,E}\left[BE^2 N_c(E)\right] = \frac{N_a(E)}{t_{\rm esc}}$$

Underlying Assumptions:

- A mono-energetic and instantaneous electron injection
- Acceleration of electrons in shock front
- Energy-dependent electron diffusion

$$\rightarrow \quad t_{\rm esc}(E) \propto \left(\frac{E}{E_0}\right)^{-\kappa} \quad ; \quad \textbf{EDD model}$$

Here, t_{esc} is the escape timescale of the accelerated electrons and κ is diffusion index, determines the energy dependence of the electron escape.

Analytical solution:

Solving the above equations in steady-state, considering energy dependency in t_{esc}, electron distribution in CR is given as,

$$N_c(E) \propto E^{-2}\exp\left[-\frac{\xi_0}{\kappa}\left(\frac{E}{E_0}\right)^{\kappa}\right]$$

Observed Synchrotron flux:

$$F_\epsilon \propto \frac{1}{\sqrt{\epsilon}}\int_0^\infty f(x)\exp\left[-\frac{\psi}{\kappa}\left(\frac{\epsilon}{mc^2 x}\right)^{\kappa/2}\right]\frac{dx}{\sqrt{x}}$$

Here, ψ and κ are the fit parameters of EDD model that determine the observed Synchrotron spectral shapes.

Model predictions:

$$\psi = \xi_0\left(\frac{\alpha m^2 c^4}{E_0^2}\right)^{\kappa/2} \qquad H_p = -\frac{\kappa}{4}$$

$$H_p \approx \frac{1}{2}\,\frac{\ln\psi}{\ln\left(\frac{\epsilon_p}{0.29\,mc^2}\right)}$$

H_p represents the spectral curvature and ϵ_p is the synchrotron peak energy.

Observations and interpretation

- Energy-dependent index **(κ)** is associated with spectral curvature (H_p)
- Comparing κ with the power-law index of the MHD turbulent spectrum **(q),**

$$t_{esc} \propto E^{q-2}$$

EDD model yields $\kappa = 2 - q$;
$\kappa = 0, 1/3, 1/2$ and 1 represent hard- sphere, Kolmogorov, Kraichnan and Bohm diffusion.

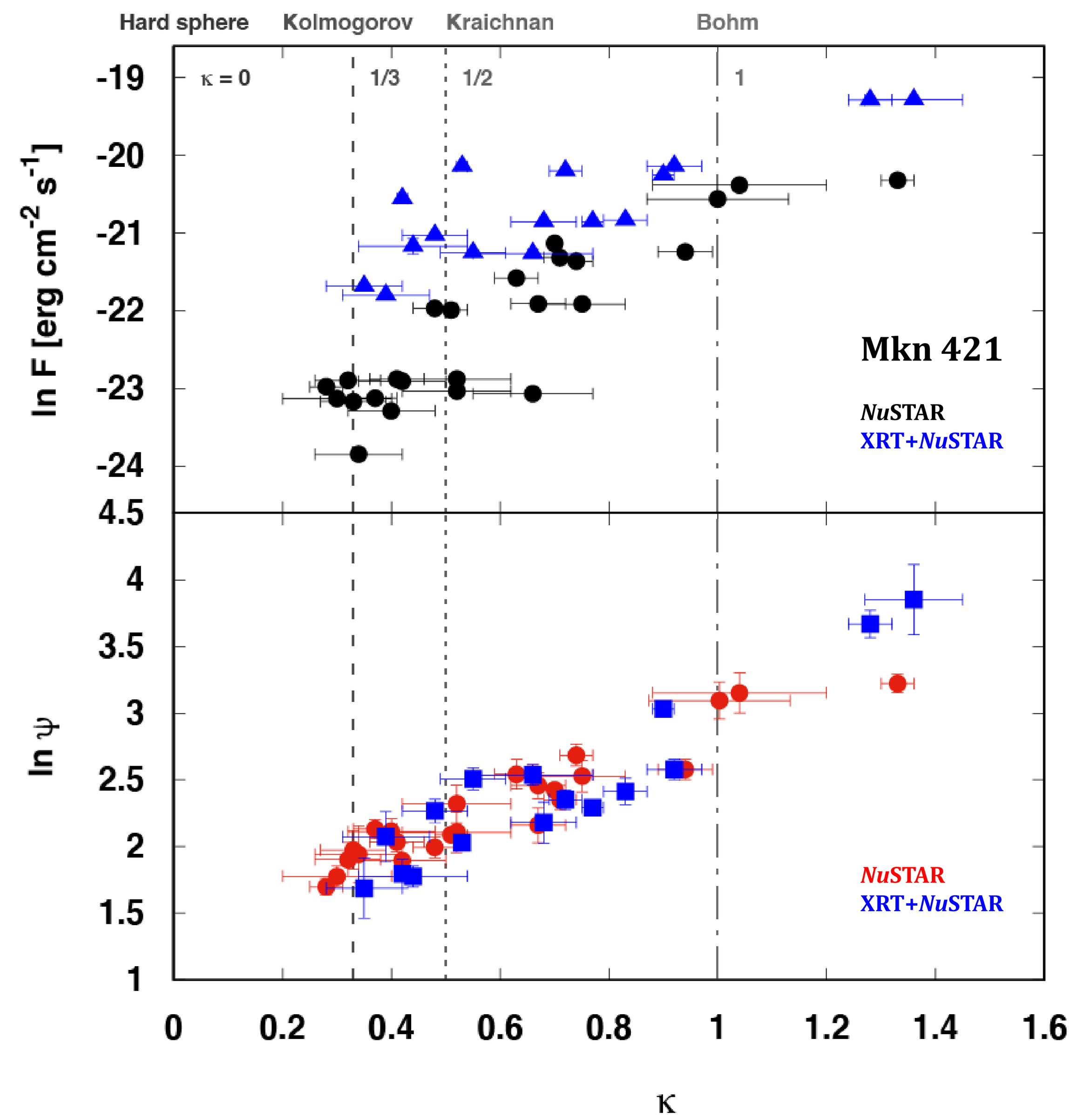

Fig1. Correlation plot between the model fit parameters

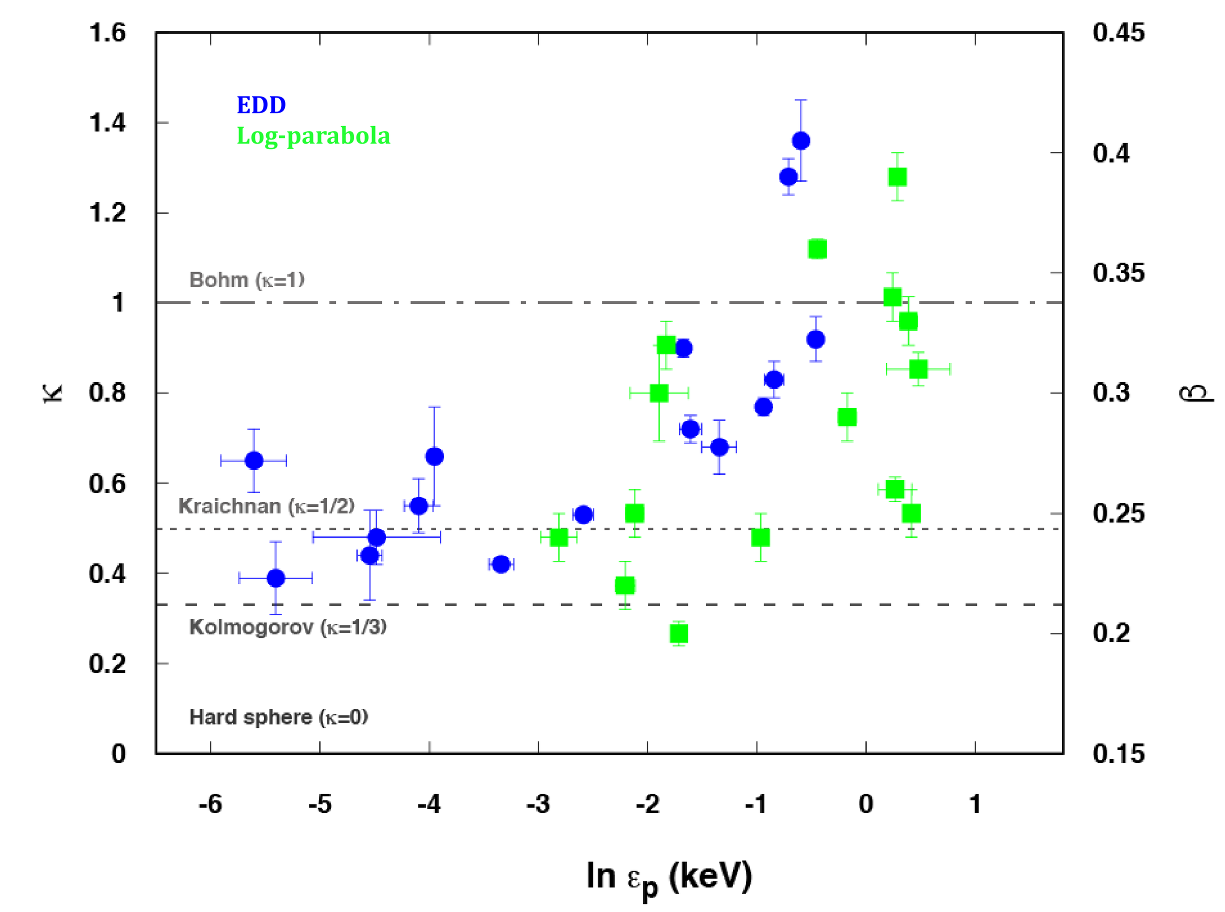

Fig2. Correlation plot between the Synchrotron peak & curvature

Estimation of source parameters

- Product of jet Doppler factor (δ) and magnetic field (B) can be expressed as:

$$(\delta B)_{\rm EDD} \approx 3.75\times10^{10}(1+z)\left(\frac{\epsilon_p}{\rm keV}\right)\left(\frac{\epsilon_{ic}}{\rm MeV}\right)^{-1}\exp\left[-2\left(a+\frac{b}{\kappa}\right)\right]$$

a, b are the slope and intercept of the linear correlation between ψ and κ.
ϵ_p and ϵ_{ic} are the Synchrotron and the corresponding inverse Compton peaks.

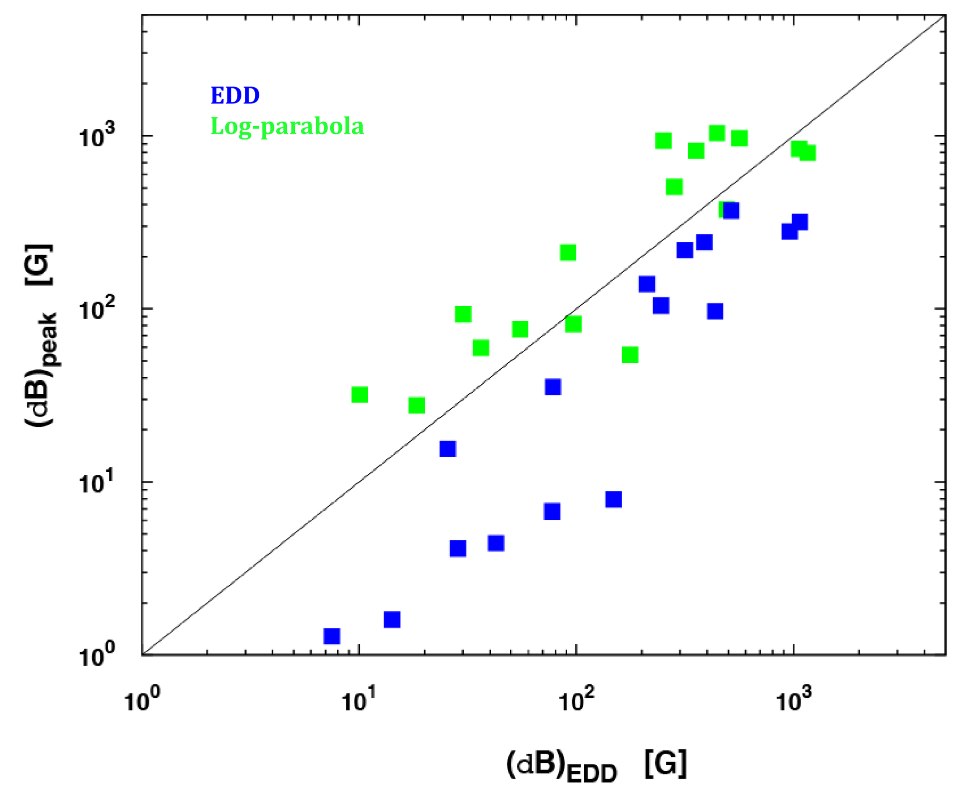

Fig3: Plot of (δ B) along with the identity line

Key results

EDD model highlights the plausible connection between the microscopic description of the electron diffusion with the macroscopic quantities deciding the broadband spectrum of Mkn 421.

- Model predicts the Synchrotron peak energy and curvature are correlated and correlation is consistent with the case of Mkn 421.
- Model probes the turbulence energy index, and the index appears to be shifted from Kolmogorov/Kraichnan type to Bohm limit during high flux states.
- Model yields an expression for the product of (δB) in terms of Synchrotron and inverse Compton peak energies.

References

- Goswami P., Sahayanathan S., Sinha A., Gogoi R.. 2020, MNRAS, 499, 2094.
- Goswami P., Sahayanathan S., Sinha A., Misra R., Gogoi R., 2018, MNRAS, 480, 2046
- Kardashev N. S., 1962, Soviet Ast., 6, 317
- Kusunose M., Takahara F., Li H., 2000, ApJ, 536, 299
- Teraki Y., Asano K., 2019, ApJ, 877, 71