Contribution of Compton-supported cascade emissions to broadband SEDs of ɣ-ray bright AGNi

Mfuphi Ntshatsha[1], Markus Boettcher[2], Soebur Razzaque[1]

Abstract

Active galactic nuclei (AGNi) are compact regions that emit throughout the electromagnetic spectrum. Blazars, a subclass of AGNi with their relativistic jets closely aligned with our line-of-sight, are especially powerful sources of ɣ-rays. Furthermore, the unified scheme for radio-loud AGNi classifies radio galaxies as the misaligned parent population of blazars. This would make them intrinsic producers of high-energy (HE, $E > 100$ MeV) and very high-energy (VHE, $E > 100$ GeV) ɣ-rays. However, early-generation observatories did not detect them at such high frequencies. It was understood that while emissions would be Doppler boosted in blazars, this would not be the case in radio galaxies. Recently, advances in ɣ-ray observatories have led to the detection of radio galaxies at these frequencies. To explain these emissions without relying on Doppler boosting, we leveraged a Monte-Carlo (MC) code that propagates ɣ-rays in an AGN environment, leading to secondary ɣ-ray and electron-positron pair cascades. In the code, we consider homogeneous external radiation from the broad-line region and anisotropic external radiation from a thin Shakura-Sunyaev accretion disk. We present the spectral energy distributions (SEDs) where a uniform magnetic field permeates the AGN environment. We then introduce our derivation of the equations of motion of an electron moving in a toroidal magnetic field. In a follow-up study we will implement these trajectories in the MC code and compare the resulting SEDs to the case of a uniform magnetic field.

Affiliation

[1]Centre for Astro-Particle Physics (CAPP), Department of Physics, University of Johannesburg, Auckland Park, 2006, South Africa.

[2]Centre for Space Research, North-West University, Potchefstroom, 2520, South Africa.

References

[1] Urry, C.M. & Padovanni, P., (1995), In: PASP 107.715, p. 803.
[2] Roustazadeh, P. & Böttcher, M., (2010). In: ApJ 717.1, p. 468.
[3] Roustazadeh, P. & Böttcher, M., (2011). In: ApJ 728.2, p. 13.
[4] Roustazadeh, P. & Böttcher, M., (2012). In: ApJ 750.1, p. 26.
[5] Godambe, S. N. et al., (2024). In ApJL 974.2, p. L31.
[6] Andati, L. A. et al., (2024). In MNRAS 529.2, pp 1626 – 1641.

Introduction

AGNi differ from inactive galaxies.

* Their central supermassive black holes (SMBHs, m_{BH}~10^6 to ~10^9 solar masses) are fed material from a torus of gas and dust.

This forms

* a thin hot accretion disk → a broad-line region (BLR). Radiate in optical and ultraviolet (UV) frequencies.

* bipolar jets of ɣ radiation "perpendicular" to the accretion disk [1].

$$\gamma + \gamma \rightarrow e^- + e^+$$

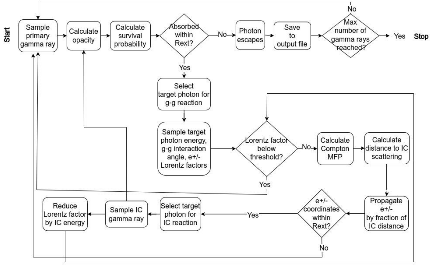
where $e^{+/-}$ is an electron/positron.

$e^{+/-}$ can inverse-Compton (IC) scatter optical/UV photons to ɣ-rays.

Sets off a chain-reaction leading to the development of $e^{+/-}$ and ɣ-ray cascades.

Code setup

This work leverages the pioneering works of [2,3,4]. They developed a MC code that propagates a primary ɣ-ray produced in the jet. Specifying a number of ɣ-rays, the code effectively simulates a beam of primary ɣ-rays, following each individual photon and subsequent interactions until it leaves the BLR volume. The diagram below illustrates how the MC simulation runs.



SEDs of NGC 1275 from uniform *B*

NGC 1275 is a radio galaxy with a jet viewing angle between 14° and 17°. The cascade code takes eight parameters as input. We've fixed five from literature and varied three. We list them below:

Fixed:

- Primary ɣ-ray spectral index = 2.5.
- Accretion disk luminosity $L_d = 1.88 \times 10^{43}$ erg s^{-1}.
- $R_{BLR} = 10^{16}$ cm.
- $m_{BH} = 10^8$ M$_{sun}$.
- Magnetic field orientation from jet axis $\theta_B = 11°$.

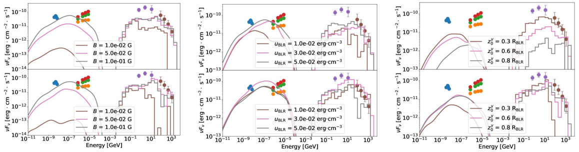
Varied:

Magnetic field strength B.

BLR energy density u_{BLR}.

Primary ɣ-ray origin $(x_0, y_0, z_0) = (0, 0, z_0)$.

Cascade SEDs against broadband SED of [5].



- ★ *Left panel*: $u_{BLR} = 50 \times 10^{-3}$ erg cm^{-3} ; $z_0 = (0.8, 0.6)$ R$_{BLR}$, in upper and lower panes, respectively.
- ★ *Center panel*: $B = 100$ mG ; $z_0 = (0.8, 0.6)$ R$_{BLR}$, in upper and lower panes, respectively.
- ★ *Right panel*: $B = 50$ mG; $u_{BLR} = (5, 50) \times 10^{-3}$ erg cm^{-3}, in upper and lower panes, respectively.

Implications & next steps

- ★ Varying B: Isotropizes $e^{+/-}$ pairs, and broadens IC spectrum.
- ★ Varying u_{BLR} : Increases synchrotron emission and then suppress it. Increases IC emission and opacity to VHE ɣ-rays.
- ★ Varying z_0: Has effect similar to u_{BLR}, validating the importance of disk radiation density as a function of height from SMBH.

Spectropolarimetric studies [6] show that magnetic field lines in AGNi have a helical morphology around the jets. Next for the cascade code, we embed a toroidal magnetic field, B_{tor}, around the jet.

Requires determination of equations of motion (EOMs) of $e^{+/-}$ in toroidal magnetic field.

EOMs in toroidal *B*

$$\mathbf{B}_{tor} = B_0\hat{\phi} = B_0(-\sin\phi, \cos\phi, 0)$$

$$\mathbf{A} = \frac{1}{2}B_0 z\hat{\rho} - \frac{1}{2}B_0\rho\hat{k}$$

$$L = -\frac{mc^2}{\gamma} + q\dot{\mathbf{r}}\cdot\mathbf{A}$$

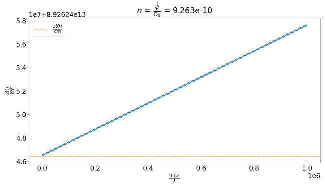
$$\frac{d}{dt}\left(\frac{\partial L}{\partial \dot{g}_i}\right) = \frac{\partial L}{\partial g_i},$$

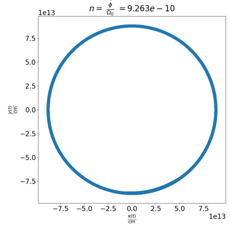
where g_i and $\dot{g}_i$ are generalized coordinates and velocities

$$\implies \ddot{\rho} - \rho\dot{\phi}^2 = -\frac{qB_0}{\gamma mc}\dot{z}$$

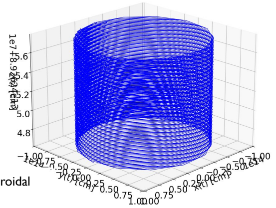
$$\rho^2\ddot{\phi} + 2\rho\dot{\rho}\dot{\phi} = 0$$

$$\ddot{z} = \frac{qB_0}{\gamma mc}\dot{\rho}.$$





3D Trajectory of $\mathbf{r}_e(t) = \langle x_e(t), y_e(t), z_e(t)\rangle$
Where jet-axis == z-axis
$n = \frac{\dot{\phi}}{\Omega_0} = 9.262667\text{e-}10$



* Trajectories of a first-generation electron moving in a toroidal magnetic field.
* Motion is helical about the field lines with a drift in a direction perpendicular to the curvature of the magnetic field.

Expected cascade SEDs

A toroidal magnetic field will also isotropize the $e^{+/-}$ pairs. In their works, [2] determined that the component of B that is transverse to the jet-axis caused the isotropization. We therefore expect a toroidal B to be more efficient at this. The noted overall SED behaviour would still be observed.