PROCEEDINGS OF SCIENCE

Anisotropy and polarization effects in blazar emission

Motseothata Tisang* **and Markus Böttcher**

Center for Space Research, North-West University, Potchefstroom 2520, South Africa

E-mail: tisangtms@gmail.com, markus.bottcher@nwu.ac.za

Blazars, characterized by radio-loud active galactic nuclei with relativistic jets directed at us, exhibit features such as polarization in various wavebands and double-peak spectral energy distribution (SED). These features are influenced by various parameters, including the viewing angle and the magnetic field orientation with respect to the jet axis. This study reports on the development of a full angle- and polarization-dependent synchrotron and synchrotron self-Compton (SSC) blazar emission model with relativistic electrons in a perfectly ordered magnetic field. Using our developed code, we simulate different magnetic field orientations (parallel, perpendicular, and oblique geometries) and viewing angles relative to the jet axis, and study the impacts on the SED and linear polarization degree of a generic blazar. We demonstrate that the synchrotron emission is much more sensitive to the viewing angle and the field orientations compared to the SSC emission. Particularly, the close alignment of the viewing direction with the magnetic field direction suppresses the synchrotron emission, while leaving the SSC emission almost unaffected.

**** 10th Annual Conference on High Energy Astrophysics in Southern Africa, ****
**** 5 - 9 September 2023 ****
**** Mtunzini, Kwa-Zulu Natal, South Africa ****

*Speaker

PoS(HEASA2023)009

1. Introduction

Blazars are jetted active galactic nuclei (AGNs) with relativistic jets directed toward us [1]. They exhibit features such as polarized emission at least in the radio through optical bands (in some cases also in X-rays [2]) and double-peak spectral energy distribution (SED) with two broad, non-thermal components, i.e., the low-energy (LE) component which is generally modeled by synchrotron emission from relativistic electrons in the jet, and the high-energy component which can be modeled by leptonic (emission is produced by Compton scattering of synchrotron/external photons) and hadronic (emission is produced by photo-pion production or proton-synchrotron mechanisms) blazar emission models (see [3, 4] for a review of blazar models).

Significant efforts have been made to understand the magnetic fields of AGN jets using multi-waveband polarimetry as a diagnostic tool [5]. The optical polarization degree (PD) is typically higher than the radio PD, implying smaller emission regions with a more uniform magnetic field compared to radio emitting regions [6]. Lister and Smith [7] found that low optical polarization ($< 3\%$) quasars have a magnetic field aligned with the jet axis, whereas high polarization ($> 3\%$) quasars usually have fields oriented perpendicular to the jet axis. Furthermore, optical-radio polarimetry probes less active jet regions which produce emission from particles that left the acceleration zone days to years earlier, and hence do not directly explore the jet's magnetic field structure [2]. In contrast, X-ray polarization signatures, which are measurable by the Imaging X-ray Polarimetry Explorer (IXPE) [8], probe the most energetic and inner regions of the jet, where strong magnetic fields prevail [2].

Several studies have been conducted considering either anisotropy or polarization effects in blazar models, but not the combination of both: Lyutikov et al. [9] evaluated the impact of purely helical magnetic fields on the synchrotron polarization, proposing their potential role for the polarization signatures observed at parsec-scale jets. Jamil and Böttcher [10] studied the angle-dependent synchrotron and synchrotron self-Compton (SSC) blazar emission with partially ordered magnetic fields and anisotropic particle distributions. They showed that the synchrotron spectrum is much more sensitive to the field orientations compared to the SSC spectrum. Zhang and Böttcher [11] analyzed the expected SSC polarization signatures of blazars in a perfectly ordered magnetic field, suggesting a significant role of SSC polarization in distinguishing leptonic from hadronic HE emission. Joshi et al. [12, 13] explored the effects of purely ordered magnetic field orientations on the SEDs of a generic blazar. They pointed out, amongst other findings, that the alignment of the magnetic field with our viewing direction leads to the cancellation of the synchrotron emission. Despite these studies, a comprehensive study of full angle- and polarization-dependent blazar emission models remains lacking.

Therefore, this study reports on a full angle- and polarization-dependent synchrotron and SSC blazar emission model with relativistic electrons in a spherical emitting region with a perfectly ordered magnetic field. Using our code, we simulate the viewing angle and the magnetic field geometries with respect to the jet-axis, and study the impact on the SED and polarization degree (PD) of a generic blazar. Considered field geometries relative to the jet axis include parallel, perpendicular, and oblique orientations. Note that this work is conducted in the frame of the emission region moving along the jet. Hence, no Doppler boosting into the observer's frame is taken into account. Our model setup is described in Section 2, along with definitions of non-thermal processes that give rise to the SEDs and polarization of blazars. The results with discussion are presented in Section 3. Finally, Section 4 presents our summary and outlook. Throughout this paper, we define $\epsilon = h\nu/m_e c^2$ as the dimensionless photon energy. Angles ψ and ϕ represent directions relative to the jet-axis (supposed to align with the $z-$axis) and in the $xy-$plane.

2. The Setup of Our Model

This section describes the formalism used to evaluate the angle-dependent spectra and linear PD arising from synchrotron and SSC mechanisms. The primary objective is to calculate the synchrotron emissivity and polarization while accounting for the effects of the magnetic field orientation relative to the jet-axis, and subsequently compute the resulting SSC emissivity and polarization. The calculation involves determining the pitch angle φ, i.e., the angle between the electron direction and the magnetic field direction, for each considered field orientation. In our approach, we assume a power-law distribution of isotropic relativistic electrons, e.g., $n_e(\gamma)d\gamma = n_0\gamma^{-p}d\gamma$ for $\gamma_{\rm min} \leq \gamma \leq \gamma_{\rm max}$, in a spherical emitting region with coordinates (r, ψ, ϕ) centered on the jet axis. Let (x, y, z) be the corresponding Cartesian coordinates with the $z-$axis orientated along the jet axis. We also assume a perfectly ordered magnetic field and that the selected field orientation remains the same across the emission region. Moreover, we consider photons to be emitted in the same direction as the electron pitch angle. Thus, given any magnetic field unit vector $\hat{\mathbf{B}}$, the cosine of the pitch angle is determined as $\cos(\varphi) = \hat{\boldsymbol{\kappa}} \cdot \hat{\mathbf{B}}$, where $\hat{\boldsymbol{\kappa}} = (\sin\psi_{\rm ph}\cos\phi_{\rm ph}, \sin\psi_{\rm ph}\sin\phi_{\rm ph}, \cos\psi_{\rm ph})$ is the photon propagation direction.

The synchrotron emissivity $j_\nu^{\rm syn}(\varphi)$ and polarization $\Pi_\nu^{\rm syn}(\varphi)$ are as defined in [14]:

$$j_\nu^{\rm syn}(\varphi) = \frac{\sqrt{3}e^3}{m_e c^2} B\sin(\varphi) \int n_e(\gamma)F(x)d\gamma, \tag{1}$$

$$\Pi_\nu^{\rm syn}(\varphi) = \frac{\langle G(x)\rangle}{\langle F(x)\rangle} = \frac{\int n_e(\gamma)G(x)d\gamma}{\int n_e(\gamma)F(x)d\gamma}, \tag{2}$$

where $x = \nu/\nu_\varphi(\gamma)$ with $\nu_\varphi(\gamma) \approx 4.2 \times 10^6 B\gamma^2 \sin\varphi$ [Hz] the critical frequency. To minimize computation time, we have approximated $F(x)$ as

$$F_{\rm approx}(x) = 1.42\sqrt{\frac{\pi}{2}}x^{3/10}e^{-x}. \tag{3}$$

Figure 1 shows comparisons of $F(x)$ and $F_{\rm approx}(x)$ in plot (a), and of the exact $j_\nu^{\rm syn}(\varphi)$ with its approximation in plot (b). The orange- and black-dashed lines in plot (b), represent the critical synchrotron frequencies corresponding to the low- and high-frequency cutoffs of the electron distribution. From these plots, our $F_{\rm approx}(x)$ proves to be sufficiently accurate and reliable for our study.

The SSC emissivity at a frequency $\nu_s = m_e c^2 \epsilon_s/h$ and in a direction ψ_s relative to the jet-axis is calculated as [15]:

$$j_{\rm SSC}^{\rm head\text{-}on}(\epsilon_s, \psi_s) = \frac{hc\epsilon_s}{4\pi}\int_1^\infty n_e(\gamma)d\gamma \int_{-1}^{+1} d\eta_{\rm ph} \int_0^{2\pi} d\phi_{\rm ph} \int_0^\infty n_{\rm ph}(\epsilon, \varphi)(1-\beta\mu)\frac{d\sigma_C}{d\epsilon_s}d\epsilon. \tag{4}$$

The synchrotron photon spectrum is given as

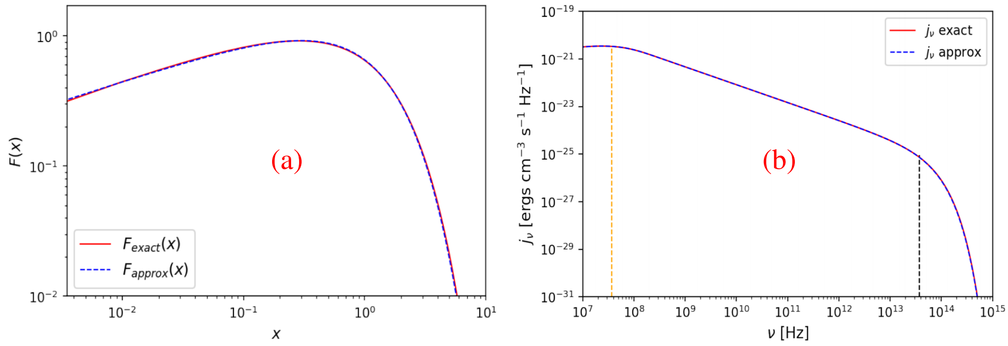

Figure 1: (a): Comparison between the exact $F(x)$ and its approximation $F_{\text{approx}}(x)$. (b): Comparison between the exact $j_\nu^{\text{syn}}(\varphi)$ and its approximation.

$$n_{\text{ph}}(\epsilon, \varphi) = \frac{j_\nu^{\text{syn}}(\varphi)}{m_e c^2 \epsilon} \langle t_{\text{esc}} \rangle, \tag{5}$$

where $\langle t_{\text{esc}} \rangle = 3R_{\text{b}}/4c$ is the average photon escape time for a sphere with R_{b} representing the radius of the emission region [10].

As it is accepted that the SSC mechanism decreases the PD of the synchrotron photon field by a factor of $\sim 1/2$ [16], we compute our SSC polarization as half of the synchrotron polarization:

$$\Pi^{\text{SSC}}(\nu^{\text{SSC}}, \varphi) \approx \frac{1}{2} \Pi^{\text{syn}}(\nu^{\text{syn}}, \varphi), \tag{6}$$

where $\nu^{\text{SSC}} \sim \gamma^2 \nu^{\text{syn}}$ in the context of the Thomson regime. As it is generally known that the dominant contribution to the seed photons for SSC emission is from synchrotron photons emitted at pitch angles around 90°, we properly weighted Equation 2 according to the contributions that synchrotron photons from different pitch angles make to the total SSC emission.

3. Results and Discussion

We perform a parameter analysis of the viewing angle and the magnetic field orientation on the SED and PD of a generic blazar. The fixed parameters in our model include a power-law index of $p = 2.5$, a magnetic field strength of $B = 1.0$ G, an electron kinetic power of $L_e = 10^{44}$ erg·s^{-1}, an emission region radius of $R_{\text{b}} = 10^{16}$ cm, an observer angle in the $xy-$plane of $\phi_{\text{obs}} = 0°$, and low- and high-energy cutoffs of $\gamma_{\text{min}} = 10$ and $\gamma_{\text{max}} = 10^4$. Using the expression for the kinetic power of the relativistic electrons in the emission frame, as defined in [3], the selection of these parameters yields a power-law electron normalization factor of $n_0 \approx 9.4 \times 10^4$ cm^{-3}.

Figure 2 shows the impacts of the viewing angle on the SED of our generic blazar (left plots) and on the polarization arising from the synchrotron (plot (b)) and SSC (plot (d)) mechanisms. Plot (c) represents the case of a perpendicular magnetic field, while the other plots represent a parallel magnetic field. Focusing on plot (a), as the viewing angle ψ_{obs} increases, the value of $\sin\varphi$ rises as well. As a result, the synchrotron flux level rises, and consequently, the corresponding synchrotron peak frequency and cutoff frequencies shift to higher values. On the other hand, the SSC flux almost maintains the same level as ψ_{obs} varies, as expected. This is in alignment with the findings of Jamil

PoS(HEASA2023)009

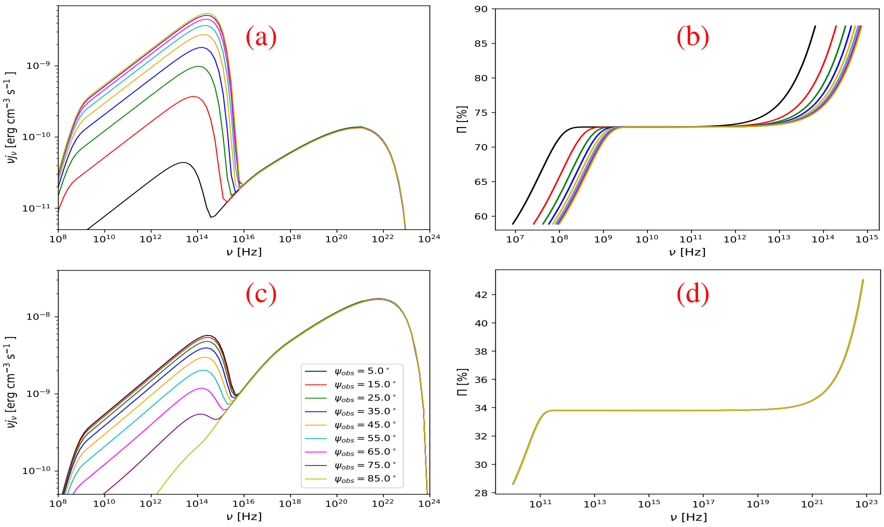

Figure 2: The influence of parallel (a, b, d) and perpendicular (c) magnetic field orientations on the SEDs of our generic blazar (left plots) and polarization arising from synchrotron (b) and SSC (d) mechanisms.

and Böttcher [10]. Moreover, the SED is dominated by SSC emission at $\psi_{\text{obs}} = 5°$, whereas, when $\psi_{\text{obs}} \in [15°, 85°]$, it becomes increasingly synchrotron-dominated emission. In plot (c), the value of $\sin\varphi$ decreases as ψ_{obs} increases. As a consequence, we observe the opposite trend compared to synchrotron flux levels in plot (a). The effects of oblique magnetic field geometry on the SED have also been explored. However, their plots have been omitted as they show the same trend as shown here, that a close alignment of the viewing direction with the magnetic field direction suppresses synchrotron emission, while leaving SSC almost unaffected.

In plot (b), the points where the polarization levels plateau or stop plateauing shift to higher frequencies while maintaining the same PD as ψ_{obs} increases. In plot (d), similar to the SSC flux level, the SSC polarization is almost unaffected as ψ_{obs} changes. Synchrotron and SSC polarization signatures under cases of perpendicular and oblique orientations are omitted as they exhibit the same trends as the cases shown here.

4. Summary and Outlook

In this paper, we have developed a full angle- and polarization-dependent synchrotron and SSC model for blazars, and subsequently, carried out a parameter analysis to understand the effects of physical parameters, such as the viewing angle and the magnetic field orientation, on the SED and PD of our generic blazar. We have demonstrated that these parameters dramatically alter synchrotron emission, while leaving SSC almost unaffected. This work was the first step in the development of a full angle- and polarization-dependent blazar radiation transfer code. In future analysis, the effects of synchrotron self-absorption and γ-ray absorption mechanisms will be taken into account, in addition to synchrotron and SSC processes. More complex magnetic field orientations such as helical field, will also be considered. For the SSC polarization analysis, we will consider contributions from anisotropic synchrotron photons (not only from those emitted at pitch angles of $\sim 90°$ as in this work), and therefore, the computation will follow the approach outlined in [16]. Finally, we will apply our model to blazar data.

References

[1] Urry, C Megan, Padovani, Paolo: *Unified schemes for radio-loud active galactic nuclei*. Publications of the Astronomical Society of the Pacific 107.715 (1995), p. 803.

[2] Liodakis, Ioannis et al.: *Polarized Blazar X-rays imply particle acceleration in shocks*. Nature 611.7937 (2022), pp. 677–681.

[3] Böttcher, M et al.: *Leptonic and hadronic modeling of Fermi-detected blazars*. The Astrophysical Journal 768 (2013), p. 54.

[4] Böttcher, Markus: "Modeling the emission processes in blazars". *The Multi-Messenger Approach to High-Energy Gamma-Ray Sources*. Springer. 2007, pp. 95–104.

[5] Marscher, Alan P et al.: *Probing the inner jet of the quasar PKS 1510−089 with multi-waveband monitoring during strong gamma-ray activity*. The Astrophysical Journal Letters 710.2 (2010), p. L126.

[6] Fraija, Nissim et al.: *Long-term optical polarization variability and multiwavelength analysis of Blazar Mrk 421*. The Astrophysical Journal Supplement Series 232 (2017), p. 7.

[7] Lister, Matthew L, Smith, Paul S: *Intrinsic differences in the inner jets of high and low optically polarized radio quasars*. The Astrophysical Journal 541 (2000), p. 66.

[8] Weisskopf, Martin C et al.: *Imaging X-ray polarimetry explorer: prelaunch*. Journal of Astronomical Telescopes, Instruments, and Systems 8.2 (2022), pp. 026002–026002.

[9] Lyutikov, Maxim, Pariev, Vladimir I, Gabuzda, Denise C: *Polarization and structure of relativistic parsec-scale AGN jets*. Monthly Notices of the Royal Astronomical Society 360.3 (2005), pp. 869–891.

[10] Jamil, O., Böttcher, M.: *An Angle Dependent SSC Model for Relativistic Jet Sources*. The Astrophysical Journal 759.1 (2012), p. 45.

[11] Zhang, Haocheng, Böttcher, Markus: *X-ray and gamma-ray polarization in leptonic and hadronic jet models of blazars*. The Astrophysical Journal 774 (2013), p. 18.

[12] Joshi, Manasvita, Marscher, Alan, Böttcher, Markus: *Theoretical Study of the Effects of Magnetic Field Geometry on the High-Energy Emission of Blazars*. Galaxies 4.4 (2016), p. 45.

[13] Joshi, Manasvita, Marscher, Alan P, Böttcher, Markus: *Impact of ordered and disordered magnetic fields on multiwavelength emission of blazars*. The Astrophysical Journal 898 (2020), p. 11.

[14] Rybicki, George B, Lightman, Alan P: *Radiative processes in astrophysics*. John Wiley & Sons, 1991.

[15] Böttcher, Markus, Harris, Daniel E, Krawczynski, Henric: *Relativistic jets from active galactic nuclei*. John Wiley and Sons, 2012.

[16] Bonometto, S, Saggion, A: *Polarization in inverse Compton scattering of synchrotron radiation*. Astronomy and Astrophysics 23 (1973), p. 9.