Synchrotron Emission from Pair Cascades in AGN Environments

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Recent detections of very-high-energy (VHE, $E > 100$ GeV) $\gamma$-ray blazars which do not belong to the high frequency peaked BL Lac (HBL) class, suggest that $\gamma\gamma$ absorption and pair cascading might occur in those objects. In the presence of even weak magnetic fields, these Compton-supported pair cascades will be deflected and contribute to the Fermi $\gamma$-ray flux of radio galaxies. We demonstrate that, in this scenario, the magnetic field can not be determined from a fit of the cascade emission to the $\gamma$-ray spectrum alone, and the degeneracy can only be lifted if the synchrotron emission from the cascades is observed as well. We illustrate this fact with the example of NGC 1275. We point out that the cascade synchrotron emission may produce spectral features reminiscent of the big blue bump observed in the spectral energy distributions of several blazars, and illustrate this idea for 3C 279.

I. INTRODUCTION

Flat spectrum radio quasars (FSRQs) and BL Lacertae objects (BL Lac) are the two main subclasses of blazars. They radiate in the entire electromagnetic spectrum, from radio up to $\gamma$-rays. The spectral energy distribution (SED) of blazars consists of a low energy peak and a high energy peak. It is strongly believed that the low energy component from the radio to optical-UV or $x$-rays is dominated by synchrotron radiation from relativistic electrons. In leptonic models, the high energy component from $x$-rays to $\gamma$-rays is produced by Compton upscattering. Soft photons for Compton upscattering may be produced by the accretion disk [4], the broad line region (BLR) [8, 16], hot dust in the central region [4] or synchrotron emission from the highly relativistic particles in the jets themselves.

If the VHE $\gamma$-ray emission is produced in the high-radiation-density environment of the broad line region (BLR) and/or the dust torus of an AGN (as commonly found in non-HBL blazars), it is expected to be strongly attenuated by $\gamma\gamma$ pair production. In [14, 15], we considered the full 3-dimensional development of Compton-supported VHE $\gamma$-ray induced cascades in the external radiation fields in AGN environments. In this paper, we summarize the salient results of our recent work in which we generalized the Monte-Carlo cascade code developed in [12] to non-negligible magnetic fields and consider the angle dependent synchrotron emission from the cascades.

II. MODEL SETUP AND CODE DESCRIPTION

The general model setup used for this work is described in [13, 14]. The primary VHE $\gamma$-ray emission is represented as a mono-directional beam of $\gamma$-rays propagating along the $X$ axis, described by a power-law with photon spectral index $\alpha$ and a high-energy cut-off at $E_{\gamma,max}$. We have verified that the shape of the cascade emission is virtually independent of the precise shape of the primary $\gamma$-ray spectrum, so that our conclusions remain unchanged when using a more realistic VHE $\gamma$-ray emission spectrum (such as a broken power-law or a power-law + exponential cut-off).

We assume that the primary $\gamma$-rays interact via $\gamma\gamma$ absorption and pair production with an isotropic radiation field with arbitrary spectrum within a fixed boundary, given by a radius $R_{ext}$.

Our code evaluates $\gamma\gamma$ absorption and pair production using the full analytical solution to the pair production spectrum of [2] under the assumption that the produced electron and positron travel initially along the direction of propagation of the incoming $\gamma$-ray. The trajectories of the particles, as they are deflected by the magnetic field, are followed in full 3-D geometry. Compton scattering is evaluated using the head-on approximation. The code calculates the synchrotron energy loss of cascade particles between successive Compton scatterings. The synchrotron emission of electrons/positrons between two Compton scatterings is evaluated using an asymptotic approximation, $P_\gamma(\gamma) \propto \nu^{\gamma/3} \exp(-\nu/\nu_c[\gamma])$, properly normalized to the energy loss, where $\nu_c \sim 3.4 \times 10^{18} (B/G)^{\gamma^2} Hz$ and $\gamma$ is the electron Lorentz factor.

III. NUMERICAL RESULTS

We have used the cascade Monte-Carlo code described in the previous section to evaluate the angle-dependent Compton and synchrotron spectra from VHE $\gamma$-ray induced pair cascades.

Figure 1 shows the cascade spectra for different values of the external radiation field energy density $\nu_{ext}$. For increasing values of the external radiation field, the spectral breaks of both radiation components, when viewed at substantial off-axis angles, shift to lower energies. This is a result of the decreasing...
Compton cooling length, implying that particles cool to lower energy before being sufficiently deflected to contribute to the emission at a given observing angle. Figure [1] also shows that the synchrotron luminosities of the cascades decrease with increasing $u_{\text{ext}}$ while the Compton luminosities of the cascades increase. For larger values of $u_{\text{ext}}$ and fixed blackbody temperature the soft target photon number density increases and so does the photon-photon absorption opacity $\tau_{\gamma\gamma}$, so that an increasing fraction of VHE photons will be absorbed, and the Compton flux from the cascades becomes larger. For very large values of $u_{\text{ext}}$, $\tau_{\gamma\gamma} \gg 1$ for
photons above the pair production threshold so that essentially all VHE photons will be absorbed and the Compton flux from the cascade becomes independent of $u_{ext}$ [14, 15]. At the same time, the relative power in synchrotron to Compton emission continues to be determined by $P_{X}/P_{C} \propto B^2/u_{ext}$.

Figure 2 illustrates the effects of a varying magnetic-field orientation with respect to the jet axis, for fixed magnetic-field strength $B = 1 \mu$G for different angular bins. The results for the Compton component have been discussed in [15], where it has been shown that the perpendicular component of the magnetic field ($B_y$) is responsible for the isotropization of secondaries in the cascade. The figure illustrates that also the synchrotron radiation depends primarily on $B_y$.

**IV. MAGNETIC FIELD DEGENERACY**

In [14], we evaluated the expected Compton emission from VHE $\gamma$-ray induced pair cascades in the radio galaxy galaxy NGC 1275 (which is known to host a low-luminosity AGN at its center), assuming that it would appear as a $\gamma$-ray blazar when viewed along the jet. This was used to fit the Fermi spectrum of this radio galaxy. We now show that the parameter choice of the magnetic field, both orientation and strength, is degenerate in this fitting procedure, if only the high energy output from the cascades is considered. Figure 3 illustrates this effect. In this plot, the external radiation field is parameterized through $u_{ext} = 5 \times 10^{-2}$ erg cm$^{-3}$ with photon energy $E_s = E_{Ly\alpha}$ and $R_{ext} = 10^{16}$ cm. This size scale is appropriate for low-luminosity AGN as observed in NGC 1275 [e.g., 12], and the parameters combine to a BLR luminosity of $L_{BLR} = 4\pi R^2_{ext} c u_{ext} = 1.9 \times 10^{42}$ erg s$^{-1}$, in agreement with the observed value for NGC 1275. The magnetic field orientation is at an angle of $\theta_B = 11^\circ$ with respect to the jet axis. The cascade spectrum shown in Figure 3 pertains to the angular bin $0.6 < \mu < 0.8$ (corresponding to $37^\circ \lesssim \theta \lesssim 53^\circ$), appropriate for the known orientation of NGC 1275. In [14, 15], we have shown that for magnetic field values of $B_y \geq 1$ nG and for an energy density of $u_{ext} \geq 10^{-3}$ erg cm$^{-3}$, there is no pronounced break in the cascade spectrum and the cascade is independent of the magnetic field. In general, we expect no break in the cascade Compton emission if $E_{IC, br} \gtrsim \frac{m_e c^2}{\theta}$ (where $E_{IC, br}$ would be the expected spectral break where the Compton cooling length of the radiating electrons is equal to their Larmor radius), which leads to the condition:

$$B_y \gtrsim \frac{(m_e c^2)^2 4\sigma_T u_{ext} \theta}{3e(E_s)^2} \sim 5 u_{ext,-3} E_{s,1}^{-2} \theta \text{ nG} \quad (1)$$

Figure 3 shows that while the high energy emission due to deflection of the cascade up to the $\gamma\gamma$ absorption trough remains virtually unchanged for different magnetic fields, the synchrotron emission from the cascade changes. Therefore, determining the B-field requires knowledge of the synchrotron emission.

**V. THE BIG BLUE BUMP**

3C 279 was among the first blazars discovered as a $\gamma$-ray source with the Compton Gamma-Ray Observatory [9]. In 2007 it was detected as a VHE $\gamma$-ray source with the MAGIC I telescope, making it the most distant known VHE $\gamma$-ray source at a redshift of 0.536 [10]. Its relativistic jet is oriented at a small angle to the line of the sight of $< 0.5^\circ$ [14]. It is also detected by Fermi [1] with photon spectral index 2.23. There is evidence of a spectral break of around a few GeV to a photon spectral index of 2.50. It is strongly believed that the radio to optical emission is due to synchrotron radiation by relativistic particles in the jet. However, the origin of the high energy emission is still not well understood [see, e.g., 3].

[13] monitored 3C 279 in the ultraviolet, using IUE, and combined their data with higher-energy observations from ROSAT and EGRET from 1992 December to 1993 January. During this period, the source was in a very low state, allowing for the detection of a UV excess (the BBB), which is typically hidden below a dominant power-law continuum attributed to non-thermal emission from the jet. [13] proposed that the $\gamma$-ray emission in the SED of 3C 279 is produced by the external Compton mechanism, and suggested that the observed UV excess might be due to thermal emission from an accretion disk.

Here we propose an alternative model to explain the BBB in blazars. Figures 1 – 3 illustrate that the synchrotron emission from VHE $\gamma$-ray induced pair cascades may peak in the UV/X-ray range, thus mimicking a BBB for sufficiently strong magnetic fields ($B \gtrsim 1$ mG). Figure 4 illustrates a possible BBB in 3C 279 produced by synchrotron emission from cascades, added to a phenomenological power-law IR – optical continuum attributed to jet synchrotron emission.

We suggest that synchrotron emission from VHE $\gamma$-ray induced pair cascades can be an alternative explanation of the BBB in the SEDs of several blazars such as 3C 279. An observational test of this hypothesis may be provided through spectropolarimetry. A BBB due to (unpolarized) thermal emission from an accretion disk will produce a decreasing percentage of polarization with increasing frequency throughout the optical/UV range. In contrast, if the BBB is produced as synchrotron emission from cascade pairs in globally ordered magnetic fields, it is also expected to be polarized. Therefore, we predict that a BBB due
FIG. 3: Synchrotron and Compton emission form the cascades for NGC 1275 (0.6 ≤ μ ≤ 0.8). Parameters: θ_B = 11°; u_ext = 5 × 10^{-2} erg cm^{-3}, R_ext = 10^{16} cm, E_s = E_L{α}, α = 2.5, E_γ,max = 5 TeV.

to cascade synchrotron emission would result in a degree of polarization showing only a weak dependence on frequency over the optical/UV range.

VI. SUMMARY

We investigated the magnetic-field dependence and synchrotron emission signatures of Compton-supported pair cascades initiated by the interaction of nuclear VHE γ-rays with arbitrary external radiation fields in the near-nuclear radiation environments of AGN.

We demonstrated that when interpreting the ∼ GeV γ-ray flux from radio galaxies (i.e., misaligned blazars) as cascade Compton emission from VHE γ-ray induced pair cascades, the magnetic field can not be well constrained by considering the high-energy (Compton) output from the cascade emission alone, without observational signatures from their synchrotron emission.

We have shown that synchrotron emission from VHE γ-ray induced pair cascades may produce UV/X-ray signatures resembling the BBB observed in the SEDs of several blazars, in particular in their low states, and demonstrated this with the example of 3C 279. We point out that spectropolarimetry may serve as a possible observational test to distinguish a thermal from a non-thermal (cascade) origin of the BBB.

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