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Time-Dependence of VHE γ-ray induced Pair Cascades in AGN Environments

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Recently, several intermediate frequency peaked BL Lac objects (IBL), low frequency peaked BL Lac objects (LBL) and flat spectrum radio quasars (FSRQ) were detected as very high energy (VHE, $E > 100 \sim$ GeV) γ-ray sources. These discoveries suggest that $\gamma\gamma$ absorption and pair cascades might occur in those objects, leading to excess γ-ray emission which may be observable also in off-axis viewing directions (i.e., like in radio galaxies) when deflected by moderately strong magnetic fields. Here, we investigate the time dependence of the Compton γ-ray emission from such VHE γ-ray induced pair cascades. We show that the cascade emission is variable on time scales much shorter than the light-crossing time across the characteristic extent of the external radiation field, depending on the viewing angle and γ-ray energy. Thus, we find that the cascade Compton interpretation for the *Fermi* γ-ray emission from radio galaxies is still consistent with the day-scale variability detected in the *Fermi* γ-ray emission of radio galaxies, such as NGC 1275, which we use as a specific example.

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1. Introduction

Among AGNs, blazars are the most luminous emitters of high-energy (HE: $E > 100$ MeV) and very high energy (VHE: $E > 100$ GeV) γ-rays in the universe. Their broadband spectral energy distribution (SED) is strongly dominated by non-thermal emission from a relativistic jet oriented at a small angle with respect to the line of sight toward the Earth, resulting in strong Doppler enhancement and relativistic aberration (beaming) along the jet direction. These effects also lead to a shortening of the observed variability time scales, in some extreme cases down to just a few minutes [2, 1]. According to the unification scheme [16], radio galaxies are the mis-aligned parent population of blazars. In the case of a large viewing angle towards the jet, the direct jet emission is expected to be unbeamed, or even de-beamed (i.e., Doppler factor $\delta \equiv (\Gamma[1-\beta_\Gamma \cos\theta])^{-1} < 1$, where Γ is the bulk Lorentz factor of the dominant emission region in the jet, β_Γ the corresponding velocity, normalized to the speed of light, and θ is the viewing angle in the AGN rest frame), and the observed variability time scales should be much longer than in the case of blazars. However, rapid (day-scale) VHE γ-ray variability has been observed in the head-tail radio galaxy IC 310 [3], which suggested that this object may, in fact, contain a blazar-like jet orientation in its core region, misaligned with the radio jet structure seen on larger scales. Also the radio galaxy NGC 1275 has exhibited HE γ-ray variability on daily time scales revealed by the *Fermi*-LAT [6].

The VHE γ-ray emission in AGN pruduced in the high radiation density environment of the broad line region (BLR) and/or the dust torus of an AGN is expected to be attenuated by $\gamma\gamma$ pair production [9, 5, 10, 8, 14]. This absorption will lead to pair cascades in the circumnuclear environment [4, 15, 11, 12, 13] supported by Compton up-scattering.

In [11, 12, 13], the full 3-dimensional development of Compton-supported VHE γ-ray induced pair cascades in the external radiation fields in AGN environments was considered and the emanating broadband (synchrotron and Compton) emission as a function of observing angle for various sources of external radiation fields and magnetic-field configurations was studied. However, time variability of the primary VHE γ-ray emission and the resulting cascade emission, was not considered in those works. Specifically, in [11] we suggested an interpretation of the *Fermi*-LAT spectrum of NGC 1275 as the Compton emission from VHE γ-ray induced pair cascades in the Lyα-dominated radiation environment of the nuclear AGN of this radio galaxy. At the time of writing of that paper, no short-term variability of the γ-ray emission of this object was known. However, prompted by the detection of day-scale γ-ray variability by *Fermi*-LAT [6], we now re-investigate this scenario to verify whether the cascading on the spatial scale of $R_{\rm ext} \sim 10^{16}$ cm as adopted in [11] and motivated by the observed properties of the central AGN in this system, is capable of producing HE γ-ray variability on the observed time scale.

In this paper, a generalization of the Monte-Carlo code developed in [11, 12, 13] is considered to investigate the time dependence of the cascade emission. The general model setup, assumptions and the description of the modified Monte-Carlo code are outlined in section 2. In section 3, we present the numerical results for generic parameters. A summary of the results is given in section 4.

2. Description and Model Setup of the Monte-Carlo Code

In this work, the general model setup is identical to the previous model described in [11, 12, 13]. The primary VHE γ-ray emission is propagating along the x-axis, which is the direction of the jet axis, as a mono-directional beam, and interacts with an isotropic radiation field of energy density $u_{\rm ext}$ with an arbitrary spectrum within a fixed boundary, given by a radius $R_{\rm ext}$, via $\gamma\gamma$ absorption and pair production. The trajectories of all particles and photons are followed in full 3-dimensional geometry. Compton and synchrotron energy losses to the electrons/positrons are properly accounted for. In our simulations, the magnetic field is considered homogeneous and oriented at an angle θ_B with respect to the jet axis. This may be considered a proper proxy for a helical magnetic field with the ratio of toroidal ($B_{\rm tor}$) and poloidal (B_x) magnetic fields given by $\tan\theta_B = B_{\rm tor}/B_x$.

In order to evaluate the smearing/broadening of variability features due to the cascade process, we assume that all primary γ-ray photons are emitted instantaneously at time $t = 0$ at the origin of our coordinate system. The resulting cascade radiation output can thus be considered as a Green's function, to be convolved with a realistic primary γ-ray light curve. Each photon is labelled with a time tag which traces the photon and electron/positron travel time since the emission of the primary γ-ray photon. In addition to the photon energy and directional information of each escaping photon at the time of leaving the simulation volume [11, 12, 13], now also the corresponding time tag is written into a photon event file. To extract time- and angle-dependent photon spectra as well as photon-energy- and angle-dependent light curves from the photon event files, a separate post-processing routine is used.

3. Simulation Results

The cascade Monte-Carlo code described in the previous section is used to investigate the time-dependent Compton spectra from VHE γ-ray induced pair cascades for a variety of generic parameter choices.

As a baseline model, we choose parameters as used in [11] to produce a fit to the *Fermi*-LAT spectrum of the radio galaxy NGC 1275. The magnetic field strength has been set to $B \approx 1$ mG, oriented at an angle $\theta_B = 5.7^o$ with respect to the x-axis ($B_x = 1$ mG, $B_y = 0.1$ mG), and we considered a viewing angle θ (with $\mu = \cos\theta$) with respect to the jet of $0.4 \le \mu \le 0.6$ (i.e., $53.1^o \le \theta \le 66.4^o$), typical for radio-loud AGN seen as radio galaxies. The parameters determining the external radiation field were motivated by direct observations of the nuclear region of NGC 1275 (see [11] for details). In particular, the BLR spectrum has been approximated by a monoenergetic line at the Lyα energy, with $u_{\rm BLR} = 5 \times 10^{-2}$ erg cm^{-3} and $R_{\rm ext} = 10^{16}$ cm. The energy and time binnings in the extraction of spectra and light curves were chosen arbitrarily as a compromise between energy and time resolution and sufficient photon statistics. Figure 1 shows the Compton spectra produced by the cascade particles from this baseline model at several different times. The beginning of the first time bin shown in Figure 1 corresponds to the direct light travel time of the primary γ-ray beam through the simulation volume, prior to which, obviously, the output is zero. The figure reveals the expected general trend of the cascade Compton spectra becoming softer as time passes, due to the continuing radiative cooling of pairs in the cascade.

Figure 2 shows the light curves of the cascade emission in various γ-ray energy ranges for the same model parameters as used in Figure 1. In accordance with the trend seen in Figure 1, the overall duration of the cascade Compton emission decreases with increasing photon energy. The

PoS(HEASA2015)018

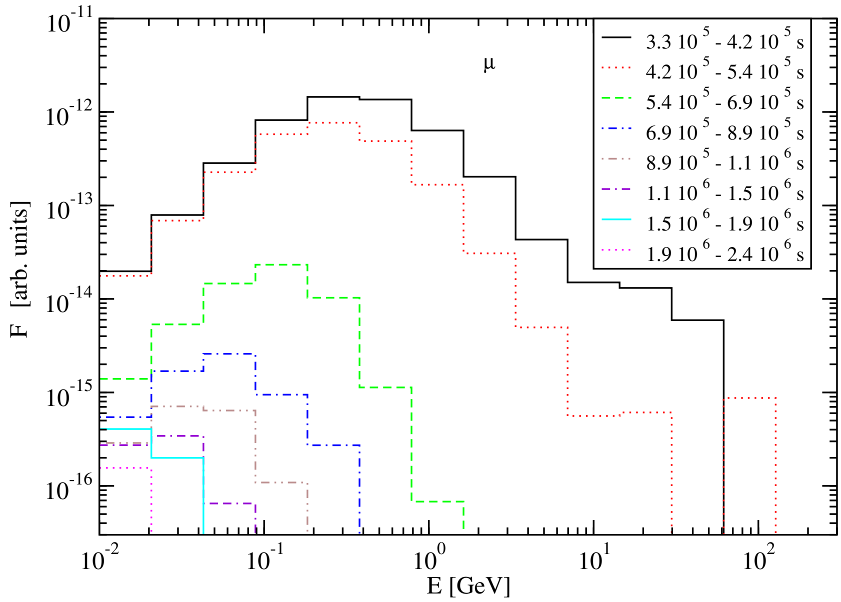

Figure 1: Cascade Compton spectra at various times after the first primary γ-ray photons have propagated through the simulation volume. The magnetic field strength is $B \approx 1$ mG, oriented at an angle $\theta_B = 5.7^o$ with respect to the x-axis ($B_x = 1$ mG, $B_y = 0.1$ mG). The parameters of the external radiation field are the same as used in [11] to produce a fit to the *Fermi*-LAT γ-ray spectrum of the radio galaxy NGC 1275, i.e., a Lyα dominated radiation field with a characteristic radial extent of $R_{\rm ext} = 10^{16}$ cm and an energy density of $u_{\rm ext} = 5 \times 10^{-2}$ erg cm^{-3}. Note that the highest-energy bins ($E \gtrsim 10$ GeV) are very sparsely populated and features like the empty bin in the 4.2×10^5 s - 5.4×10^5 s spectrum are due to limited photon statistics.

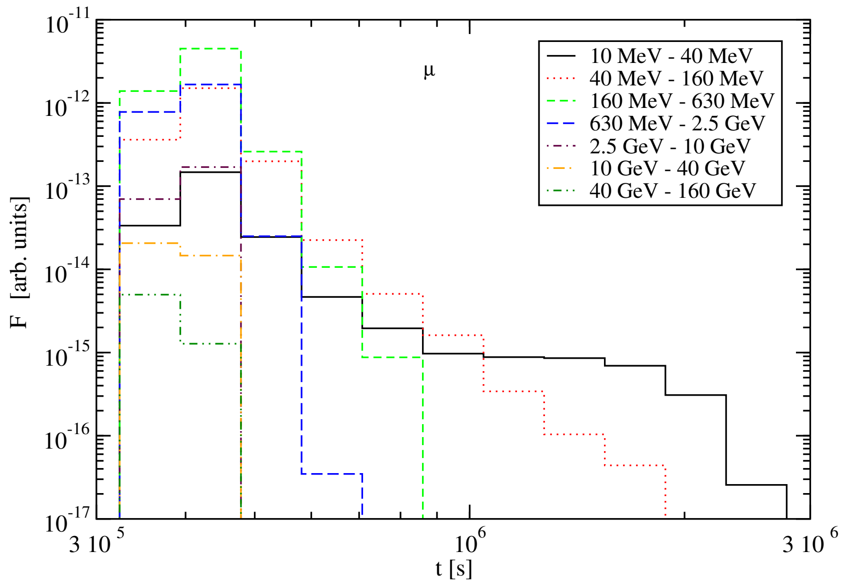

Figure 2: Light curves of the cascade Compton emission in various γ-ray energy bands, for the same simulation as illustrated in Figure 1.

corresponding decreased amplitude of variability at lower energy reflects the longer cooling time scales for particles emitting at lower energies. For a further in-depth analysis of the trends seen in our simulations, we measure the width of the light curve pulse from the Compton emission in the various light curves, defined as the time for which a smooth (piecewise power-law) interpolation of a simulated light curve remains above 10 % of its peak value. The width measured in this way reflects the minimum time scale of variability that may be expected if the γ-ray emission from radio galaxies is indeed produced by VHE γ-ray induced pair cascades. As is obvious from Figure 2, the light curve width is a decreasing function of photon energy.

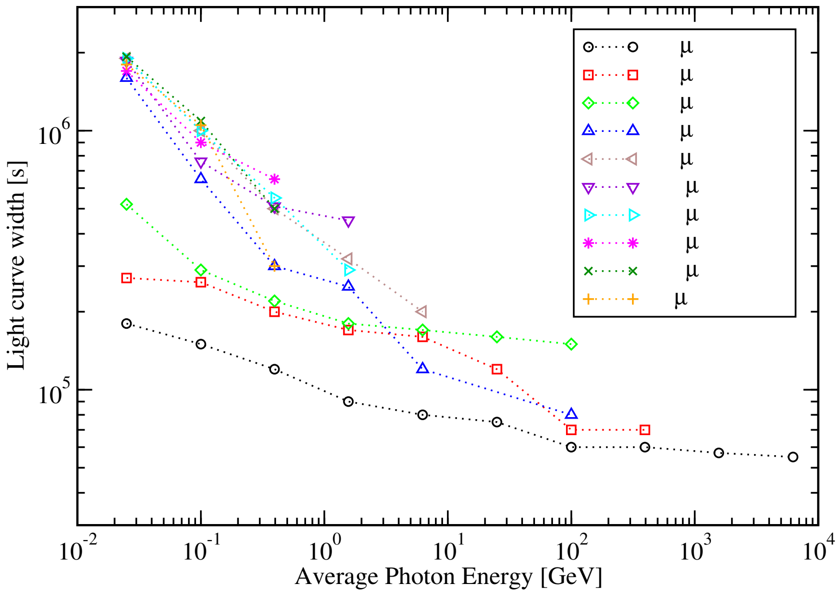

Figure 3: Light curve width of the cascade emission as a function of photon energy (at the arithmetic average energy of each energy bin) at different viewing angles ($\mu = \cos\theta_{\rm obs}$). Parameters of the target photon field are the same as for Figure 1.

Figure 3 illustrates the energy dependence of the light curve width for various viewing angles, for the same simulation as illustrated in Figures 1 and 2. It confirms the trend seen in Figure 2 that the width of the γ-ray pulse decreases with increasing photon energy. It also shows that the light-curve width increases with increasing viewing angle for any given photon energy bin. This is explained by the fact that at larger viewing angles, we observe the emission from cascade particles that have been deflected more strongly, which occurs preferentially for lower-energy particles. In particular, we note that for HE γ-rays, the cascade Compton emission can be variable on time scales much shorter than the light travel time through the extent of the external radiation field ($R_{\rm ext}/c \sim 3 \times 10^5$ s). The figure suggests that, for the parameters adopted in [11], variability on daily time scales ($\sim 10^5$ s) at photon energies $E \sim 1$ GeV can be expected only for viewing angles of $\mu \gtrsim 0.4$ (i.e., $\theta \lesssim 66^o$). This is in agreement with the estimates for NGC 1275, in the range of $30 - 55^o$ [17].

Naturally, one would expect the minimum variability time scale in the cascading scenario to

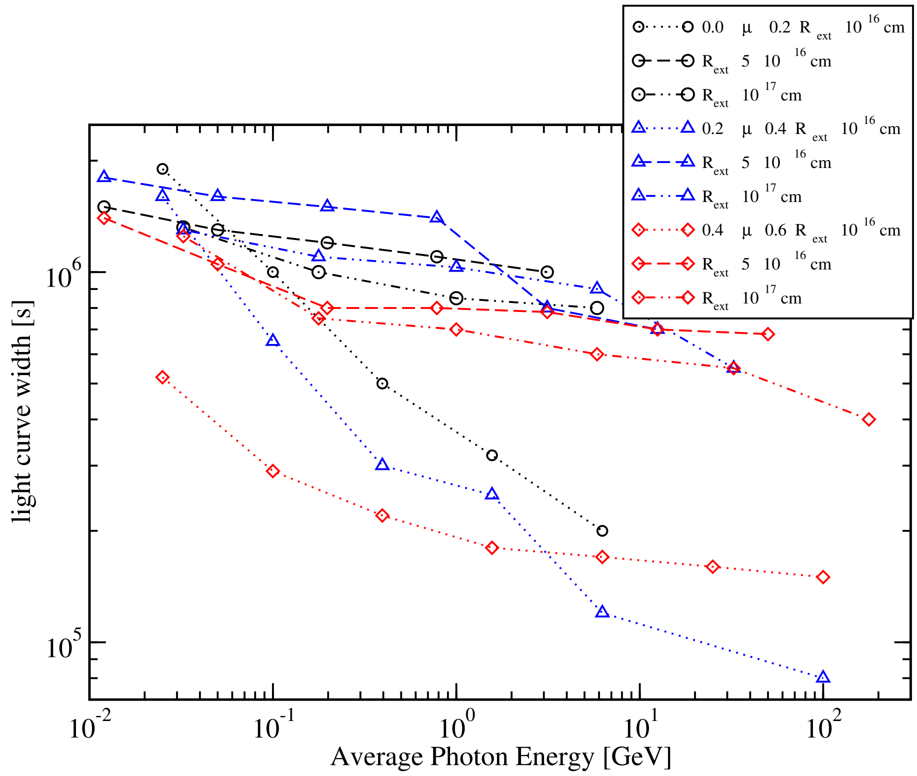

Figure 4: The effect of the extent of the external radiation field on the expected minimum variability time scale of the cascade Compton emission. Other parameters (except $R_{\rm ext}$) are held fixed at the values used for figures 1 – 3.

scale linearly with the extent of the external radiation field, $R_{\rm ext}$. In order to test this hypothesis, we carried out several simulations with parameters unchanged from the simulation illustrated in Figures 1 – 3, except for increasing $R_{\rm ext}$ up to 10^{17} cm. Figure 4 shows the resulting light-curve widths as a function of energy for a few selected viewing angle bins. As expected, the widths generally increase with increasing $R_{\rm ext}$. However, the widths — especially in the HE γ-ray regime — remain significantly smaller than the light-crossing time scale $R_{\rm ext}/c$.

4. Summary

We investigated the time dependence of the γ-ray emission from Compton-supported pair cascades initiated by the interaction of VHE γ-rays from the central regions of AGN with circumnuclear external radiation fields. We focused on a parameter regime used in [11] to model the *Fermi*-LAT γ-ray emission from the radio galaxy NGC 1275. We evaluated minimum variability time scales from a cascading scenario assuming the instantaneous injection of VHE γ-rays from the central engine at time $t = 0$. Our results show that the cascade Compton emission in the HE γ-ray regime can be variable on time scales significantly shorter than the light crossing time through the characteristic extent of the external radiation field, $R_{\rm ext}/c$ (i.e., 3×10^5 s in this scenario). The minimum variability time scales systematically decreases with increasing photon energy, but increases with increasing viewing angle. For the model setup used for the spectral fit to NGC 1275 by [11], we have verified that variability on time scales of ~ 1 day, as observed by *Fermi*-LAT [6], is consistent with the cascading scenario.

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