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Time dependent production of gamma-rays in the inverse Compton e^+e^- pair cascades in AGNs.

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We investigate the most general version of the external Compton model for the gamma-ray production by considering 3-dimensional, inverse Compton e^+e^- pair cascades initiated by leptons which interact with the thermal radiation from an accretion disk. The spectral properties and the time evolution of the GeV-TeV gamma-ray emission produced in such cascade for different locations of the observer in respect to the direction of the jet are studied in detail. We compare the results of calculations with the GeV-TeV observations of AGNs viewed at small and large inclination angles, taking as an example the parameters of the two famous sources Cen A and 3C 279.

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1. Introduction

TeV observations of active galaxies in the TeV gamma-rays show extremely variable nature of this emission on various time scales from a few minutes (e.g. [7, 5]) up to months/years [17]. While the precise location of the emission site within the active nuclei still remains unclear, theoretical arguments based on the absorption suggest that it should be rather distant from the black hole. On the other hand, the strong radiation field can create a target on which gamma-rays could be produced. Moreover recent observations of the nearby active galaxy, M87, whose jet is observed at a relatively large angle, suggest that the TeV gamma-ray emission region can likely appear within a few tens of Schwarzschild radius from the black hole [4, 2, 8]. It is likely that the emission region is close to the accretion disk inside the inner jet as suggested by the recently discovered connection between the TeV γ-ray flare and the subsequent appearance of the radio blobs [3]. Also Cen A, another nearby active galaxy inclined at large angle, has been recently detected as a TeV γ-ray source [6]. This emission is as well interpreted as originated very close to the central black hole [20].

It is widely believed that gamma-rays are produced in active galaxies by particles accelerated in the jet propagating perpendicularly to the plane of the accretion disk. Many simple radiation mechanisms are possible, i.e. synchrotron self-Compton (SSC) [e.g. 19], external Compton (EC) [e.g. 10, 23], Also hadronic models have been discussed, e.g. proton initiated cascade (PIC) model [18]. For typical parameters of blazars detected in GeV-TeV gamma-ray energies, the optical depths for gamma-rays produced relatively close to the disk can be clearly above unity (see e.g. recent calculations for 3C 279 and 3C 273, [24], or for Cen A, [25]). Therefore, the cascade processes can be important in these sources. Those more realistic models involving 3D cascade occurring in the strong radiation of the accretion disk are starting to be considered only recently [25, 26, 21]. In this proceedings we investigate the production of gamma-rays in terms of the EC accretion disk model [26]. In the framework of this model we calculate the spectral, angular and also time properties of the gamma-ray emission.

2. Model for gamma-ray production

We assume that the thermal radiation of the accretion disk create the only target for relativistic primary electrons, injected in a point-like blob. We adopt a classical optically thick and geometrically thin accretion disk model around a supermassive black hole [22]. The blob is moving along the jet with a constant velocity v. Primary electrons injected with specific spectrum are isotropic in the blob frame. They interact with the anisotropic radiation of the disk in the inverse Compton (IC) scattering process producing first generation of high energy gamma-rays. These gamma-rays can propagate, in principle, at an arbitrary angle to the disk axis. If the acceleration of electrons occurs relatively close to the accretion disk, then these gamma-rays can be absorbed in the e^+e^- pair production process [24, 25, 26]. The secondary e^+e^- pairs can scatter the disk radiation producing further generation of cascade gamma-rays in the whole volume above the disk. Therefore, our present calculations follow significantly more complicated and complete model than offered by the previously considered scenario with the isotropic injection of primary gamma-rays produced in the blob in SSC model [25].

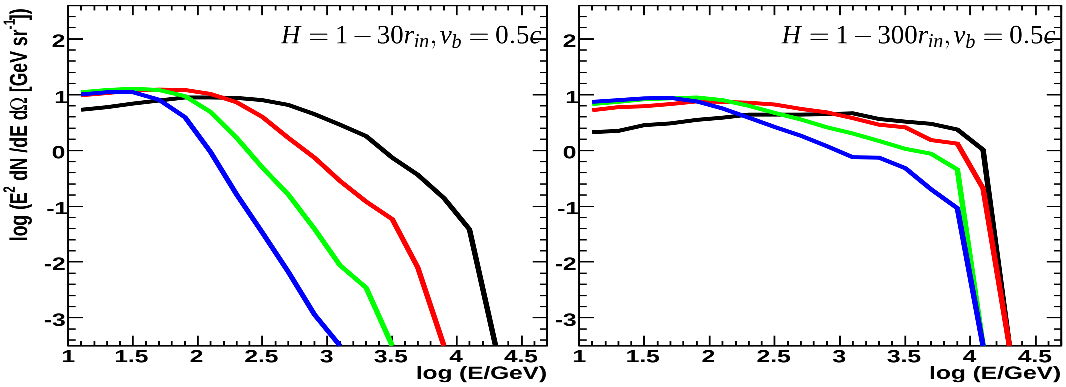

Figure 1: Gamma-ray spectra from the IC e^+e^- pair cascade initiated by electrons injected with differential spectral index -2 between 10 GeV and 10 TeV (in the blob frame). Electrons are injected isotropically in the blob moving along the jet with the velocity: 0.5c in the height range 1-30r_{in} (left panels) and 1-300r_{in} (right). The gamma-ray spectra are shown within the range of observation angles: $\alpha < 40°$ (black), $40° < \alpha < 60°$ (red), $60° < \alpha < 75°$ (green), $75° < \alpha < 90°$ (blue).

3. Blazars visible at large observation angle: the case of Cen A

We apply the parameters expected for the misaligned blazar Cen A, as an example of an AGN seen at large inclination angle. The spectral index of the gamma-ray spectrum of Cen A observed at TeV energies by H.E.S.S (-2.7, see [6]) is comparable to that one observed at GeV energies by EGRET (-2.58, [13]) and *Fermi*-LAT (-2.71, [1]). A clear jet is observed in this radio galaxy. However it's inclination to the line of sight is poorly known ($\alpha = 15° - 80°$, [16]). We apply the inner disk temperature equal to $T_{in} = 3 \times 10^4$ K, and the inner disk radius, $r_{in} = 2.5 \times 10^{13}$ cm. The velocity of the emission region in the jet of Cen A is estimated on 0.5c [28].

We investigate the gamma-ray spectra expected at different observation angles assuming that primary electrons are injected into the blob when it moves through a range of distances above the accretion disk (see Fig. 1). The shape of the gamma-ray spectra strongly depends on the range of injection distances of electrons. The gamma-ray spectra are flatter and extend to higher energies for the injection of primary electrons farther from the accretion disk. The GeV gamma-ray fluxes produced at large inclination angles dominate for slow jets. However, for large inclination angles the gamma-ray spectra at TeV energies become steeper. They also have a cut-off at lower energies. Slower jets produce lower gamma-ray fluxes with steeper spectra at TeV energies due to a weaker relativistic beaming and a more significant Klein-Nishina effect. We conclude that the location of the break in the gamma-ray spectrum and its spectral index above $\sim$100 GeV is clearly related to the inclination angle of the jet towards the observer.

We compare calculated cascade gamma-ray spectra with the observations of Cen A (see Fig. 2). Reasonable agreement with the spectral shapes observed by the EGRET detector and the H.E.S.S. telescopes is obtained for low observation angles ($\alpha < 40°$) and the electron spectral index equal to -3. The gamma-ray spectra expected in our model for the larger inclination angles of the accretion disk-jet system are too steep to be able to explain these measurements.

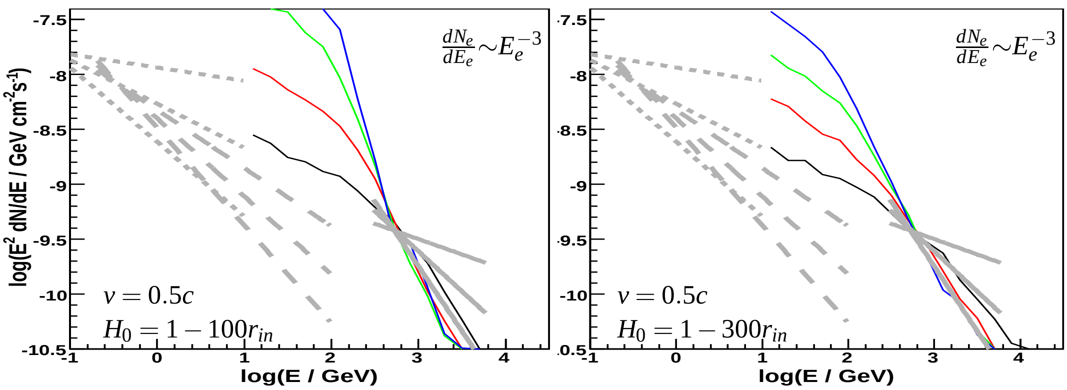

Figure 2: Comparison of the cascade gamma-ray spectra (thin curves) with various observations of Cen A. The IC $e^{\pm}$ pair cascade is initiated by electrons injected with a power law with an index -2.5 (left panels) and -3 (right) inside a blob propagating with a velocity: $0.5c$. The injection process of electrons occurs in the range of heights above the disk $1-100\,r_{in}$ (top panels), and $1-300\,r_{in}$ (bottom). The gamma-ray spectra are shown for a range of inclination angles: $\alpha < 40^\circ$ (black), $40^\circ < \alpha < 60^\circ$ (red), $60^\circ < \alpha < 75^\circ$ (green), $75^\circ < \alpha < 90^\circ$ (blue). Grey curves (with error bow-ties) show the observations of Cen A: EGRET [dotted, 27], *Fermi*-LAT [dashed, 1], and H.E.S.S. [solid, 6] The cascade spectra are normalized to the total energy output in the 0.5 – 5 TeV range as measured by the H.E.S.S. telescopes.

4. Blazars visible at small observation angle, the case of 3C 279

3C 279 is a rather distant source (redshift z = 0.538). It has been detected by the EGRET telescope in all observation periods (see e.g. [15]), and also recently by the *Fermi*-LAT instrument [1], showing a variety of the flux and spectral index stages. More recent observations performed in December 2008 with the *Fermi*-LAT telescope show a flare with constantly rising flux during ~ 15 days followed by a slower decay lasting for $\sim$30 days (the LAT monitored source list, Atel #1864). A similar, long flare has been observed by *Fermi*-LAT in July/August 2009 (the LAT monitored source list, Atel #2154). 3C 279 has been also detected by the MAGIC telescope [9]. Due to a severe absorption in the extragalactic background light (EBL) radiation, the observed spectrum in the sub-TeV range is very soft, with the spectral index of -4.11 ± 0.68. For this source, we apply the temperature $T_{in} = 2 \times 10^4$ K at the inner radius of the accretion disk $r_{in} = 4.2 \times 10^{15}$ cm.

Moreover, due to ultrarelativistic speed of the blob in the jet of 3C 279 the cascade gamma-ray spectra strongly depend on the observation angle. Large redshift of 3C 279, causes strong absorption of the resulting gamma-ray spectra above 200 GeV. Therefore, the shape of the gamma-ray spectra above 100 GeV are quite independent on the blob Lorentz factor and the extend of the injection region within the jet (see Fig. 3). This creates problems for extracting physical parameters of the gamma-ray emission region based on the comparison of the observed and calculated spectra. However still the spectral index at $\sim$100 GeV depends on the injection parameters.

In general the gamma-ray light curves (see Fig. 4) show a plateau, created by fast cooling of electrons, with a strong exponential decay. It can be followed by a long tail of slowly decaying emission due to escaping, partially cooled electrons. Depending on the range of injection heights, observation angle and the speed of the jet, the emission can last at a fairly constant level even tens of days. At the beginning of the flare, the TeV and sub-TeV gamma-rays are strongly attenuated.

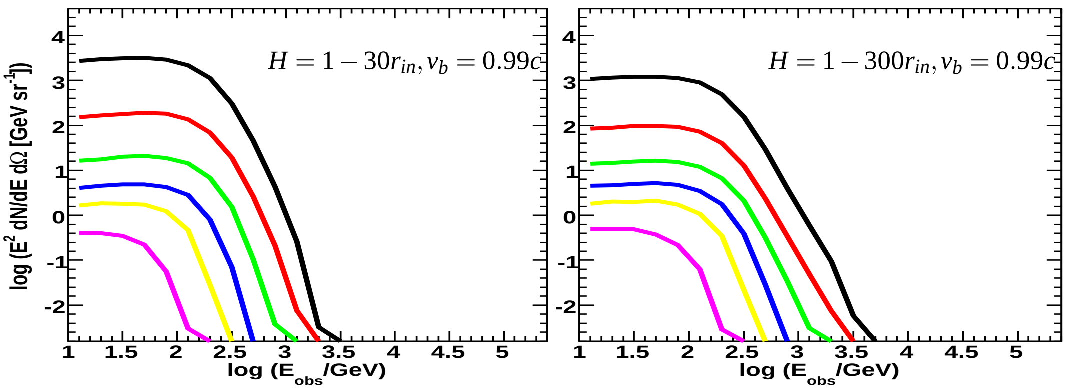

Figure 3: Gamma-ray spectra from the IC e^+e^- pair cascade initiated by electrons injected with the spectral index -2 between 10 GeV and 10 TeV (in the blob's frame). The blob velocity is $v = 0.99c$. The injection of electrons occurs in the range of heights above the disk 1–30 r_{in} (left panels), and 1 – 300 r_{in} (right). The spectra are shown in the bins of the observation angle: $\alpha < 10^\circ$ (black curves), $10^\circ < \alpha < 20^\circ$ (red), $20^\circ < \alpha < 30^\circ$ (green), $30^\circ < \alpha < 40^\circ$ (blue), $40^\circ < \alpha < 50^\circ$ (yellow), and $\alpha > 50^\circ$ (magenta). The propagation in the EBL is calculated according to the model by [12]

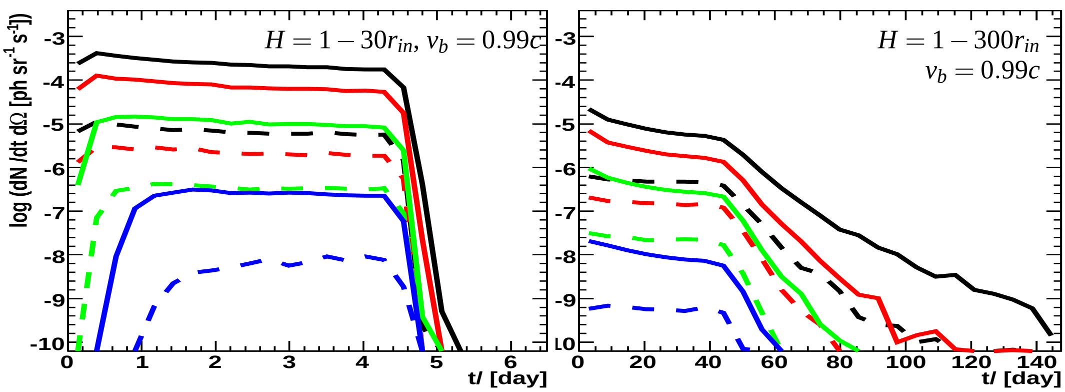

Figure 4: Gamma-ray light curves in the observer's frame from the IC e^+e^- pair cascade calculated for 3C 279 after the propagation through the intergalactic radiation field according to the model by [12]. Gamma-ray fluxes are shown for energies $E > 10$ GeV (black), > 30 GeV (red), > 100 GeV (green), and > 300 GeV(blue).

They are converted into GeV gamma-rays. Therefore, the model predicts a soft to hard evolution in the case of the gamma-ray flares observed from blazars. This effect is even more pronounced for large observation angles.

Using our model, we interpret the two high states of the source seen by the EGRET and the MAGIC telescope, and the mean flux level spectrum seen by the *Fermi*-LAT instrument (see Fig. 5. The spectrum calculated for the beginning of the flare ($t = 0 - 23$ days) and for the range of injection distances from 1 r_{in} to 300 r_{in}, can fit the EGRET and the MAGIC measurements provided that electrons are injected with a power law spectrum and spectral index in the range from -2.5 to -3. For those parameters, the gamma-ray flux is predicted to drop to the mean emission level determined by the Fermi-LAT observations after ∼60–90 days.

We confront the shape of the calculated gamma-ray light curve with the recent large *Fermi*-

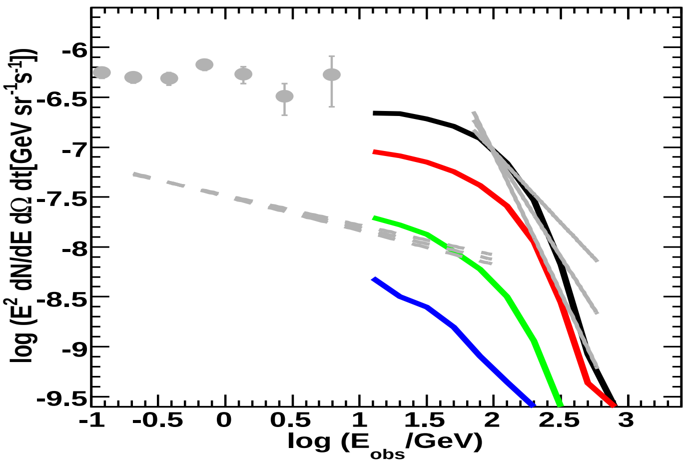

Figure 5: The IC e^+e^- pair cascade gamma-ray spectrum calculated for 3C 279 after absorption in the EBL, compared with the MAGIC observations in flaring state [solid gray line, 9] and the EGRET [points, 14]. The average spectrum observed by the *Fermi*-LAT is shown with dashed line ([1]). The primary electrons are injected in a range of distances from the base of the jet: 1–300 r_{in} with a power law index -3 between 10 GeV and 10 TeV (in the blob's frame of reference). The gamma-ray spectra are shown for the time intervals: t = 0–23 days (black), 23–45 days (red), 45–68 days (green), 68–90 days (blue). The black curve is normalized to the gamma-ray flux observed by the MAGIC telescope. The velocity of the blob is fixed on $v = 0.998c$ ($\gamma = 15.8$).

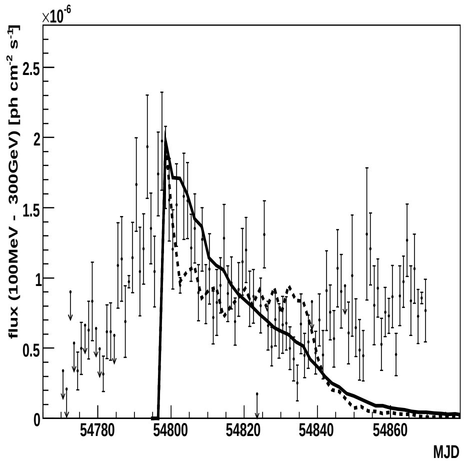

Figure 6: The cascade gamma-ray light curve (> 10 GeV) compared with the shape of the gamma-ray flare observed from 3C 279 by the *Fermi*-LAT instrument at energies > 0.1 GeV (the LAT monitored source list). The primary electrons are injected in the blob, with a power law index -2.5 and a constant rate, moving along the jet with the velocity of 0.998c through a range of distances from the base of the jet, 1–300 r_{in}. The observation angle is assumed to be 9° (solid curve) or 15° (dashed).

LAT flare observed from 3C 279 (see Fig. 6). The dropping part of the observed light curve is consistent with our calculations for the observation angle of 9°. However, the rising part of the calculated light curve is very steep which is due to our simplified assumption on the injection of electrons into a point-like blob at a fixed moment of time. In the case of an extended blob or the injection mechanism operating at the base of the jet for a specific period of time with rising efficiency, the finite rise time of the gamma-ray flare from 3C 279 should be naturally explained in terms of our model.

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