Gamma-rays from the IC $e^{\pm}$ pair cascade initiated by primary gamma-rays in the radiation field of the accretion disk

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***Abstract*. Very short time scale variability of TeV gamma-ray emission from BL Lacs suggests that the acceleration process of electrons likely occurs relatively close to the accretion disk. We calculate the gamma-ray spectra produced in the Inverse Compton $e^{\pm}$ pair cascade initiated by relativistic electrons close to the surface of the accretion disk. Possible synchrotron energy losses of secondary $e^{\pm}$ pairs are also taken into account. The photon spectra, emerging at different directions in respect to the disk axis, are investigated for different basic parameters describing such a model. We apply the model to the misaligned blazar Cen A which has been recently detected in the TeV γ-rays.**

***Keywords*: Gamma rays - Galaxies**

I. INTRODUCTION

Up to now the GeV-TeV γ-ray emission has been observed from a few tens of active galactic nuclei. It is widely believed that this radiation is emitted by particles accelerated in the jet launched from the inner part of the accretion disk around super massive black hole. Short scale variability of this γ-ray emission (see e.g. recent results in the case of Mrk 501 and PKS 2155-304 [2], [3]) strongly suggest that the radiation is produced in the inner jet close to the accretion disk. The primary γ-rays, produced close to the disk surface, can be severely absorbed in the disk radiation developing IC $e^{\pm}$ pair cascade in the whole volume above the accretion disk. Therefore, the role of the radiation field of the accretion disk (and/or the radiation surrounding the inner part of the accretion disk) in the process of γ-ray production and propagation can be essential (see e.g. the recent calculations of the effects of γ-ray absorption in the case of two famous sources 3C 273 and 3C 279 [1]).

In this paper we analyze in detail the cascade initiated by primary TeV γ-rays injected from the compact region within the jet in the radiation field of the accretion disk. Such cascade can develop in the whole volume above the disk where the radiation field is strongly anisotropic. We calculate the cascade γ-ray spectra emerging at different directions in respect to the disk axis. The possible role of the magnetic field above the accretion disk is also investigated. As an example, we consider the nearby active galaxy, Cen A, which have been detected in GeV and TeV γ-rays [4], [5], and shows a jet aligned at a relatively large angle to the observer. Note that similar processes can be also characteristic for the γ-ray production in the accretion disks around solar mass black holes within our Galaxy (so called microquasars).

II. ESCAPE OF GAMMA-RAYS FROM THE DISK RADIATION FIELD

We adopt the optically thick and geometrically thin accretion disk model around super massive black hole as a dominant source of radiation in the central region of active galactic nuclei (see Shakura & Sunyaev disk model [8]). The emission of the accretion disk is treated as a black body with a power law temperature dependence on the distance, r, from the black hole, $T = T_{\rm in}(r/r_{in})^{-3/4}$, where $T_{\rm in}$ is the temperature at the inner disk radius $r_{\rm in}$.

As an example, we consider the misaligned blazar Cen A which has been recently detected in TeV γ-rays [5]. It is supposed that the central engine of Cen A harbors a super massive black hole with the mass estimated on $M_{\rm Cen\,A} = (5.5 \pm 3.0) \times 10^7 M_\odot$ [6]. A clear jet is observed in this radio galaxy. It is propagating at the angle towards the observer estimated on $15° - 80°$ [7]. We apply the inner disk temperature equal to $T_{\rm in} = 3 \times 10^4$ K which is of the order of that one observed directly in other AGNs (e.g. 3C 273). The disk luminosity with these parameters does not overcome the total optical emission from the core of Cen A.

We calculate the optical depth for γ-rays in the radiation field of the accretion disk according to the standard prescription:

$$\tau = \int_\ell dl \int d\epsilon d\Omega n(l, \epsilon, \Omega)\sigma_{\gamma\gamma}(\epsilon, \theta)(1 - \cos\theta), \quad (1)$$

where $n(l, \epsilon, \Omega)$ is the differential number density of soft photons with energy ϵ which arrive inside the solid angle Ω to instantaneous location of the γ-ray photon at the propagation distance l, $\sigma_{\gamma\gamma}$ is the pair production cross section, and θ is the angle between the momentum vectors of the gamma-ray and soft photon. ℓ denotes the path along propagation direction of the gamma-ray photon in the soft radiation field. Note that in the most general situation of the γ-ray photon injected at an arbitrary place above the accretion disk and at an arbitrary direction, the calculations are not straightforward since considered radiation field is highly anisotropic [9], [10].

We investigate the optical depths for γ-rays as a function of their energies, injection place and injection

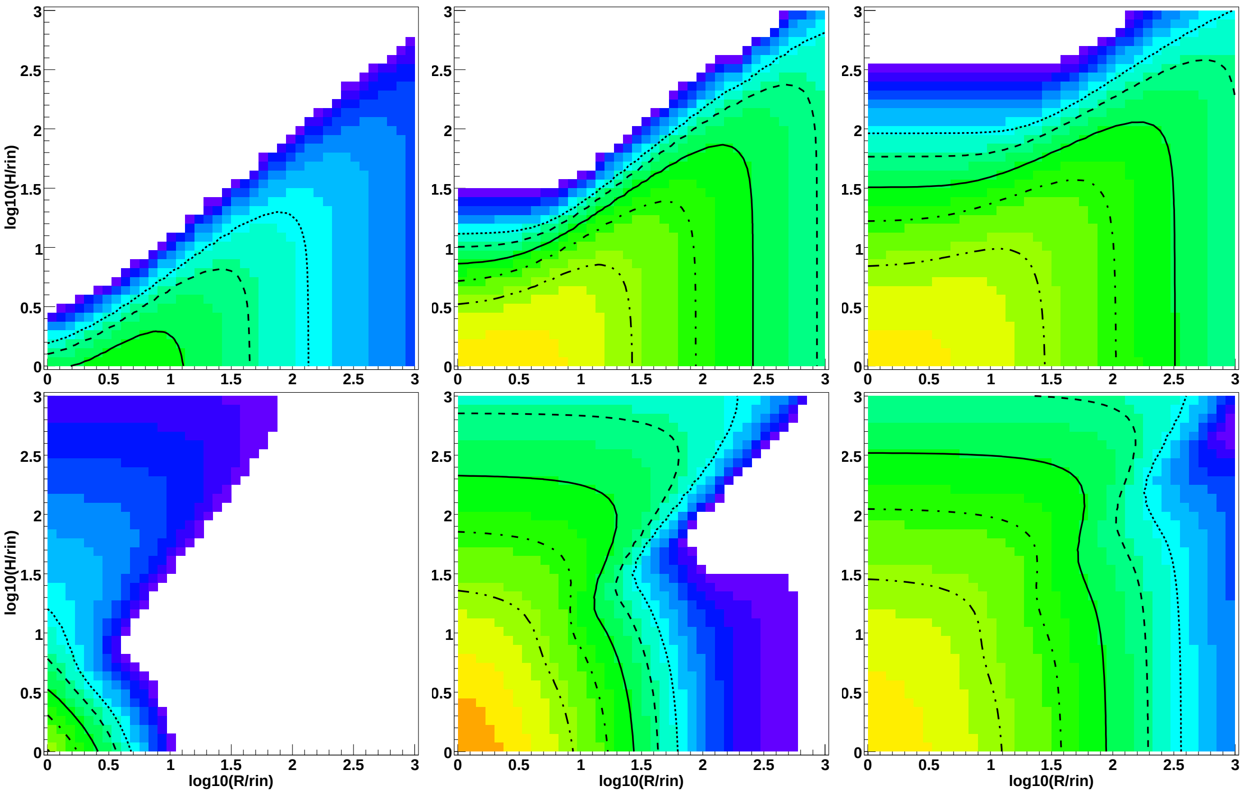

Fig. 1. Three-dimensional γ-spheres around the accretion disk in Cen A with the parameters mentioned in the text. The γ-rays are injected at the angle to the jet axis equal to $\alpha = 0°$ (upper panel) and $60°$ (bottom panel). The energies of γ-rays are equal to $E_\gamma = 0.1$ TeV (left figure), 1 TeV (middle), and 10 TeV (right) Different curve styles represent lines of constant optical depth: $\tau = 0.1$ (dotted), 0.3 (dashed), 1 (solid), 3 (dot-dashed) and 10 (dot-dot-dashed).

angle for the radiation field defined by the parameters characteristic for Cen A (see above). Based on the above calculations, we determine the three-dimensional surfaces around the central engine of AGN at which the optical depths for γ-rays with specific energies, E_γ, and injection angles, α (measured in respect to the direction perpendicular to the disk surface), are equal to specific value. If this value is fixed on unity, then such surface is called the γ-sphere. The shape of the γ-sphere can be in general quite complicated (see recent calculations for two OVV blazars, 3C 273 and 3C 279, in Sitarek & Bednarek [1]. However, evaluation of such a surface is very practical since γ-rays produced inside the γ-sphere are strongly absorbed, while those ones produced outside the γ-sphere can escape with a negligible absorption.

The γ-spheres calculated for the parameters of the supposed accretion disk around the black hole in Cen A are shown in Fig. 1. Specific figures show the γ-spheres for two values of the injection angle $\alpha = 0°$ and $60°$ and three selected values of γ-ray energies: $E_\gamma = 0.1$, 1, and 10 TeV. These γ-spheres shows very interesting features. For the injection angle of the γ-rays equal to $\alpha = 0°$, the lowest values of the optical depths are along the axis of the accretion disk. It is usually assumed that in this direction the jet is propagating. Thus, γ-rays injected along the jet axis have the highest probability of escape. Such is the case of the TeV γ-ray sources observed from BL Lacs in which case the observation angle is typically low. On the other hand, γ-rays injected at the same distance above the disk but farther from the jet axis suffer strong absorption. These general features are easy to understand if we keep in mind that most of the disk radiation is produced in the inner part of the accretion disk where the temperature is the largest. If γ-ray photon is moving along the jet, the $e^\pm$ pair production process in collisions with the disk radiation is strongly suppressed by an increasing energy threshold and a geometrical factor $1 - \cos\theta$ in the eq. 1. On the other hand if γ-rays are injected far from the jet ($R \gtrsim H$) the hot center of the accretion disk is seen by them at a larger angle θ, which results in a stronger absorption. Note, moreover, the TeV γ-rays injected close to the disk surface meet very large optical depths, preventing their direct escape from the disk radiation.

The optical depths for γ-rays injected at a large angle to the disk axis have different features (see bottom panel in Fig. 1). TeV γ-rays produced in a jet even as far as $\sim 200 r_{in}$ can be efficiently absorbed. The γ-spheres in this case have more complicated shape due to a weaker absorption of γ-rays for the directions fulfilling the condition $R/H \sim \tan 60°$.

III. Cascade γ-ray spectra

We consider the inverse Compton (IC) $e^\pm$ pair cascade initiated by primary γ-rays in the anisotropic radiation

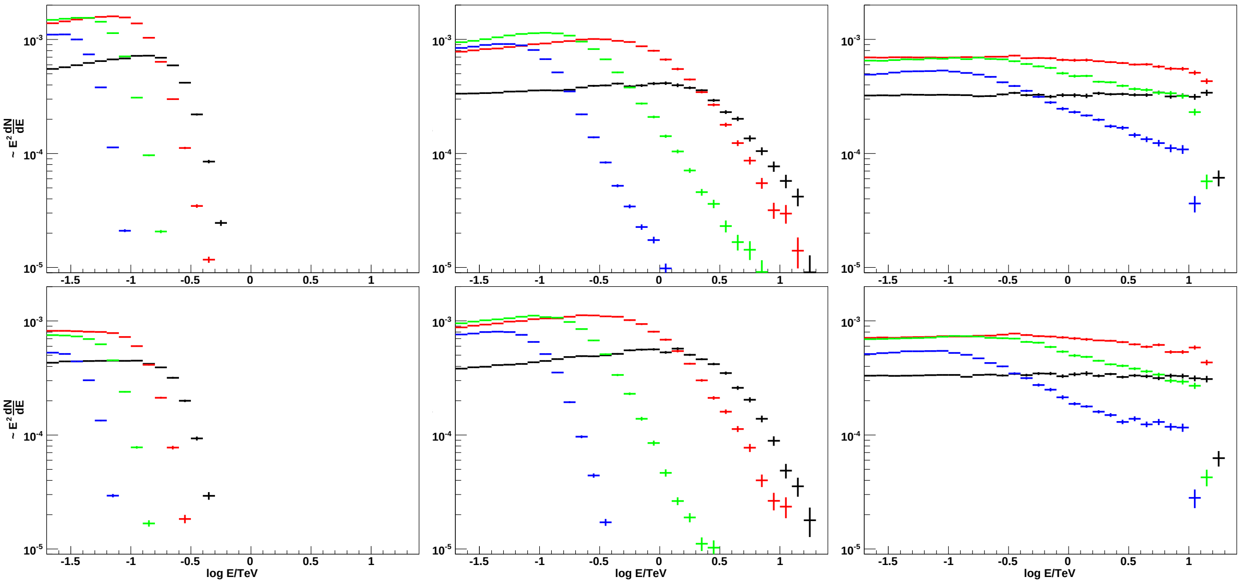

Fig. 2. Gamma-ray spectra produced in the $e^{\pm}$ pair cascade initiated by primary γ-rays injected isotropically from the point source moving along the jet with velocity $\beta = 0.5$ at specific distances from the base of the jet: $H = 3R_{\rm in}$ (left figures) and $30R_{\rm in}$ (middle), and $300R_{\rm in}$ (right). The spectrum of primary γ-rays is of the power law type with the differential spectral index -2. The calculations have been performed without any magnetic field over the accretion disk (upper panel) and with the dipole magnetic field above the accretion disk which is normalized to 300 G at the inner disk radius (bottom panel). Different line styles correspond to the escaping cascade spectra produced within the range of angle α measured in respect to the jet axis: $\alpha = 0° - 20°$ (black), $20° - 40°$ (red), $40° - 60°$ (green), and $60° - 80°$ (blue).

field of the accretion disk. The cascade can develop in the whole volume above the accretion disk. We assume that primary γ-rays are injected isotropically from the region within the jet (a blob) at the distance H from its base. The blob moves along the jet with specific velocity which is assumed equal to $\beta = 0.5c$, where c is the velocity of the light. Moreover, we assumed that above the accretion disk a magnetic field exists with a dipole structure. This magnetic field may significantly re-distribute the directions of the secondary cascade $e^{\pm}$ pairs which additionally suffer the synchrotron energy losses. This process has been also taken into account when considering the energy losses of secondary cascade $e^{\pm}$ pairs. Therefore, we can also obtain simultaneous synchrotron emission which should accompany the high energy γ-ray emission.

In Fig. 2, we show the γ-ray spectra emerging from the cascades in the radiation field of the accretion disk at different range of angles α, measured in respect to the disk axis. The primary γ-rays have been injected in this case in the blob with the power law spectrum above 10 GeV up to 10 TeV with the differential spectral index equal to -2. We transform energy and the direction of the primary γ-rays to the disk frame of reference and track the cascade. Note the dependence of the cut-off in the cascade γ-ray spectra as a function of the distance from the black hole and the observation angle. At larger distances from the base of the jet the escaping γ-ray spectra are steeper but also show the power law shape whose spectral index depends on the observation angle.

The energy density of the dipole magnetic field falls more rapidly with a distance from a black hole then a energy density of the radiation field. In the calculations shown in the bottom panel of Fig. 2, we show the results for the case of the magnetic field which is in the equipartition with the energy density of the disk radiation (i.e. $B = 300$ G for $T_{\rm in} = 3 \times 10^4$ K). The effect of the presence of the magnetic field above the disk is only important in the case of an injection relatively close to the base of the jet.

We also show the cascade γ-rays spectra produced by the blob injecting primary γ-rays as in the previous case but after integrating over the range of propagation distances along the jet (see Fig. 3). As an example, we consider the cases of the blob moving from the base of the jet (at $H = r_{\rm in}$) up to the distance of $H = 100r_{\rm in}$ or $300r_{\rm in}$. Note the interesting features. The lower energy part of escaping γ-rays spectra is very similar to the injected spectrum of primary γ-rays (effects of the absorption and the cascading negligible). However, for larger angles, the γ-rays spectra becomes steeper at the higher energy part. This part of the spectrum can be also well described by a simple power law with the spectral index increasing with the observation angle. Also the break in the γ-ray spectrum (due to the cascade process) shifts to lower energies with the larger observation angle α.

IV. Conclusion

We have calculated the γ-ray spectra expected in the case of a complicated IC $e^{\pm}$ pair cascade developing in the whole volume above the accretion disk, the source of soft radiation. The cascade is initiated by primary γ-rays produced in the blob moving along the jet. These primary γ-rays might be produced in the mechanism

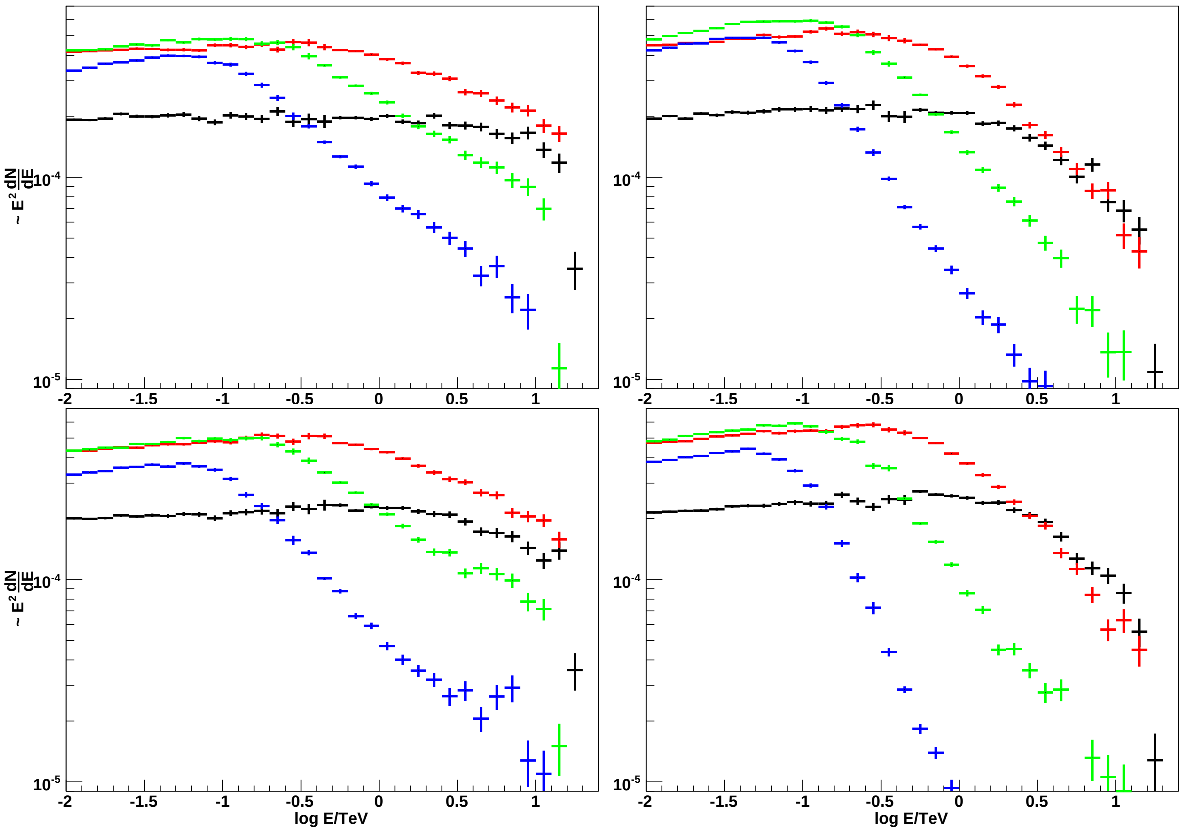

Fig. 3. Gamma-ray spectra produced in the $e^{\pm}$ pair cascade initiated by primary γ-rays injected isotropically from the point source moving along the jet with velocity $\beta = 0.5$ in the range of distances $H = 1 - 300 r_{\rm in}$ (left figures) and $H = 1 - 100 r_{\rm in}$ (right). The spectrum of primary γ-rays is of the power law type with the differential spectral index -2. The calculations have been performed without any magnetic field above the accretion disk (upper panel) and with the dipole magnetic field normalized to 300 G at the inner disk radius (bottom panel). Line colours as in fig. 2.

internal to the blob (e.g. SSC model). The model is specially interesting in the case of close active galaxies observed at relatively large angles to the disk axis (often identified with the direction of the jet) at mildly relativistic speeds, such as recently detected in TeV γ-rays radio galaxy Cen A. We have performed cascade calculations for the parameters of this source and conclude that the observed TeV γ-ray spectrum can be naturally explained in terms of this cascade model for the range of angles constrained by the observations (i.e. $15° - 80°$) provided that the primary γ-rays are injected isotropically with the power law spectrum and differential spectral index -2 at specific range of distances along the jet (from $1 r_{\rm in}$ up to $100 - 300 r_{\rm in}$). The low energy break in the TeV γ-ray spectrum depending on the observation angle is expected in terms of this model. This feature might serve as additional diagnostic of the consistency of the model with the observations. Moreover, it can give information on the primary spectrum of injected γ-rays.

Note that for a source with a larger redshift, the absorption effects considered in this model can be difficult to distinguish from the absorption effects due to propagation of γ-rays in the extragalactic background light.

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