Anisotropic Inverse Compton $e^\pm$ pair model for the $\gamma$-ray emission from the blazar PKS 1510-089

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Abstract: A few distant FSRQ type blazars have been recently detected not only in the GeV energies but also in the sub-TeV energy range by Cherenkov telescopes. The fast variability of the $\gamma$-ray emission from these sources is difficult to understand in the model which assumes $\gamma$-ray production outside of the Broad Line Region, extending up to a fraction of a parsec from the central engine. We wonder whether this $\gamma$-ray emission can not originate in the Inverse Compton (IC) $e^\pm$ pair cascade occurring in the dense radiation field of the accretion disk in the inner part of the jet. Using the anisotropic IC pair cascade scenario we model the observed $\gamma$-ray spectrum of PKS 1510-089. It is shown that the observed shape of the GeV-TeV $\gamma$-ray spectrum can be well described by electrons injected with the simple power law spectrum if the absorption effects at the radiation from the accretion disk, the broad line region (BLR) and in the Extragalactic background Light (EBL) are included. We also interpret the short scale variability of this emission in terms of such model.

Keywords: gamma-rays, FSRQ, pair cascade

1 Introduction

Three distant flat spectrum radio quasars (FSRQs), 3C 279 [1], PKS1222+21 [2] and PKS 1510-089 [3, 4], have been detected in the GeV energies and recently also in the sub-TeV $\gamma$-rays by Cherenkov telescopes. The $\gamma$-ray spectra of these sources are flat in GeV energies and becomes steep in TeV energies. This feature can be caused by the absorption in the Extragalactic Background Light (EBL), the internal absorption at the source or a mixture of both. In the case of PKS 1510-089, variability in the GeV $\gamma$-ray range with flux doubling time scales reaches the values as small as $\sim$20 min [5, 6]. In the sub-TeV $\gamma$-ray range doubling time scale of 10 min has been observed in light curves of PKS1222+21 [2]. Such short variability time scales argue for relatively small emission region. In addition it is believed that the emission region has to be located at large distance from the base of the jet in order to avoid strong absorption in the radiation fields of the accretion disk and the broad line region (BLR). On top of that, this small emission region (or regions), being at large distance from the central engine, should still move with very large Lorentz factors in order to be consistent with the observed $\gamma$-ray power. Such large Lorentz factors are difficult to reconcile with the observations of the superluminal motion in these sources which give the values of the order of $\sim$20 in the case of PKS 1510 [6]. Therefore, the location of the $\gamma$-ray emission region remains in fact a mystery.

We perform Monte Carlo calculations of the $\gamma$-ray emission in terms of an anisotropic IC $e^\pm$ pair cascade model. They are compared with the GeV and TeV observations of an example source of this class, PKS 1510-089. PKS 1510-089 is a luminous FSRQ located at a redshift $z = 0.361$, harboring a black hole with the mass $\sim 5 \times 10^9 M_{\odot}$. In our model electrons are accelerated in the inner part of the jet close to the accretion disk and deep within the BLR. They Comptonize thermal radiation from the accretion disk. Electrons produce first generation of $\gamma$-rays which initiate the IC $e^\pm$ pair cascade in the radiation field of the accretion disk. The final $\gamma$-ray spectra are obtained by taking into account the absorption of cascade $\gamma$-rays in the soft radiation from the BLR and in the EBL.

2 IC $e^\pm$ cascade model for FSRQs

The details of the anisotropic IC $e^\pm$ pair model, which we apply in order to interpret the GeV-TeV emission from PKS 1510-089, are reported in [10, 11]. Here we mention only the general features of this model. We assume that electrons are accelerated and confined in a blob which moves along the jet with a fixed Lorentz factor $\gamma_e$. The directions of the electrons at any given moment are assumed to be isotropic in the blob’s frame of reference. The electrons are injected with the simple differential power law spectrum ($\propto E^{-\delta}$) and the high energy cut-off at $E_{\text{max}}$. Note, that due to the Doppler boosting, the energies of electrons in the disk’s frame of reference will reach higher values. The injection occurs with constant rate at a specific range of distances from the base of the jet, i.e. between $D_{\text{min}}$ and $D_{\text{max}}$.

Since we consider the acceleration of electrons close to the base of the jet, the main cooling process of electrons is the interaction with the anisotropic radiation from the accretion disk. The emission of the disk is treated as a black body with the power-law dependence on the distance, $r$, from the black hole, $T(r) = T_{\text{in}} (r/r_{\text{in}})^{-3/4}$, where $T_{\text{in}}$ is the inner disk temperature and $r_{\text{in}}$ is the disk inner radius. We assume that the disk extends up to the radius of $500 \ r_{\text{in}}$. The total disk luminosity, $L_D = 4\pi \sigma T^4_{\text{disk}}$, is normalized to the observations of the UV bump with the power $\sim 3 \times 10^{45}$ erg s$^{-1}$ [12]. For this disk luminosity and the inner radius $r_{\text{in}} = 3 \ r_{\text{BH}} = 5 \times 10^{14}$ cm (corresponding to the black hole mass of $M_{\text{BH}} = 5 \times 10^9 M_{\odot}$) the inner disk temperature is $T_{\text{in}} \sim 6.5 \times 10^4$ K.

Note that the accretion disks are expected to have hot
We calculate the cascade IC region \[14\]. We include the absorption effects of the cascade \gamma\)-ray spectra produced close to the accretion disk process initiated by the relativistic electrons from the jet. The cascade \gamma\)-ray spectra, produced in the sequence of processes: IC production of \gamma\)-rays in collisions of electrons with disk photons and subsequent absorption of these \gamma\)-rays in collisions with disk photons, as a function of the angle measured in respect to the axis of the jet. Such spectra are strongly affected by the anisotropic radiation field. The emerging \gamma\)-ray spectra are defined by the three-dimensional \gamma\)-spheres, i.e. the optical depths for \gamma\)-rays in different directions. The optical depths are computed following the approach of \[10\] and shown in Fig. 1. Our calculations show that for small angles in respect to the jet axis \((< 10^\circ)\) the \gamma\)-rays with energies below \(\sim 10\) GeV escape from the disk radiation without any absorption if produced even at the base of the jet. However, \gamma\)-rays with energies above 100 GeV can only escape provided that they are produced at distances greater than \(\sim 10\) inner radii from the accretion disk. \gamma\)-ray with energies of a few hundred GeV (which were observed from PKS 1510-089 by H.E.S.S. and MAGIC telescopes) escape without absorption only from distances above \(\sim 30\) \(r_{in}\). The \gamma\)-ray spectra produced close to the accretion disk have to pass through the disk radiation which is scattered or absorbed and re-emitted in the broad emission line region (BLR). Such radiation has more favorable angles for the absorption of \gamma\) rays, and thus can affect them also at larger distance from the black hole and at lower energies, even while the total luminosity of BLR is much smaller than the one of the accretion disk. Moreover, contrary to the absorption in the disk radiation field, the absorption in BLR nearly does not depend on the direction of the propagation of the production distance and the propagation angle of the \gamma\)-ray, as long as it is produced deep within the BLR region \[14\]. We include the absorption effects of the cascade IC e^± pair spectra by multiplying them by the reduction factors e^\(-\tau_{RL}\). In our calculations we assume the radius of the BLR to be \(\sim 1500r_{in}\), similar to the value used in the \gamma\)-rays in collisions with disk photons, as a function of the angle measured in respect to the axis of the jet. Such spectra are strongly affected by the anisotropic radiation field. 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\begin{align}
R_b &= 0.5\xi Dc/\tau_{var}/(1+z),
\end{align}

Figure 1: Optical depths for absorption of \gamma\) rays in the accretion disk radiation field of PKS1510-089 as the function of the energy measured in the Earth’s frame for 3 observation angles with respect do the direction of the jet: 0\(^\circ\) (left panel), 10\(^\circ\) (middle panel) and 30\(^\circ\) (right panel). \gamma\) rays are injected at different distances from the black hole: 1 \(r_{in}\) (solid lines), 3 \(r_{in}\) (dashed), 10 \(r_{in}\) (dotted), 30 \(r_{in}\) (dot-dashed), 100 \(r_{in}\) (dot-dot-dashed), 300 \(r_{in}\) (dot-dot-dot-dashed).

Figure 2: Optical depths for \gamma\) rays in the BLR radiation field of PKS1510-089 as the function of the energy measured in the Earth’s frame. The dashed line shows the optical depth in the lines of BLR, the dotted line in the continuum emission, and the solid one is the sum of both.

3 Gamma-ray spectra and variability

The shortest observed variability time scale of the GeV \gamma\) ray emission from PKS 1510 allows us to constrain the velocity of the emission region along the jet. If the blob forms close to the base of the jet, then its radius has to be not larger than the inner radius of the accretion disk, \(R_b = \xi R_{in} \sim 3 R_{BH} \xi \approx 5 \times 10^{14} \xi \) cm, where \(\xi < 1\) is the ratio of the radius of the blob to the radius of the jet. The variability time scale of GeV emission, \(\tau_{var} \sim 20\) min, depends on the radius of the blob and its Doppler factor, \(R_b = 0.5\xi Dc/\tau_{var}/(1+z),\)
We collect the gamma rays emitted in the viewing angle of $\beta$ where $\xi = \gamma / (1 - \beta \cos \alpha)$ is the Doppler factor, and $\alpha$ is the viewing angle. Eq. 1 allows us to constrain the Doppler factor of the blob on $D \approx 40 / \xi$. If the observer is located on the axis of the jet then the Lorentz factor of the blob is $\gamma_b \approx 0.5 D \approx 20 / \xi$. Based on the estimated Lorentz factor of the blob, we can constrain the inner part of the jet in which the observed emission originates,

$$D_{\text{max}} \sim \frac{c^2 \tau_{\text{var}}}{\xi^2} \left( \frac{1 + \beta_b}{1 + z} \right) \approx 40 r_{\text{in}} \xi^2 \approx 1.9 \times 10^{16} / \xi^2 \text{ cm,}$$  

(2)

where $\beta_b$ is the velocity of the blob in units of the velocity of light. For reasonable value of $\xi$ equal to 0.6 (corresponding to $\gamma_b \approx 30$), we estimate that the active region of the jet (in which electrons are accelerated) has to extend up to $D_{\text{max}} \approx 100 r_{\text{in}}$ from the base of the jet.

Applying the parameters estimated above, we perform Monte Carlo calculations of the $e^\pm$ pair cascade spectra. In Fig.3 we show the spectral energy distribution obtained in the framework of the model described in the previous section. For the calculations we assume a simple differential power law spectrum of electrons with slope $-2.7$. The spectrum has an high energy cut-off at $E_{\text{max}} = 600 \text{GeV}$ (measured in the reference frame of the blob). Note however that as sub-TeV and TeV $\gamma$ rays are strongly absorbed in the EBL the precise value of this cut-off has little influence on the obtained SED, as long as $E_{\text{max}} \gtrsim 100 \text{GeV}$. The electrons are injected homogeneously within the blob in the range of distances $1-100 r_{\text{in}}$. Note that those primary electrons are injected deep in the BLR. Therefore the $\gamma$ rays produced in the IC $e^\pm$ pair cascade will be strongly attenuated by the absorption in BLR (according to Fig.2). We collect the gamma rays emitted in the viewing angle of $< 5^\circ$ with respect to the jet axis. We correct the SED for the absorption in the EBL (according to [16]) and in BLR (according to Fig.2). The Fermi-LAT and H.E.S.S. spectrum can be reasonably well described by our model. For the basic scenario, we assume that 1% of the radiation of the accretion disk is reflected by BLR in a form of continua radiation, and another 1% is reprocessed in the form of emission lines. Note that as the value of the optical depth in BLR is not far from unity, the $\gamma$-ray spectrum is very sensitive to even small difference in the reflectivity (compare dot-dashed and dot-dot-dashed lines with the solid line in Fig.3 for the effect of the slight change of the reflectivity coefficient).

Note that the model prediction goes slightly above two of the Fermi-LAT points in the energy range close to $\sim 10 \text{GeV}$. As we commented above, such an effect can be caused by fact that we have not taken in the present calculations the additional absorption in the hot corona above the accretion disk (see e.g. [14]). This hot corona is expected to emit UV and soft X-rays which provide additional target for $\gamma$ rays with energies of a few tens of GeV. We do not consider this additional accretion disk radiation component since its emission geometry is not well known at present.

In Fig.4 we study the shape of light curves predicted by the IC $e^\pm$ pair cascade model above different energy thresholds. We apply the same parameters of the electron injection as for the SED study. The GeV light curves in this model consist of three phases. First, they exhibit a small peak at the beginning of the emission. It is caused by efficient cooling of electrons and multiplication of $\gamma$ rays in cascade processes in the inner part of the jet, which is immersed in the strong radiation field close to the surface of the accretion disk. The peak is then followed by a slowly dropping emission generated from electrons injected along the jet with total time spread corresponding to the injection range according to Eq. 2. The shape of this part of the emission is nearly independent on the energy threshold. The last part of the emission, an exponential decay, is caused by electrons being in pure cooling phase. The decay
phase is much sharper for higher energy thresholds. On contrary, the light curve in the sub-TeV range shows a rapid raise time caused by the blob coming out of the intense absorption region in the beginning of the jet. Note that the raise time of both GeV and sub-TeV γ-rays may be extended due to the time scale of electron acceleration, and rate of their injection in the blob. Therefore, precise investigation of the shape of the γ-ray flare should give us information on the injection efficiency of electrons along the jet.

4 Conclusion

We show that the basic emission features of FSRQs, i.e. flat spectrum in GeV energies and steep in the sub-TeV energies and very short variability time scales of this emission, can be understood in terms of the IC $e^\pm$ pair cascade model. In this model electrons are accelerated in a relativistic blob in the inner part of the jet and the dominating radiation field comes from the accretion disk. Good description of the observed γ-ray spectrum (see Fig. 3) can be obtained in the case of electrons with a simple power spectrum provided that γ-rays interact very strongly with the soft radiation already at the source (i.e. with the accretion disk radiation and the disk radiation reprocessed in the broad line emission region). Such model naturally explains extremely short time scale variability of the order of $\sim 20$ min observed in the GeV emission by Fermi.

Discussed above modeling do not require any extraordinary parameters for the widely accepted classical model of the comptonization of disk radiation by electrons in the jet. We have assumed that the blob accelerates electrons starting from the base of the jet up to the distance of 100 jet inner radius and moves relativistically already there with the Lorentz factor equal to 30.

Acknowledgment: This work is supported by the grant from the Polish MNiSzW through the NCN No. 2011/01/B/ST9/00411.

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