Modification of the gamma-ray spectra by internal absorption in optically violently variable blazars: the example cases of 3C 273 and 3C 279

J. Sitarek1,2* and W. Bednarek1⋆

1 Department of Experimental Physics, University of Łódź, ul. Pomorska 149/153, 90-236 Łódź, Poland
2 Max-Planck-Institut für Physik, D-80805 München, Germany

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ABSTRACT
Recent observations with the low-threshold Cherenkov telescopes proved that sub-TeV γ-rays are able to arrive from active galaxies at relatively large distances in spite of the expected severe absorption in the extragalactic background light (EBL). We calculate the γ-ray spectra at TeV energies from two example optically violently variable quasars, 3C 273 and 3C 279, assuming that γ-rays are injected in the inner parts of the jets launched by the accretion discs. It is assumed that γ-rays in the broad energy range (from MeV up to TeV) are produced in these blazars with a power-law spectrum with the spectral index as observed from these objects by the EGRET telescope at GeV energies. We take into account the internal absorption of these γ-rays by considering a number of models for the radiation field surrounding the jet. The classical picture of a relativistic blob in a jet for the injection of primary γ-rays is considered, with the injection rate of γ-rays as observed by the EGRET telescope in the GeV energy range. The results of calculations are compared with positive detection and the upper limits on the sub-TeV γ-ray fluxes from these two sources. It is concluded that, even with the Stecker EBL model, the level of γ-ray emission from 3C 279 is close to the recent measurements in the sub-TeV γ-ray energies, provided that the injected γ-ray spectrum extends from the GeV energies over the next two decades with this same spectral index. We also suggest that a flare with a time-scale of a few days from 3C 273 could be detected by the MAGIC II stereo telescopes.

Key words: radiation mechanisms: non-thermal – galaxies: active – galaxies: individual: 3C 273 – galaxies: individual: 3C 279 – gamma-rays: theory.

1 INTRODUCTION

TeV γ-rays are detected from compact sources (for example massive binary systems and active galactic nuclei) in which their absorption at the source has to be carefully investigated, as not enough attention has been dedicated to this problem up to now. In fact, the escape conditions of γ-ray photons from the vicinity of accretion discs surrounding compact objects have been studied in the past in the context of the γ-ray production close to the accretion disc radiation, starting with the first reports of TeV γ-ray emission from binary systems in the 1980s and including GeV γ-ray emission from active galaxies: see, for example, early calculations of absorption in the disc radiation by Protheroe & Stanev (1987), Carraminana (1992), Bednarek (1993), Becker & Kafatos (1995), and in the quasi-isotropic radiation around the disc-jet by Blandford & Levinson (1995). The problem of γ-ray escape once again became very attractive with the discovery of TeV γ-ray emission from BL Lac-type active galaxies (see more recent calculations by, for example, Protheroe & Biermann 1997; Bednarek 1997; Donea & Protheroe 2003; Liu & Bai 2006; Reimer 2007). Thanks to the low energy threshold of the MAGIC telescope, it is at present clear that also quasars of the optically violently variable (OVV) type at very large distances emit at least sub-TeV γ-rays (e.g. quasar 3C 279, Albert et al. 2008).

However, higher-energy γ-rays (above ∼100 GeV) should be efficiently absorbed in the soft radiation field filling intergalactic space. Therefore, observations of TeV γ-rays from the population of active galactic nuclei (AGNs) at different distances could be used to put upper limits on the extragalactic background light (EBL). The conclusions reached based on this method depend strongly on the assumptions made concerning the production spectrum of the γ-rays at the source. Usually a simple power law is applied with a spectral index that in the extreme case can be constrained by the likely radiation mechanisms of particles accelerated at AGNs (for the most recent analyses see, for example, Aharonian et al. 2006a; Mazin & Raue 2007). If, however, the internal absorption inside the
source is important, the shape of the emerging γ-ray spectrum can be quite complex; that is, the spectrum can become significantly flatter (see, for example, fig. 9 in Bednarek 1997; Aharonian, Khangulyan & Costamante 2008) than considered limiting values \( \propto E^{-1.5} \) or even \( \propto E^{-2.5} \). Therefore, derived upper limits on EBL are in fact model-dependent, strongly depending on the details of the production of γ-rays inside the source.

In this paper we calculate the opacities for γ-rays emitted from the central regions of AGNs in the most general case; that is, for arbitrary angles of injection of γ-rays with respect to the jet axis and also for arbitrary inclinations of the jet with respect to the plane of the accretion disc. The opacities for the γ-rays propagating in the spherically symmetric broad-line region are also taken into account. We can thus obtain three-dimensional γ-spheres around the central engine, which can be especially useful in the case of jets highly inclined towards the observer, for example as might occur in the case of the strongly variable TeV γ-ray radio galaxy M87 (Aharonian et al. 2006b; Aciari et al. 2008).

Moreover, we show how the intrinsic spectra of γ-rays emitted from AGNs should be modified in the case of two example EGRET blazars, 3C 273 (Hermes et al. 1993; von Montigny et al. 1993; Lichten et al. 1995) and 3C 279 (Klinken et al. 1993; Wehrle et al. 1998; Hartman et al. 2001a,b). The second source has also recently been detected by the MAGIC telescope (Albert et al. 2008), and is at present the most distant sub-TeV γ-ray source. Based on the new observations of 3C 279 in the sub-TeV energies, we estimate the location of the production region inside the jet assuming that: (i) the γ-ray flare observed by the MAGIC telescope was comparable to the highest activity state observed by the EGRET telescope at GeV energies; (ii) the production spectrum of γ-rays at the source extends from GeV energies up to TeV energies without a break. The effects of possible absorption of TeV γ-rays during propagation in the EBL are taken into account by applying EBL extreme estimates derived by Primack, Bullock & Sommerville (2005) and Stecker, Malkan & Scully (2006).

2 THE MODEL FOR SOFT RADIATION INSIDE ACTIVE GALAXIC NUCLEI

To date, a number of scenarios have been considered in which absorption of γ-rays in collisions with the soft photon field surrounding the inner jets of AGNs is expected to be important. The soft radiation can be produced inside the jet (synchrotron origin), in the accretion disc (thermal origin), in the broad-line region (BLR, disc-scattered emission and emission lines), or in the large equatorial torus (thermal IR emission) (see references cited in the Introduction). Absorption in the synchrotron radiation field is important mostly in the case of BL Lac objects, for which the accretion disc radiation field is rather weak and the γ-ray emission regions are very compact (estimated from observations of very short-variability time-scales). Because radiation from the torus is mainly in the IR band, it contributes mainly to the absorption of higher-energy gamma rays. In this paper we consider the absorption of γ-rays only in the accretion disc and in the BLR. These two radiation fields seem to be the most important because the very short-variability time-scale of TeV γ-ray emission (of the order of a few minutes as observed recently in the case of Mrk 501 (Albert et al. 2007) and of PKS 2155 – 304 (Aharonian et al. 2007)) strongly suggests that the emission regions in blazars are located within the inner part of the jet (i.e. relatively close to the accretion disc).

\[ L_{\delta} = 4 \pi \sigma_{SB} r_{in}^2 T_{in}^4 \]

where \( \sigma_{SB} \) is the Stefan–Boltzmann constant. In the case of some quasars, the disc emission, its luminosity and the location of the peak in the spectrum, is clearly observed (e.g. 3C 273). The above
formula can then be used to estimate the inner radius of the accretion disc.

The observed luminosity of the accretion disc in 3C 273 is $L_{\text{disc}} = 2 \times 10^{41} \text{ erg s}^{-1}$, and the temperature of the inner part of the disc is estimated as $T_{\text{in}} = 2.6 \times 10^4 \text{ K}$ (Malkan & Sargent 1982; Malkan 1983). Paltani & Türrler (2005), using the reverberation method, gave an estimation of the black hole mass as $M = 7 \times 10^8 \text{ M}_\odot$ and the size of the BLR as $r_{\text{BLR}} = 986^{+21}_{-17} \text{ d}$. Based on the observed luminosity and the location of the peak emission, the inner radius of the disc can be fixed at $r_{\text{in}} = 7.8 \times 10^3 \text{ cm}$. This value is consistent with an independent estimate of the gravitational radius of the black hole, $r_g = GM/c^2 \approx 10^{15} \text{ cm}$, from its estimated mass. The outer radius of the accretion disc is fixed at $r_{\text{out}} = 10^4r_{\text{in}}$.

We also considered a second OVV-type blazar, 3C 279. For this source we applied the disc luminosity $L_{\text{disc}} = 2 \times 10^{43} \text{ erg s}^{-1}$ and the inner temperature $T_{\text{in}} = 20000 \text{ K}$ (Pian et al. 1999). The inner radius of the accretion disc in 3C 279 was estimated as $r_{\text{in}} = 4.2 \times 10^3 \text{ cm}$.

The second model (model II) for the disc radiation is suggested by observations of the prominent bump in the optical–UV energy band in 3C 273. This bump shows a clear power-law tail at soft X-rays, which seems to continue smoothly after the UV peak. It can be interpreted as being caused by the emission from the hot disc corona above the surface of an optically thick, geometrically thin accretion disc (see Staubert et al. 1992; Leach, McHardy & Papadakis 1995). We added such a component to the thermal emission of the optically thick, geometrically thin disc. This soft X-ray tail is described by a simple power law with differential spectral index $\sim 2.7$ (Kriss et al. 1999), the extrapolation of which meets the peak in the thermal emission. Therefore, in model II, to the thermal SS-type disc emission we added emission from the disc corona with the power-law spectrum mentioned above.

We also considered a third model (model III) for the radiation of the accretion disc, in which the inner disc temperature is significantly higher than that predicted by the classical SS model. This might occur in the case of an accretion disc around a rapidly rotating black hole (a Kerr black hole). In such a case the gravitational energy released per unit area of the disc increases faster with the disc radius than in the case of the classical SS model (Page & Thorne 1974), resulting in an increase of the inner disc temperature by a factor of $\sim 3$. Slim discs, which are expected in the case of high accretion rates on the lower-mass black hole (see Szušszkiewicz, Malkan & Abramowicz 1996), can also produce disc spectra extending to higher energies, due to higher effective temperatures of the disc radiation than in the case of SS thin discs. Note that an interpretation of the UV results from 3C 273 as arising from such hotter accretion discs cannot be excluded because the peak of the emitted radiation falls into the UV region, which is unobservable owing to interstellar absorption. Therefore, in our model III we also considered accretion discs with inner temperatures a factor of 3 larger than in the case of the classical SS disc model but with a similar temperature profile. Note that a three-times higher temperature at the inner disc radius requires a simultaneous decrease of the inner disc radius $r_{\text{in}}$ by a factor of $3^{4/3} \approx 4.3$ in order to satisfy the condition on the total power emitted by the accretion disc.

2.2 The broad-line region radiation

The quasi-spherical region around the central black hole, in which broad emission lines are produced (the BLR), consists of a large number of clouds. In these clouds the disc UV radiation is absorbed and re-emitted isotropically in the form of emission lines. For the calculations of line emission from the BLR we followed Liu & Bai (2006), who calculated the emissivity $j_l$ of 35 lines (in the wavelength range of $\lambda = 1–6.5 \times 10^3 \text{ Å}$). The photon density of this re-processed radiation was calculated by integration along an arbitrary direction through the BLR. However, in contrast to Liu & Bai, we considered only the upper hemisphere of the BLR (with respect to the accretion disc), as the lower hemisphere is in fact obscured by the accretion disc. Owing to the presence of free electrons in the BLR, part of the disc radiation is reprocessed in the Compton scattering process. Because this scattering process occurs in the Thomson regime, the angular distribution of the scattered photons is roughly isotropic and their spectrum is conserved. Therefore, the energy spectrum of the continuous part of the BLR emission is the same as the blackbody spectrum integrated all over the disc. The BLR continuous spectrum, obtained in the above way, has a long low-energy tail, which is important in calculating the absorption of gamma-rays above $\approx 1 \text{ TeV}$.

The total luminosity of the line, $L_{\gamma}$, and of the continuous, $L_{\text{cont}}$, part of the BLR spectrum was normalized to the disc luminosity by introducing two parameters, namely the conversion efficiency of the disc luminosity to the BLR line luminosity, $\eta_l$, and to the continuous luminosity, $\eta_c$. Therefore, $L_{\gamma} = \eta_lL_d$ and $L_{\text{cont}} = \eta_cL_d$. Note that the BLR emission shows a much larger level of isotropy than the direct disc emission. Therefore, the maximum contribution to the absorption of high-energy $\gamma$-rays due to BLR radiation is shifted to lower energies.

The dimension of the BLR in 3C 273 was estimated as $h_{\text{BLR}} = 500r_{\text{in}}$ (in agreement with results from reverberation mapping; Paltani & Türrler 2005). The inner radius of the BLR is difficult to estimate by any argument. We applied the value of $h_{\text{BLR}} = 100r_{\text{in}}$. In the example calculations shown below, it is assumed that $\eta_l = \eta_c = 0.01$. Bear in mind that optical depths for $\gamma$-rays interacting with the BLR radiation scale linearly with an appropriate $\eta$ coefficient. The size of the BLR in 3C 279 was re-scaled from the size of 3C 273 according to the general prescription $h_{\text{BLR}} \propto L_{\gamma}^{0.7}$ (Kaspi et al. 2000). Therefore, we assumed that the clouds of the BLR in 3C 279 are confined between 20 and 190$r_{\text{in}}$.

3 OPTICAL DEPTHS FOR GAMMA-RAYS

We calculated the optical depth for $\gamma$-rays in the radiation field inside the central parts of the AGNs according to the standard prescription

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

where $n(l, \epsilon, \Omega)$ is the differential number density of soft photons with energy $\epsilon$ that arrive inside the solid angle $\Omega$ to the instantaneous location of the $\gamma$-ray photon at the propagation distance $l$ (soft photons arrive from the accretion disc, or from its corona, or from the BLR), $\sigma_{\gamma\gamma}$ is the pair-production cross-section, and $\theta$ is the angle between the momentum vectors of the gamma-ray and soft photon. $l$ denotes the path along the propagation direction of the gamma-ray photon in the soft radiation field. Note that, in the most general situation, namely $\gamma$-rays injected at an arbitrary place above the accretion disc and in an arbitrary direction, the calculations are not straightforward because the considered radiation field is highly anisotropic (see Bednarek 1993).

As a first step, we calculated the optical depths for the case of the $\gamma$-ray blazar 3C 273, in which clear disc emission is observed in the optical–UV energy range. We also performed such calculations to another OVV blazar, 3C 279, which has recently been discovered.
Gamma-ray spectra in OVV blazars

3.1 Absorption in the disc radiation

We investigated the optical depths for $\gamma$-rays as a function of injection place, injection angle and energy for the radiation field defined by the parameters characteristic for 3C 273 and for the simple SS temperature profile (see Fig. 2a–c). Our calculations show that the absorption effects of the TeV $\gamma$-rays can be very important for this source. The basic features of these results (i.e. strong dependence on the distance from the accretion disc and on the injection angle of the $\gamma$-rays) can be simply understood. Note that the number of photons emitted from the specific ring on the accretion disc with radius $r$ scales as $N \sim r T^3 \sim r^{-5/4}$. This means that most of the disc radiation comes from the inner part of the disc. Therefore, the radiation field seen by the $\gamma$-rays is highly anisotropic. In the case of small propagation angles $\alpha$, the collision angle, $\theta$, between the directions of $\gamma$-ray and soft photons, is also small. Therefore, the $e^\pm$ pair-production process is strongly suppressed owing to the higher energy threshold and geometric factor $(1 - \cos \theta)$ included in equation (2).

The dependence of the optical depths on the injection place is the strongest for $\alpha \approx 0^\circ$ (see solid curves in Fig. 2a). For $\gamma$-rays injected at $\alpha = 0^\circ$ and relatively close to the black hole, most of the soft photons from the accretion disc interacts with the $\gamma$-ray photons at a large angle $\theta$, resulting in their efficient absorption. The dependence of the optical depths on the distance from the accretion disc is weaker in the case of higher-energy $\gamma$-rays, when the threshold on $e^\pm$ pair production is not so important (compare the slopes of the thin and thick curves in Fig. 2a). Note how quickly the absorption of $\gamma$-rays in disc radiation increases for higher values of the angle $\alpha$. The reason is that the brightest inner part of the disc is better seen and the interaction angle, $\theta$, between photons is large.

The radiation field of the accretion disc considered in the case of 3C 273 seems to be one of the strongest compared with other blazars observed in GeV $\gamma$-rays by the EGRET telescope. This might be
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Figure 3. Comparison of the optical depths for γ-rays in the radiation field of the Shakura–Sunyaev accretion disc model (model I, thin curves), and this same accretion disc with an additional hot corona (model II, thick) for (a) 3C 273 and (b) 3C 279. The optical depths are shown for γ-rays injected at the angle α = 0° and for various distances from the base of the accretion disc: xγ = 10rin (solid curves), xγ = 30rν (dashed), xγ = 100rν (dotted) and xγ = 300rν (dot-dashed). The radiation field produced inside the accretion disc corona has a differential spectrum of a power-law type (E−2.7) and extends over the whole disc.

the reason why the spectral index of the GeV emission from 3C 273 is steep with respect to the spectral indexes of other γ-ray OVV blazars, for example 3C 279. Owing to greater optical depths, the primary TeV γ-ray photons can develop more efficient cascades in the radiation field surrounding the central engines of blazars. Such inverse Compton e± pair cascades in the anisotropic radiation are very complicated. Therefore, detailed calculations of the cascade γ-ray spectra emerging from the optically thick central regions of AGNs (with highly anisotropic radiation fields) will be discussed in a future paper.

We also compared the optical depths for γ-rays in the case of the presence of a hot disc corona above an optically thick disc (model II). It is clear that the disc corona can significantly contribute to the optical depth at lower energies of γ-rays owing to the higher energies of soft photons with respect to photons coming from the thin disc alone (see Fig. 3). This additional absorption in the radiation field of the disc corona can have an effect on the correct normalization of the calculated γ-ray spectra from 3C 273 and 3C 279 to their spectra observed by the EGRET telescope in the GeV energies.

3.2 Absorption in the BLR radiation

It is assumed that the emission of separate clouds in the BLR is isotropic. Thus, γ-ray photons collide with the large number of soft BLR photons at relatively large interaction angles θ. Therefore, their absorption in BLR radiation can be more important than that in the radiation coming directly from the accretion disc, even for relatively small re-radiation factors ηl and ηs.

The optical depths are roughly constant for injection locations that are inside the BLR (i.e. xγ < hbl) (note that the thin curves in the middle and lower (c) figures of Fig. 2 are nearly horizontal). However, the optical depths fall rapidly with increasing xγ inside the BLR, hbl < xγ < hout. This is because γ-rays injected close to the black hole (xγ ≪ hbl) see a very similar BLR radiation field, which is nearly independent of the γ-ray injection angle. Because part of the BLR is obscured by the accretion disc, the values of the optical depths slightly decrease with increasing injection angle α. By contrast, for γ-rays injected inside the BLR (xγ < hbl), their propagation distance through the BLR increases with the injection angle α. Therefore, the optical depths also increase with the angle α.

We assumed for simplicity that ηl = ηs; that is, the fractions of the power of the accretion disc that is re-processed in the line and continuous radiation inside the BLR are comparable. There is, however, an important difference in the dependence on the optical depths for γ-rays with their energy in these two radiation fields. In the case of line emission from the BLR, all soft photons are concentrated in a small energy range. Therefore, absorption is the strongest for γ-rays with energies E ≈ lν/m c^{3}/h ≈ 0.3 TeV. On the other hand, the continuous part of the BLR radiation is composed of all wavelengths corresponding to the spectrum radiated by the accretion disc. This spectral distribution has a long low-energy tail that is the dominant target for the higher-energy γ-rays.

3.3 Three-dimensional γ-spheres

Based on the above calculations of the escape of γ-ray photons, we determined the three-dimensional surfaces around the central engine of the AGN at which the optical depths for γ-rays with specific energies, Eγ, and injection angles, α (measured with respect to the direction perpendicular to the disc surface), are equal to unity. The shape of this surface can in general be quite complicated, although it is termed a γ-sphere in the literature. The evaluation of such a surface is very useful because γ-rays produced inside the γ-sphere are strongly absorbed, whereas those produced outside it can escape with negligible absorption.

The observation of the superluminal motion in 3C 273, with an apparent velocity of ≈5–10c (Unwin et al. 1985; Abraham et al. 1996), allows us to put constraints on the jet viewing angle, αjet < 15° and Γjet > 10. However, modelling of the disc emission gives the best results for the inclination angle of the accretion disc close to αd ≈ 60° (Kriss et al. 1999). This discrepancy suggests that in general jets do not need to propagate along the accretion disc axis. Thus, the proper consideration of the escape of γ-rays in such a more complicated geometrical situation requires the calculation of full three-dimensional γ-spheres.

For the example values of the re-radiation factors, ηl and ηs (mentioned above), the locations of the γ-spheres due to their absorption
in the disc radiation and in the BLR radiation are at similar distance from the accretion disc provided that γ-rays are injected along the disc axis. The locations of these specific γ-spheres are shown in Fig. 4 in the case of both OVV blazars (3C 273 and 3C 279), for the parameters of the radiation fields described above. However, these two different radiation fields have different effects on the escape of γ-ray photons with TeV energies. The γ-spheres in the BLR radiation are only weakly dependent on energies of γ-rays above 0.1 TeV and on their injection angles α, because the BLR radiation field is quite isotropic. On the other hand, the γ-spheres resulting from absorption in the disc radiation depend strongly on the energies and injection angles of γ-rays. In general, γ-spheres broaden with energies of TeV γ-rays and also with their injection angles. This is because of the relatively narrow peak in the spectrum of soft photons coming from the accretion disc.

The detailed structures of the three-dimensional γ-spheres for these two sources are shown in Fig. 5. We investigated the location of the γ-sphere as a function of the injection angle, α, and the energy...
of $\gamma$-rays. In the case of their absorption in the BLR radiation, the $\gamma$-spheres depend only weakly on the injection angle owing to the high level of isotropy of BLR radiation. However, the shapes of the $\gamma$-spheres arising from absorption in the disc radiation are quite complicated. Note the curious shapes of the $\gamma$-spheres for different injection angles of $\gamma$-ray photons. The $\gamma$-spheres at the axis of the accretion disc depend strongly on the injection angle of the $\gamma$-rays. However, they are closest to the central engines along directions corresponding to the values of the injection angles of $\gamma$-rays. Therefore, even in the case of a jet highly inclined to the disc, the $\gamma$-rays can escape efficiently.

According to our calculations, the $\gamma$-spheres around the central engine of 3C 273 are located at significantly larger distances than they are in the case of 3C 279. Therefore, in principle, TeV $\gamma$-rays originating closer to the central engine can escape from 3C 279.

4 MODIFICATION OF THE INJECTED GAMMA-RAY SPECTRA

As we have shown above, the $\gamma$-ray emission produced inside jets of blazars, but relatively close to the accretion disc and/or the BLR, may suffer significant absorption as a result of collisions with the soft radiation field. Therefore, the emerging $\gamma$-ray spectra from the source region can be strongly modified in respect to the injected $\gamma$-ray spectra. Applying the above-discussed models for the soft radiation field from the disc and around the jet, we calculated the $\gamma$-ray spectra that escaped from the source by assuming their simple modification according to the law $F = F_0 e^{-\tau_{\text{tot}}}$, where $F$ and $F_0$ are the observed and intrinsic flux, respectively, and $\tau_{\text{tot}} = \tau_{\text{d}} + \tau_{\text{BLR},1} + \tau_{\text{BLR},c}$ is the sum of the optical depths on different radiation fields. Such a simple modification can only be considered in the case of complete isotropization of secondary $e^\pm$ pairs produced in $\gamma$–$\gamma$ absorption processes. In this case, the next generation of $\gamma$-rays (which appear as a result of the inverse Compton $e^\pm$ pair cascade process) is produced in different directions than the location of the observer. On the other hand, $e^\pm$ pairs produced by $\gamma$-rays propagating in other directions can contribute to the $\gamma$-ray spectrum towards the observer. However, detailed calculations of $\gamma$-ray spectra, which also include such complicated cascade processes in the anisotropic radiation fields, are very difficult to perform realistically because of the strong dependence of the final results on the unknown structure of the magnetic field around and inside the jet. We leave this very complicated problem for future work.
Note that, because the optical depths for $\gamma$-rays depend on their energy, the spectrum of escaping $\gamma$-rays (in the case of simple absorption) can change its spectral index significantly. This is a very important feature because in some cases the spectral index in a specific energy range may become very flat; that is, flatter than expected from any single radiation production process (see, for example, calculations by Bednarek 1997). Below we show the $\gamma$-ray spectra, modified by absorption, escaping from both OVV quasars considered here.

4.1 3C 273

The EGRET quasar 3C 273, at redshift $z = 0.157$, has been observed by the EGRET telescope onboard the Compton GRO during several periods. A positive signal has been detected a few times (Lichti et al. 1995; von Montigny et al. 1997; Collmar et al. 2000). The $\gamma$-ray flux from 3C 273 shows strong variability during which the spectral index changes between 3.2 and 2.2 (von Montigny et al. 1997). It has the form of flares characterized by a rise time of the order of $\sim 2$ weeks and a fall time of $\sim 1$ week (Collmar et al. 2000). The strongest outburst was observed during 7 weeks of monitoring in 1996–1997. Its spectrum in the high state can be described by a simple power law: $F = (3.0 \pm 1.7) \times 10^{-4} (E/\text{MeV})^{-2.39 \pm 0.13} \text{[ph cm}^{-2}\text{s}^{-1}\text{MeV}^{-1}]$ (Lichti et al. 1995). At TeV energies only the upper limit has been reported to date, by the Whipple group (von Montigny et al. 1997). The upper limit lies clearly above the extrapolation of the EGRET spectrum. The multi-wavelength spectrum of 3C 273 (Lichti et al. 1995) shows two general peaks, the first in the infrared (likely synchrotron origin) and the second in the MeV energies. An additional strong peak in the optical–UV range is usually interpreted as being the result of thermal emission from the accretion disc (e.g. Kriss et al. 1999).

We calculated the $\gamma$-ray spectra expected from 3C 273 at TeV energies by including the absorption effects of primary injected $\gamma$-rays in the accretion disc and BLR radiation. It is assumed that the $\gamma$-ray spectrum, injected from the jet of 3C 273, extends to TeV energies, with the spectral index and flux extrapolated from the EGRET energy range during the high state of activity. Note that the production of TeV $\gamma$-rays in OVV blazars has been postulated from some models (e.g. see Georgopoulou et al. 2006). The $\gamma$-ray spectra emerging from the vicinity of the source are shown for various parameters of the considered models (see Fig. 6). On the left of Fig. 6, we show the results for the simple SS disc model. As expected, $\gamma$-rays injected close to the base of the jet are very strongly absorbed. The observed superluminal motion in 3C 273 puts strong constraints on the viewing angle of the jet. However, we consider a range of angles for the propagation of the $\gamma$-rays with respect to the surface of the accretion disc because, as we noted above, the estimated inclination angle of the accretion disc in 3C 273 is quite large. Note that this situation might not be so surprising, as the jet does not need to be perpendicular to the disc surface. Thus, the observation of the superluminal motion in this source does not exclude injection of $\gamma$-rays at large angles to the disc axis.

In general, absorption effects depend strongly on the injection distance from the accretion disc and on the injection angle $\alpha$. In the case of gamma-rays injected at larger distances (see the case for $x_r = 300r_{\text{in}}$), the shape of the spectrum depends strongly on the propagation angle $\alpha$. Only for small angles $\alpha$ do $\gamma$-ray spectra clearly extend through the TeV energy range with only moderate absorption (see the case for $\alpha = 0$ and $x_r = 300r_{\text{in}}$). Absorption of $\gamma$-rays in the BLR radiation produces a clear flattening of the spectrum around $\sim 1$ TeV. As a result of this feature, the emerging spectrum is actually harder in the TeV energies than the injected spectrum (see the dashed thick curve in Fig. 6).

The emerging $\gamma$-ray spectra calculated in the case of models II and III for the disc radiation field are shown in Figs 6(b), (c), (e) and (f), respectively. The biggest difference in optical depths with and without the corona occur at multi-GeV energies. Because of the sharp exponential cutoff in the Planck spectrum emitted by the accretion disc, there are not enough UV photons for the efficient absorption of $\gamma$-rays. In the case of additional power-law radiation from the accretion disc corona, the number of these photons is much greater, so the optical depths in the case of the model with an additional disc corona are much larger than the optical depths in the case of only SS disc radiation. However, the absolute values of the optical depths are still quite small at these energies (compare with Fig. 3). Thus, differences in the resulting spectra with and without a corona are visible only at sub-TeV energies.

The model with a very hot disc (the temperature at the inner radius a factor of 3 higher than in the case of the SS model) produces very strong absorption of the $\gamma$-ray spectra injected at distances $x_r < 300r_{\text{in}}$ at energies above $\sim 30$ GeV. Note that, in this model, $r_{\text{in}}$ is 4.3 times smaller than it is in models I and II. Therefore, not only is the radiation field much stronger, but $\gamma$-rays are injected significantly closer to the central engine.

4.2 3C 279

The OVV blazar 3C 279, at redshift $z = 0.538$, was observed by the EGRET telescope simultaneously with 3C 273, as the two objects are separated by an angular distance of only a few degrees. A strong flare with a very flat spectrum (differential spectral index 1.89) was detected from 3C 279 in June 1991 (Hartman et al. 1992). The flux increased over $\sim 1$ week and declined over 2 d (Kniffen et al. 1993). An even stronger $\gamma$-ray flare was observed by the EGRET in 1996 with a similar time structure and spectral index (Wehrle et al. 1998). In spite of the much larger distance than that to 3C 273, 3C 279 has been positively detected by the EGRET telescope in all observation periods (Hartman et al. 2001a), showing a variety of TeV and spectral index stages. The shortest-variability time-scales observed in these flares were below $\sim 1$ day (Wehrle et al. 1998; Hartman et al. 2001b).

As in the case of 3C 273, we assume that the injection spectrum of 3C 279 extends from the GeV energy range through the TeV energy range with a similar spectral index. As an example, the EGRET $\gamma$-ray spectra observed during the strong flares are considered (i.e. spectral index close to 2). In the case of the flare in 1996, the differential $\gamma$-ray flux can be fitted with the simple power law $4.3 \times 10^{-10} (E/\text{TeV})^{-2.02} \text{TeV cm}^{-2} \text{s}^{-1} \text{sr}^{-1}$ (Hartman et al. 2001). We calculated the $\gamma$-ray spectra emerging from the source by including absorption of $\gamma$-rays in the disc and BLR radiations and by applying the above-described models for these radiation fields (see Section 2). However, in the case of 3C 279, there is no information on the inclination angle of the accretion disc to the observer’s line of sight. We limit our calculations to small values of the angle $\alpha$.

The $\gamma$-ray spectra modified by absorption are shown for various injection distances of primary $\gamma$-rays from the accretion disc (see Fig. 6). It is clear that emerging $\gamma$-ray spectra can be very strongly modified provided that the injection distances are $x_r < 100r_{\text{in}}$. The dependence on the injection angle below $\sim 10^\circ$ is small.

As a result of the generally weaker disc radiation in 3C 279 (with respect to 3C 273), a significant fraction of the TeV $\gamma$-rays are able to emerge from distances of the order of a few hundred inner disc radii, even in the case of model III, in which the inner disc temperature...
3C 273

3C 273

3C 273

3C 279

3C 279

3C 279

(a) (b) (c)

(d) (e) (f)

Figure 6. Modification of the γ-ray spectrum extrapolated from the EGRET energy range to TeV energies, for 3C 273 (panels a, b, c) and 3C 279 (panels d, e, f), by internal absorption in the disc and the broad-line region radiation for various models of radiation produced in the accretion disc: Shakura–Sunyaev disc model (model I, a; d); Shakura–Sunyaev model + power-law high-energy tail (model II, b; e); high-temperature disc model (model III, c; f). In the upper panels the injection angle of γ-rays is \( \alpha = 0^\circ \) (dashed), 30° (dotted) or 60° (dot–dashed curves), and the distance from the accretion disc is \( x_\gamma = 30r_{\text{in}} \) (thin curves) or \( x_\gamma = 300r_{\text{in}} \) (thick). In the bottom panels the injection angle of γ-rays is \( \alpha = 0^\circ \) (thin curves) or 10° (thick), and the distance from the accretion disc is \( x_\gamma = 10r_{\text{in}} \) (solid curves), \( x_\gamma = 30r_{\text{in}} \) (dashed), \( x_\gamma = 100r_{\text{in}} \) (dotted) or \( x_\gamma = 300r_{\text{in}} \) (dot–dashed).

is three times larger. However, the γ-ray spectrum emerging in this last case is strongly modified. A strong absorption dip is seen at \( \sim 300 \) GeV, with a very flat spectrum above this energy.

5 GAMMA-RAY SPECTRA AFTER PROPAGATION IN THE EBL

In the case of both of the quasars discussed, the absorption of TeV γ-rays during their propagation through intergalactic space has to be taken into account. However, the radiation field filling intergalactic space (the EBL) is not precisely known. Two limiting estimates are usually considered in the literature. In the model by Stecker et al. (2006), the EBL is relatively strong and the absorption effects on the TeV γ-ray spectra even from close sources are strong. In this model the EBL spectra are calculated from the so-called ‘backward-evolution’ scheme. In this approach, luminosities of galaxies at higher redshifts are predicted using present galaxy spectral energy distributions (SEDs), luminosity functions and redshift evolution of the luminosity function. The SED of a galaxy is deduced from its relationship to luminosity in one IR band. The luminosity function of galaxies used in this model is an analytic fit of a smoothed broken power law to the observational data. The redshift evolution of galaxies adopted in this model is a pure luminosity evolution, which is more important than the number density evolution. There are two possibilities for the redshift evolution of galaxies considered in the Stecker model: the so-called baseline and fast evolution models. The former model predicts slightly lower values of optical depths then the latter one. In this work we use the baseline Stecker model. The Stecker EBL model requires very flat injection spectra of TeV γ-rays even for the TeV gamma-ray sources at distances of observed BL Lacs. Such production spectra are not widely accepted. However, they cannot be excluded (Katarzyński et al. 2006; Stecker, Baring & Summerlin 2007). They are, however, possible in the case of strong internal absorption as postulated by, for example, some cascade models for γ-ray production in BL Lacs (see e.g. Bednarek 1997). In the Primack et al. (2005) model, the absorption of TeV γ-rays from the observed BL Lacs is moderate. This model follows the ‘forward-evolution’ approach. The emission of galaxies is predicted from the general theory of cosmology and galaxy formation. Note, however, that this model is not a viable lower limit to the EBL because it lies below the solid observational lower limits from galaxy counts at infrared wavelengths, as shown.
in Albert et al. (2008). In the case of the second model, for quasars at the distance of 3C 279, the γ-ray absorption becomes severe at energies above a few hundred GeV. Below, we show how the γ-ray spectra are modified in the case of both EBL models for the injection spectra discussed above, in which we also take into account the internal absorption at the source (as shown in Fig. 6).

5.1 Gamma-rays injected at specific places in the jet

The γ-ray spectra, calculated for the specific parameters of our models (considered in Fig. 6), are shown in Figs 7 and 8, after including the effects of propagation in the EBL estimated according to the Stecker and Primack models. Let us first consider the spectra obtained with the Stecker model. The γ-ray emission above ∼0.4 TeV (in the case of 3C 273) and above ∼1 TeV (in the case of 3C 279) is severely attenuated in all considered models for the soft radiation field of the accretion disc and the BLR. Note that the spectra can extend to higher energies in the case of 3C 279 as a result of the significantly flatter injection spectrum of γ-rays inside the jet (spectral index ∼2 in 3C 279 compared with ∼2.4 in 3C 273). In Fig. 7 we also show the γ-ray spectrum from 3C 279 measured by the MAGIC telescope (Albert et al. 2008) and the available upper limit on the spectrum from 3C 273 measured by the Whipple telescope (von Montigny et al. 1997). The observed spectrum from 3C 279 can be consistent with the calculated spectra only if the maximum rate of the injection of primary γ-rays occurs at distances significantly larger than \( x_\gamma \sim 100 r_{in} \) from the base of the jet. However, in the case of the Primack EBL model the maximum of the flare might occur at distances as close as a few tens of \( r_{in} \). The injection locations of primary γ-rays have to be located at much greater distances from the base of the jet in the case of the radiation model with a three-times larger temperature at the inner radius.

The γ-ray spectra expected from 3C 273 steepen significantly above a few hundred GeV, even for greater distances from the base of the jet. For the considered parameter range, they are also below the present sensitivity of the MAGIC I telescope (differential spectrum at 5σ detection, within a 50-h observation period, and sensitivity re-calculated for the spectrum of γ-rays with the index 2.6). Therefore we conclude that detection of 3C 273 by the present Cherenkov telescopes is unlikely if the injection region is located within the jet at distances for which calculations are shown in
Figs 6 and 7. However, such emission should be within the sensitivity limits of the planned Cherenkov Telescope Array (CTA), whose sensitivity will be an order of magnitude better (Hermann 2007).

5.2 Model for injection of primary $\gamma$-rays

The strong $\gamma$-ray flares observed from these two OVV quasars in the GeV energy range develop typically on a time-scale of a few days to two weeks (the rise time, $\tau_r$) and fall on a time-scale of a day up to a few days (the fall time, $\tau_f$) in the cases of 3C 279 and 3C 273, respectively. These time-scales could be related to the distances at which the production of $\gamma$-rays occurs inside the jet. However, these distance scales are also related to the Doppler factors ($D$) of the emission regions and to a smaller extent to the distance to the quasar. The characteristic distance scales on which the flares occur can be estimated from

$$L \approx D^2c(\tau_r + \tau_f)/(1 + z),$$

where $c$ is the velocity of light and $z$ is the redshift of the source. For the above-mentioned durations of the observed $\gamma$-ray flares and estimated Doppler factors (typically of the order of $\sim 10$), $\gamma$-ray injection has to occur along quite a large region extending along the jet in respect to the characteristic dimension of the source scaled by the inner radius of the accretion disc. The absorption of the TeV $\gamma$-rays throughout such an extended region can change drastically, as we showed in the previous Section (5.1). Here, we calculate the emerging spectra in the TeV energy range by taking into account the absorption effects of primary $\gamma$-rays in the case of a specific model for the development of the flare inside the jet.

Let us consider a model for the injection of $\gamma$-rays in which the emission region in the jet (the blob) is very compact; that is, its dimension is much smaller than the characteristic distance scale along the jet on which the injection of $\gamma$-rays occurs. As noted above, the shortest variability detected from 3C 279 is below $\tau_s \sim 1$ day. This allows us to put an upper limit on the dimension of the blob:

$$R_b < Dc\tau_s/(1 + z).$$

(4)

The Doppler factor of the blob moving along the jet is independent of time. We assume that $\gamma$-rays are injected from the blob at a rate corresponding to the observed $\gamma$-ray light curve measured by the EGRET telescope (i.e. with an initial slow increase and a final fast decrease). The basic assumption of our calculations is that the injection spectra can be extrapolated from the EGRET energy range without a break and extend up to at least $\sim 1$ TeV. Note that our assumption is less rigorous than recent interpretations of the TeV $\gamma$-ray observations of some BL Lacs, in which the upper limits on the EBL are derived based on assumptions regarding the spectral indexes of $\gamma$-ray spectra at the source (spectral indexes $\propto E^{-1.5}$ or even $\propto E^{-2/3}$, Katarzyński et al. 2006). We assume that GeV...
5.3 Gamma-ray spectra at the observer

Applying the model for the development of the flare inside the jets of these two OVV blazars (defined above), we calculate the γ-ray spectra at the observer by integrating over the duration of the flares (see Fig. 9). In these spectra all the effects of the internal absorption and the absorption in the EBL (with both Stecker and Primack models) are taken into account. It is assumed that the flare starts to develop from the base of the jet. The example calculations are shown for two values of the Doppler factor of the emission region, $D = 7$ (full curves) and $D = 11$ (dashed). The grey curves mark the positive detection, the upper limit, and the sensitivity of the Cherenkov telescopes as in Fig. 7.

γ-rays are able to escape freely from the central region without absorption. Therefore, our hypothesis of the common origin of the GeV and TeV emission in blazars allows us to postulate that the rate at which the TeV γ-rays are injected has a time structure similar to that observed by the EGRET telescope.

Below, we investigate the effects of spectral changes resulting from internal absorption at the source in the above-described model for the injection of primary γ-rays in the case of both sources, 3C 273 and 3C 279. We calculate the expected spectra at the observer (i.e. after propagation in the EBL) in terms of both EBL models considered and then compare them with the observations of the TeV γ-rays from these two objects and/or with the sensitivities of present and future Cherenkov telescopes.

Figure 9. Gamma-ray spectra at the observer calculated for injection of primary γ-rays into the jet of 3C 273 (panels a, b, c) and of 3C 279 (panels d, e, f), for various models of the radiation field created by the accretion disc and the broad-line region: Shakura–Sunyaev disc model (model I, a, d); Shakura–Sunyaev + power-law tail from the disc corona (model II, b, e); high-temperature disc profile model (model III, c, f). The γ-ray spectra are shown taking into account the absorption in the extragalactic background light according to the Stecker et al. model (thin curves) and the Primack et al. model (thick). The injection rate of γ-rays into the jet has been estimated based on observations in the GeV energy range by the EGRET telescope (see Collmar et al. 2000; Wehrle et al. 1998). They are characterized by the rise times of the flares, equal to 2 weeks in 3C 273 and to 7 d in 3C 279, and the fall times of the flares, equal to 1 week (3C 273) and to 2 d (3C 279). The spectra are integrated over the part of the jet corresponding to the above-mentioned duration of the flares (see equation 4). The Doppler factor of the emission region is equal to $D = 7$ (full curves) and $D = 11$ (dashed). The grey curves mark the positive detection, the upper limit, and the sensitivity of the Cherenkov telescopes as in Fig. 7.
Figure 10. Example time evolution of the $\gamma$-ray spectra during the development of the $\gamma$-rays flares from 3C 273 and 3C 279 for the Doppler factor $D = 10$. Specific spectra have been calculated in specific time windows ($\Delta t = 4$ d in the case of 3C 273 and 2 d in the case of 3C 279). It is assumed that the injection of $\gamma$-rays starts at the base of the jet. Specific curves are obtained for 0–4 d (double-dot–dashed curve), 4–8 d (dashed), 8–12 d (dotted), 12–16 d (dot–dashed), 16–20 d (treble-dot–dashed) in the case of 3C 273; and for 0–2 d (double-dot–dashed curve), 2–4 d (dashed), 4–6 d (dotted), 6–8 d (dot–dashed) in the case of 3C 279. The absorption effects in the extragalactic background light according to the Stecker et al. model (panels b, d) and Primack et al. model (panels a, c) are included. For the description of the grey curves see Fig. 7.

an important effect only very close to the base of the jet from which only some of the observed $\gamma$-rays are produced.

A comparison of these calculations with the sensitivity of the MAGIC I telescope shows that detection of the $\sim$2-week flare from 3C 273 is unlikely. Only future CTA telescopes, with sensitivity an order of magnitude better, should detect this source. The situation is much better with 3C 279, for which sub-TeV emission has already been detected (Albert et al. 2008). The spectrum observed from 3C 279 by the MAGIC telescope is generally consistent with the model considered here for $\gamma$-ray production in the inner part of the jet. Moreover, with a slight modification of the Stecker EBL model (smaller absorption at lower energies), the high estimate of the EBL
also gives a correct description of the sub-TeV $\gamma$-ray spectrum. So then, positive detection of 3C 279 by the MAGIC telescope does not need any extraordinary assumptions on the production spectrum at the source (e.g. very flat spectra), but a simple extrapolation from the EGRET energy range is enough. In the case of the low estimate of the EBL (Primack et al. model), the $\gamma$-ray spectrum above several GeV should have a clear break in order not to exceed the reported flux level and to be consistent in the sub-TeV energies with the MAGIC observations. Note, however, that the above comparisons concern the $\gamma$-ray spectrum integrated over the whole duration of the flare but that the MAGIC observations are limited to two days, with most of the signal detected within a few hours. Therefore, in Fig. 10 we predict the evolution of observed $\gamma$-ray spectra from these two objects at different stages of the development of their flares. According to our calculations, the power in the $\gamma$-ray spectra should increase with time (as expected from the normalization to the EGRET energy range), but in addition the cut-off in the spectrum should shift to higher energies. Therefore, we predict a specific behaviour of the $\gamma$-ray emission from OVV blazars that could be tested by future sub-TeV observations even with the second phase of the present Cherenkov telescopes (e.g. MAGIC II, HESS II) or the GLAST telescope at $\sim$100-GeV energies. As discussed above, the Stecker model for the EBL is consistent with the detected sub-TeV $\gamma$-ray emission from 3C 279 during the peak of the flare. In the case of the Primack model, a significant part of a one-week flare might be observed in sub-TeV energies (provided that the spectrum extrapolated from the GeV energies does not break) or the significant break in the $\gamma$-ray spectrum should appear at several GeV.

It looks, however, as if there is a chance to detect the sub-TeV $\gamma$-rays from 3C 273 during peak emission with the MAGIC II stereo system (at least twice better sensitivity than the MAGIC I telescope). Note marked on these figures differential sensitivity of the MAGIC I telescope at the 5$\sigma$ detection within a 50-h observation period. The peak of the flare detected by the EGRET from 3C 273 lasts for a few days. With the MAGIC II sensitivity, and 15-h low-zenith-angle observations within a few days, detection of the peak of the flare from 3C 273 at the level of $\sim$5$\sigma$ seems reasonable.

## 6 Conclusions

We have discussed in detail the effects of the internal absorption of $\gamma$-rays produced in jets of OVV-type blazars concentrating on two well-known sources: 3C 279 and 3C 273. The first source has recently been detected in sub-TeV energies with the MAGIC telescope (Albert et al. 2008), but only the upper limit has been reported on the TeV emission from the second source (von Montigny et al. 1997).

It is shown that the model for $\gamma$-ray production in the jet of 3C 279, in which the spectrum is extrapolated from the EGRET energy range (observed up to several GeV) to the $\sim$1 TeV energy range, is consistent with the $\gamma$-ray spectrum reported by the MAGIC collaboration, even in the case of the upper estimate on the EBL derived by Stecker et al. (2006). Note that this is the most-distant TeV $\gamma$-ray source ($z = 0.536$) detected to date. Therefore, we conclude that the observation of this most distant sub-TeV source does not introduce any new important constraints on the EBL. Such constraints are often derived for the population of the closer BL Lac-type objects, in which case the TeV emission extends to much higher energies. However, if the EBL is closer to the estimate given by the Primack et al. (2005) model, the $\gamma$-ray spectrum injected from the considered active region in the jet has to show a clear break above several GeV.

At present it is difficult to conclude purely on theoretical grounds if the $\gamma$-ray spectra in OVV blazars continue to higher energies or have a significant break.

We also showed that detection of 3C 273 with the present MAGIC telescope is problematic even if the source is captured in the highest emission state observed to date by the EGRET telescope and the EBL is well described by the Primack et al. model. However, there is a real chance to detect the peak of a few-day flare from this source with the MAGIC II stereo system (which should have a sensitivity twice as high), provided that the EBL is close to the Primack et al. model.

We have only shown the results of calculations for two values of the Doppler factor of the emission region in the jet ($D = 7$ and 11). In the case of emission regions moving with larger Doppler factors, the internal absorption of $\gamma$-rays in the radiation field around the jet should be reduced owing to the larger distance travelled by the EBL, and related to this the on average more distant injection of $\gamma$-rays from the accretion disc and BLR clouds. We also assumed that the flare in the jet starts to develop from its base. However, farther away from the accretion disc, the internal absorption is certainly weaker. Therefore, we consider the most pessimistic case for the escape of TeV $\gamma$-rays from these OVV blazars. Note that the location of the injection region of $\gamma$-rays inside the jet could in the future be constrained by more sensitive observations that allow detection of much shorter-variability time-scales of the $\gamma$-ray emission. The discovery of a very short time-scale variability in blazars of BL Lac type (of the order of a few minutes, see Mrk 501 (Albert et al. 2007), and in PKS 2155–304 (Aharonian et al. 2007) and also in radio galaxy M87 (Aharonian et al. 2006b) strongly suggests that the $\gamma$-ray emission region is rather located very close to the base of the jet (i.e. close to the surface of the accretion disc).

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