Formation of hard very high energy gamma-ray spectra of blazars
due to internal photon–photon absorption

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ABSTRACT
The energy spectra of TeV gamma-rays from blazars, after being corrected for intergalactic absorption in the extragalactic background light (EBL), appear unusually hard, a fact that poses challenges to the conventional models of particle acceleration in TeV blazars and/or to the EBL models. In this paper, we show that the internal absorption of gamma-rays caused by interactions with dense narrow-band radiation fields in the vicinity of compact gamma-ray production regions can lead to the formation of gamma-ray spectra of an almost arbitrary hardness. This allows significant relaxation of the current tight constraints on particle acceleration and radiation models, although at the expense of enhanced requirements to the available non-thermal energy budget. The latter, however, is not a critical issue, as long as it can be largely compensated by the Doppler boosting, assuming large (>10) Doppler factors of the relativistically moving gamma-ray production regions. The suggested scenario of formation of hard gamma-ray spectra predicts detectable synchrotron radiation of secondary electron–positron pairs which might require a revision of the current ‘standard paradigm’ of spectral energy distributions of gamma-ray blazars. If the primary gamma-rays are of hadronic origin related to $pp$ or $p\gamma$ interactions, the ‘internal gamma-ray absorption’ model predicts neutrino fluxes close to the detection threshold of the next generation high-energy neutrino detectors.

Key words: BL Lacertae objects: general – diffuse radiation – gamma-rays: observations – gamma-rays: theory.

1 INTRODUCTION
The recent reports on detections of very high energy (VHE) gamma-rays from blazars with redshifts $z \geq 0.1$ (see e.g. Hinton 2007, for a review) initiated renewed debates on the interpretation of TeV gamma-ray spectra of blazars, in particular in the context of the level of the diffuse extragalactic background radiation at optical and infrared (IR) wavelengths, often called also as extragalactic background light (EBL). Initially, the tight link between these two topics – TeV blazars and EBL – became a subject of hot discussions prompted by multi (up to 20) TeV gamma-rays detected from a nearby BL Lac object, Mkn 501 (Aharonian et al. 1999), and by the reports claiming detection of high fluxes of EBL at far-infrared (FIR) wavelengths (Hauser et al. 1998; Schlegel, Finkbeiner & Davis 1998; Lagage et al. 1999; Finkbeiner, Devis & Schlegel 2000). However, it was quickly recognized that these two claims hardly could be compatible within any standard model of TeV blazars (see Aharonian 2001, for a review).

A distinct feature of extragalactic gamma-ray astronomy is that VHE gamma-rays emitted by distant ($\geq 100$ Mpc) objects arrive after significant absorption caused by their interactions with EBL via the process $\gamma\gamma \rightarrow e^+e^-$ (Nikishov 1962; Jelley 1966; Gould & Schr`eder 1967). The reconstructed, i.e. the absorption-corrected gamma-ray spectrum from a source at a redshift $z$, $J_{\text{obs}}(E) = J_{\text{obs}}(E) e^{\tau_E z}$ depends on the flux and energy spectrum of EBL through the optical depth $\tau(E, z)$. Thus, at energies where $\tau(E, z) \geq 1$, the primary gamma-rays suffer strong spectral deformation. The EBL consists of two emission components produced by stars and partly absorbed/re-emitted by dust throughout the entire history of galaxy evolution. As a result, two distinct bumps are expected in the spectral energy distribution (SED) of EBL at near-infrared (NIR) and FIR wavelengths, with a mid-infrared (MIR) ‘valley’ between these two bumps (see e.g. Hauser & Dwek 2001). Generally, for almost all EBL models, $\tau(E)$ is a strong function of energy below 1 TeV and above 10 TeV, between 1 and 10 TeV, the energy dependence of $\tau(E)$ is much weaker (Aharonian 2001). Consequently, one
should expect significant distortion of the VHE spectra of blazars at energies below 1 TeV and above 10 TeV, provided that at these energies $\tau \geq 1$. One can reformulate this statement in a different way. Namely, for a standard (‘decent’) intrinsic gamma-ray spectrum, the observer should detect very soft (steep) spectra at energies below 1 TeV and above 10 TeV from objects for which $\tau \geq 1$ at corresponding energies. This condition is safely satisfied, given the constraints on the minimum EBL flux imposed by galaxy counts, for blazars with redshifts $z \geq 0.15$ like IES 1101–232 and for nearby objects with $z \sim 0.03$ like Mkn 501. Even though the detected gamma-ray spectra from both objects in the corresponding energy intervals are indeed quite steep with a photon index $\sim -3$ (Aharonian et al. 1999, 2006a), they appear not sufficiently steep to compensate the function $f(E) = e^{\lambda_0 \tau (E)}$, and thus to prevent a robust conclusion that the intrinsic VHE gamma-ray spectra of these blazars are unusually hard.

In the case of Mkn 501, the intrinsic spectrum has a ‘non-standard’ shape with a possible pile-up above 10 TeV which has been interpreted as a ‘IR background – TeV gamma-ray crisis’ (Protheroe & Meyer 2000) or a need to invoke dramatic assumptions like a violation of the Lorentz invariance (see e.g. Kifune 1999). However, a more pragmatic view which presently dominates in both IR and gamma-ray astronomical communities, treats this ‘crisis’ as somewhat exaggerated, especially given the ambiguity of extraction of the truly diffuse extragalactic FIR component from the much higher backgrounds of local origin (see e.g. Hauser & Dwek 2001). Nevertheless, the recently reported low limits on the EBL at MIR wavelengths from the Spitzer deep cosmological surveys appeared quite high, for example at 70 $\mu$m the EBL flux should exceed $\gtrsim 7.1 \pm 1.0$ nW m$^{-2}$ sr (Dole et al. 2006). This implies that the problem is not yet over, and one may still face a challenge with the interpretation of the energy spectra of Mkn 501 and Mkn 421 in the multi-TeV energy domain.

On the other hand, the recent detections of TeV gamma-rays from blazars with redshifts $z \geq 0.15$ renewed the potential problems and challenges for standard models of TeV blazars. This time the issue has a more solid experimental background because the gamma-ray spectra corrected for the intergalactic absorption appear very hard (‘harder than should be’) even for the minimum possible EBL fluxes at optical and NIR wavelengths. Namely, the HESS collaboration reported, based on the detection of TeV gamma-rays from the BL Lac object IES 1101–232, that any significant deviation from the lower limits of EBL determined by the integrated light of galaxies resolved by the Hubble telescope (Madau & Pozzetti 2000), would lead to very hard intrinsic gamma-ray spectrum with a slope characterized by a photon index $\Gamma_0 \leq 1.5$ (Aharonian et al. 2006a). The analysis based on a larger sample of TeV blazars leads to the same conclusion (Mazin & Raue 2007). Recently, the HESS collaboration reported detection of multi-TeV gamma-rays from IES 0229+200, a BL Lac object located at a redshift $z = 0.1396$ (Aharonian et al. 2007a). It is remarkable that the detected hard gamma-ray spectrum of this source with a photon index $\Gamma_{obs} \sim 2.5$ extends up to 15 TeV. This, to a certain extent, surprising result can be explained by the shape of the energy flux of EBL, which between the NIR and MIR bands is expected to be proportional to $\lambda^{-1}$ (Aharonian 2001). Yet, the absolute EBL flux, derived from a rather conservative assumption that the photon index of the intrinsic spectrum of TeV gamma-rays does not exceed 1.5, appears again close to the EBL lower limit, this time at MIR ($\sim 2–3$ nW m$^{-2}$ sr at 10 $\mu$m), derived from the Spitzer galaxy counts (Fazio et al. 2004; Dole et al. 2006). Thus, the gamma-ray observations of IES 1101–232 and IES 0229+200 can be interpreted as an argument that the galaxies resolved by the Hubble and Spitzer telescopes provide the bulk of the EBL flux from optical to MIR wavelengths. Given the importance of such a statement, in particular for understanding of contribution of the first stars to the EBL (see e.g. Kashinsky 2005; Mapelli, Salvaterra & Ferrara 2006), it is essential to explore alternative ways of explanation of very hard intrinsic gamma-ray spectra or even sharper spectral features (like pile-ups) in TeV blazars. In this context, recently some extreme assumptions regarding the distributions of accelerated particles have been proposed. In particular, Katarzynski et al. (2006) argued that a gamma-ray spectrum as hard as $\Gamma_0 \sim 0.7$ can be formed in a synchrotron-self Compton (SSC) model assuming a narrow-parent electron distribution, e.g. power law within $E_1$ and $E_2$, with a low-energy cut-off $E_1$ not much smaller than the high-energy cut-off, $E_2$. In similar lines, Stecker, Baring & Summerlin (2007) argued that electron spectra with power-law index $1.25 \leq s \leq 2$ can be accommodated within the models of relativistic shock acceleration. It should be noted, however, that in compact objects relativistic electrons usually suffer very fast synchrotron losses, therefore the assumptions about hard electron acceleration cannot yet guarantee hard gamma-ray spectra. Indeed, fast synchrotron losses result in an electron spectrum which cannot be harder than $dN/dE \propto E^{-2}$, independent of the initial (acceleration) spectrum (see e.g. Aharonian 2004). If so, the inverse-Compton (IC) scattering would result in a gamma-ray spectrum steeper than $E^{-1.5}$. It should be noted that if the energy losses of electrons are dominated by IC scattering in the Klein–Nishina limit, the resulting electron spectrum appears harder than the acceleration spectrum. However, the related gamma-ray spectrum cannot be harder than the electron acceleration spectrum because of the same Klein–Nishina effect (since it works twice in different directions) (Khangulyan & Aharonian 2005; Moderski et al. 2005).

In principle, one can avoid the synchrotron cooling of electrons, e.g. in a cold ultrarelativistic wind. However, such an hypothesis suggested for Mkn 501 (Aharonian, Timokhin & Plyasheshnikov 2002), in analogy with pulsar winds, needs thorough theoretical studies to clarify whether such cold ultrarelativistic winds can be formed and survived around supermassive black holes in the cores of active galactic nuclei (AGN).

In this paper, we suggest a new scenario which allows the formation of very (in practice, arbitrary) hard gamma-ray spectra in a quite natural way. The model is based on a postulation that gamma-rays before leaving the source suffer significant photon–photon absorption due to interactions with dense radiation fields inside or in the vicinity of compact gamma-ray production region(s). Interestingly, the presence of high-density radiation fields of different origin in the inner parts of blazars generally is treated as a problem for the escape of high-energy gamma-radiation from their production region, and, in this regard, the current models of TeV blazars are designed in a way to avoid the internal gamma-ray absorption. Below we show that, in fact, a moderate internal photon–photon absorption can be a clue to the very hard intrinsic energy spectra of TeV blazars.

## 2 Internal Absorption of Gamma-rays in Blazars

When propagating through an isotropic source of low-frequency radiation, the gamma-ray absorption at photon–photon interactions is characterized by the optical depth:

$$\tau(E) = \int_0^R \int_{\epsilon_1}^{\epsilon_2} \sigma(E, \epsilon) n_{ph}(\epsilon, r) \, d\epsilon \, dr,$$

(1)
where $n_{\text{u}}(\varepsilon, r)$ describes the spectral and spatial distributions of target photons in the source of size $R$.

With a good accuracy, the total cross-section in the monoenergetic isotropic photon field can be represented in the form (see e.g. Aharonian 2004):

$$\sigma_{\gamma\gamma} = \frac{3\sigma T}{2\varepsilon^2} \left[ (s + \frac{1}{2}) \ln \left( \frac{\varepsilon}{s} \right) - \left( s + \frac{1}{2} \right) \ln \left( \frac{\varepsilon + \frac{1}{2}}{s - \frac{1}{2}} \right) \right].$$

The cross-section depends only on the product of the primary ($E$) and target photon ($\varepsilon$) energies, $s = E\varepsilon/m^2 c^4$. Close to the threshold, $s \to 1$, the pair production cross-section behaves as $\sigma_{\gamma\gamma} \approx (1/2) \sigma T (s - 1)^{3/2}$. The cross-section decreases with $s$ also when $s \gg 1$: $\sigma_{\gamma\gamma} \approx (2/3) \sigma T s^{-1} \ln s$. The cross-section achieves its maximum at $s \approx 3.5$: $\sigma_{\gamma\gamma} \approx 0.2 \sigma T$.

For an homogeneous source with a narrow-spectral distribution of photons (with energy $\varepsilon$), of the order of magnitude estimates one can use the approximation $\tau(E) \approx R\sigma_{\gamma\gamma} (E, \varepsilon) n(\varepsilon)$. In this case, we should expect maximum absorption effect at gamma-ray energy $E^* \approx m^2 c^4 / \varepsilon$. Both at lower and higher energies, the source becomes more transparent, thus we should expect a quite strong deformation of the primary spectrum. In the case $\tau(E^*) \geq 1$, the effect could be dramatic, given the exponential dependence of the absorption on the optical depth. Note that while for a narrow-spectral distribution of target photons, the monoenergetic approximation gives a quite accurate estimate of the effect at $E \gg E^*$, at low energies, $E \leq 1/4E^*$, this approximation implies a completely transparent source (i.e. $\tau = 0$) although, a non-negligible absorption can also take place below $E^*$. For example, because of interactions with the Wien tail, the absorption effect in the blackbody radiation field cannot be disregarded even at very low energies, $E \ll m^2 c^4 / kT$.

In Fig. 1 (upper panel), we present the gamma-ray attenuation factor, $\kappa = \exp(-\tau)$ in a grey-body radiation field described by Planckian distribution with three different temperatures $T = 10^3$, $10^4$ and $10^5$ K calculated for an optical depth fixed at the energy corresponding to the maximum absorption, $E^* \approx m^2 c^4 / kT$ (Gould & Schrédinger 1967); since the optical depth is a function of the product $E \varepsilon$, three curves are identical, but shifted relative to each other by a factor proportional to the radiation temperature. In Fig. 1, we also show the attenuation factors for a fixed temperature $T = 10^3$ K calculated for three different optical depths $\tau_{\text{max}} = 0.5, 3$ and 6. It is seen that the gamma-ray attenuation, starting from the energy $E \sim 0.1 E^*$, gradually increases up to $E \sim E^*$, after which the source becomes more and more transparent [$\kappa \propto \exp(-E^{-1} \ln E) \to 1$], and, consequently, the primary spectrum starts to recover. As a result, in this energy interval the spectrum appears harder than the primary spectrum. The bottom panel of Fig. 1 shows the change of the slope of gamma-ray spectrum, $\Delta \Gamma$, which can be interpreted as a change of the local photon index, assuming that the initial gamma-ray spectrum is described by a power-law distribution, $\text{d}N / \text{d}E \propto E^{-\Gamma}$. The emerging spectrum of gamma-rays in the energy interval $(0.1 - 1)E^*$ is steeper than the initial spectrum ($\Delta \Gamma \geq 0$); it recovers at $E = E^* (\Delta \Gamma = 0)$, and at energies $E \geq E^*$ the spectrum becomes significantly harder than the initial spectrum ($\Delta \Gamma \leq 0$). For example, in the case of initial gamma-ray spectrum $E^{-2}$ and $\tau_{\text{max}} = 6$, the emerging spectrum of gamma-rays in the energy interval $(1 - 10)E^*$ can be very hard with $\Gamma = \Gamma_0 + \Delta \Gamma \sim 0$.

![Figure 1](https://example.com/image1.png)

**Figure 1.** Upper panel: attenuation factor $\kappa = \exp(-\tau)$ for three different temperatures of target photons, $T = 10^3$, $10^4$ and $10^5$ K (for the optical depth $\tau_{\text{max}} = 6$). For $T = 10^5$ K, calculations are performed for three different optical depths: $\tau_{\text{max}} = 6$ (a, red line), 3 (b, green line) and 0.5 (c, blue line). Bottom panel: variation of the local photon index of the gamma-ray spectrum. (See the electronic version of the paper for a colour version of this figure.)

Note that the requirement of a narrow-spectral distribution of the target photons is a key condition for this remarkable effect. It should not necessarily be a Planckian or monoenergetic distribution, but may have any other shape, for example power law with a low-energy cut-off: $n(\varepsilon) \propto \varepsilon^{-\alpha}$ at $\varepsilon \geq \varepsilon_1$ and $n(\varepsilon) = 0$ at $\varepsilon \leq \varepsilon_1$. In this case, the low-energy cut-off $\varepsilon_1$ plays a similar role as the temperature in the Planckian distribution. This is demonstrated in Fig. 2 for a power-law distribution of the background field with $\alpha = 2$ and sharp cut-off $\varepsilon_1 = 1$ and $10^{-3}$ eV. Indeed, for the same $\tau_{\text{max}} = 6$, the case of $\varepsilon_1 = 1$ eV is quite similar to the case of Planckian distribution with temperature $T = 10^4$ K shown in Fig. 1. The main difference appears in the low-energy part, $E \ll E^*$. The absorption curve in Fig. 2 at low energies is smoother because the $n(\varepsilon) \propto \varepsilon^{-2}$ type distribution provides more high-energy target photons compared to the Wien tail of the thermal distribution, for interactions with low-energy gamma-rays.

The hardening of the initial spectrum caused by internal absorption compensates, to a large extent, the steepening of the spectrum due to intergalactic absorption. This is demonstrated in Figs 3 and 4. For the EBL flux, we use a ‘reference’ shape close to the one calculated by Primack, Bullock & Somerville (2005), but with two different absolute flux normalizations at the wavelength $\lambda = 2.2$ $\mu$m: $n_{\text{EBL}} (2.2 \mu$m) = 16 (Fig. 3) and 32 nW m$^{-2}$ sr (Fig. 4). The first flux is a factor of 2 larger than the lower limit of EBL corresponding to the integrated light contributed by resolved galaxies (Madau & Pozzetti 2000), while the second flux can be treated as an upper limit at 2.2 $\mu$m, it is slightly higher than the fluxes claimed from the COBE/DIRBE and Two-Micron All-Sky Survey (2MASS) measurements (Cambray et al. 2001; Wright 2001). Note that for the primary (unabsorbed) differential gamma-ray spectrum with a
Figure 2. Upper panel: attenuation factor calculated for a power-law distribution of target photons with a low-energy cut-off: $n_{ph} \propto \varepsilon^{-2}$ for $\varepsilon < \varepsilon_{1}$ and $n_{ph} = 0$ for $\varepsilon > \varepsilon_{1}$. Solid curves: $\varepsilon_{1} = 1 \text{ eV}$ and dashed curves: $\varepsilon_{1} = 10^{-3} \text{ eV}$. The three different optical depth are shown: $\tau_{\text{max}} = 6$ (a, red lines), 3 (b, green lines) and 0.5 (c, blue lines). Bottom panel: variations of the local photon index of the gamma-ray spectrum. (See the electronic version of the paper for a colour version of this paper.)

Figure 3. Internal and intergalactic absorption of gamma-rays. Upper panel: attenuation factors. The internal absorption is calculated for a Planckian distribution of target radiation with temperature $T = 5 \times 10^{4} \text{ K}$. The four dashed curves correspond to the internal optical depths $\tau_{\text{max}} = 6$ (a, red lines), 3 (b, green lines), 0.5 (c, blue lines) and 0 (d, black lines). The corresponding solid curves include both the internal and intergalactic absorption. The intergalactic absorption is calculated for a source at $z = 0.186$ (the redshift of the BL Lac object 1ES 1101–232), assuming a reference shape of the EBL spectrum close to the one calculated by Primack et al. (2005), and normalized to the EBL flux at $2 \mu \text{m}$: $h_{\text{EBL}} (2.2 \mu \text{m}) = 16 \text{ nW m}^{-2} \text{ sr}$. Bottom panel: variation of the local photon index. (See the electronic version of the paper for a colour version of this paper.)
Generally, it is believed that the internal absorption leads to the reduction of the corresponding apparent gamma-ray flux, which, in fact, is not far from the TeV sensitivity, especially at multi-GeV energies, should provide the first effective probes of TeV blazars in the MeV/GeV domain in general, and for the ‘internal gamma-ray absorption’ scenario, in particular.

Finally, in the case of hadronic origin of TeV gamma-rays produced at pp and/or pv interactions, the flux of accompanying TeV neutrinos, which freely penetrate through the internal and extragalactic radiation fields, can be as high as $10^{−10}$ neutrinos cm$^{−2}$ s$^{−1}$, i.e. above the detection threshold of the next generation km$^{3}$ scale neutrino detectors. The detection of both gamma-rays and neutrinos from TeV blazars, and the comparison of fluxes of these two components of radiation would provide principal information about the high-energy processes in blazars as well as about the attenuation of gamma-rays due to the (combined) internal and intergalactic absorption. An additional information about the internal photon–photon absorption alone (separated from the extragalactic absorption) is contained in the radiation of secondary (pair-produced) electrons.

3 RADIATION OF SECONDARY ELECTRONS

The propagation of high-energy gamma-rays through a low-energy photon field cannot be reduced to the simple effect of absorption. When the gamma-ray photon is absorbed, its energy is transferred to the electron–positron pair. The secondary electrons interacting with the ambient magnetic and radiation fields produce high-energy photons, either via synchrotron radiation or IC scattering. The synchrotron photons are produced with much smaller energies, thus they do not interact with the background low-energy photons. In a target field with narrow-spectral distribution, IC scattering of the photo-produced electrons proceeds in the Klein–Nishina limit; the upscattered photon receives the major fraction of the electron energy, thus is able to interact again with background photons. The second generation pairs again produce gamma-rays, thus an electromagnetic cascade develops.

While the energy of gamma-rays interacting with EBL dissipates in the intergalactic medium, and in this way contributes to the diffuse extragalactic background radiation, the secondary radiation caused by internal absorption may accompany the primary (unabsorbed) fraction of gamma-rays. In this regard, the development of an electromagnetic cascade is not a desirable process, because it

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1 The detected gamma-ray flux around 200 GeV is an order of magnitude larger than at 1 TeV; however, because of the dramatic reduction of the absorption effect, the contribution of low energies to the (absorption corrected) apparent luminosity, is relatively small.
Abstract

This paper presents a detailed analysis of the production and absorption of gamma-rays in blazar-like sources. It explores the relationship between the primary gamma-ray spectrum and the internal absorption within these objects, focusing on the role of synchrotron radiation and pair production. The authors use theoretical models to predict and compare the observed gamma-ray spectra with the expected spectra from different internal absorption scenarios.

Key findings include:

1. The development of pair cascades significantly affects the gamma-ray spectrum, washing out absorption features.
2. The energy density of the magnetic field plays a crucial role in determining the gamma-ray spectrum.
3. The contribution from the foreground cascade radiation is shown to be significant, with up to 100 times larger than the energy density of the magnetic field.
4. The condition for suppression of the cascade component is derived, based on the energy density of the magnetic field and the absorption depth.

The implications of these findings are discussed in the context of blazar models, with a particular focus on TeV blazars and SSC models.

Introduction

The gamma-ray spectra measured from blazars are often described as ‘hard’, with a characteristic spectrum of $\propto E^{-2}$ above a few tens of GeV. The origin of such strong gamma-rays is attributed to the acceleration of electrons in the relativistically moving source and their subsequent synchrotron or inverse-Compton emission. The gamma-ray spectrum is therefore a convolution of the primary spectrum with the energy loss function of the accelerated electrons, including synchrotron cooling and absorption processes.

In this work, we present an analytical treatment which allows us to calculate the gamma-ray spectrum in blazars in the absence of external absorption and internal absorption (pair cascades). This approach is justified by the small size of the gamma-ray production region in blazars, where the optical depth exceeds the energy density of the magnetic field, i.e. $\tau_{\gamma\gamma} \gg \delta B/\delta T$. The absorbed fraction of gamma-rays is given in the form: $dN/dE \propto E^{-\gamma} \exp(-E/E_0)$, where $E_0$ describes the energy density of the magnetic field, $\gamma_j$ is determined by the energy density of radiation, $B^2/8\pi \geq 3kT\gamma_j$, or $B \geq 0.4(R/10^{17}\text{cm})^{-1/2}\gamma_j$. GeV. The implications of such a strong magnetic field for the primary gamma-ray production mechanism are discussed in Section 4.

In Fig. 6, the broad-band SED of the radiation initiated by absorption of primary gamma-rays with a power-law spectrum $dN/dE \propto E^{-\gamma}$ is shown, assuming that the absorption of gamma-rays takes place inside the source (gamma-ray production region) for two values of the magnetic field: $B = 100 \text{G}$ (solid curves) and $B = 0.1 \text{G}$ (dashed curves). Calculations are performed for the case $\gamma_j = 1$ (no bulk motion). The implications of such a strong magnetic field for the primary gamma-ray production mechanism are discussed in Section 4.

(i) Absorption of gamma-rays outside the production region.

In this case, the ‘foreground’ cascade radiation cannot screen the unabsorbed fraction of gamma-rays. Indeed, although the energy in the cascade radiation exceeds, by a factor of 100, the energy of the unabsorbed fraction of primary radiation, the observer may not see the primary radiation, which is dominated by synchrotron cooling.

Thus, the condition of suppression of the cascade component is derived, based on the energy density of the magnetic field and the absorption depth.

(ii) Secondary electrons cooled through synchrotron radiation.

This condition can be satisfied if the energy density of the magnetic field exceeds the energy density of radiation $B^2/8\pi \geq 3kT\gamma_j$, or $B \geq 0.4(R/10^{17}\text{cm})^{-1/2}\gamma_j$. GeV. The implications of such a strong magnetic field for the primary gamma-ray production mechanism are discussed in Section 4.
The position of the synchrotron peak depends, in a quite interesting way, also on the Lorentz and Doppler factors of the source. While in the standard models of blazars, the Doppler effect shifts the overall SED towards higher energies by a factor of $\delta_j$, in the ‘gamma-ray absorption’ scenario this synchrotron peak is shifted towards lower energies (see Fig. 7). The reason is quite simple. In the frame of the relativistically moving source illuminated by an external radiation with a characteristic energy $\bar{\epsilon}$, the electrons are produced with energies $E_{\min} \geq m_e c^2 \epsilon_j / (\gamma_j T)$, thus the position of the synchrotron peak in the frame of the observer is proportional to $\delta_j E_{\min} \propto \delta_j \gamma_j^2$. Thus, in a source moving towards the observer at a small angle, the position of the synchrotron peak in the frame of the observer is inversely proportional to the Doppler factor $\delta_j$, just opposite to the spectrum of gamma-rays which is shifted towards higher energies by the same Doppler factor.

The position of the synchrotron peak depends strongly also on the average energy (or temperature) of the target radiation field. Indeed, with an increase of the temperature of background radiation $T$, the threshold of photon–photon interactions, and consequently the minimum energy of produced secondary electrons decreases as $E_{\min} \propto 1/T$, and hence the synchrotron peak moves towards lower energies as $h\nu_{\min} \propto 1/E_\gamma^2 \propto 1/T^2$. Generally, the position of the synchrotron peak of pair-produced electrons depends on the temperature of the target radiation field, the magnetic field and the Doppler and Lorentz factors of the jet, as

$$h\nu_{\min} \propto BT^{-2} (\delta_j \gamma_j^2) .$$

It is easy to derive a simple analytical expression which described the high-energy part of the synchrotron spectrum, $h\nu \gg h\nu_{\min}$, produced by electrons for which the source becomes optically thin, $\tau(E) \leq 1$. In this case, the production spectrum of electrons $Q(E) \propto 1/\epsilon N_\epsilon / d\epsilon$ (here, we ignore the weak logarithmic term in the photon–photon interaction cross-section). Then, for the power-law gamma-ray spectrum, $dN_\gamma / d\epsilon \propto E^{-\Gamma_\gamma}$, the cooled electron spectrum is also power law, $dN_e / d\epsilon \propto E^{-\Gamma_e - 2}$, and correspondingly the SED of synchrotron radiation, $\nu F_\nu \propto \nu^{-\Gamma_\gamma + 2}$ for example. For $\Gamma_\gamma = 2$, the SED of synchrotron radiation is rather steep, $\nu F_\nu \propto \nu^{-1.5}$. In fact, because of the cut-off in the gamma-ray spectrum, the high-energy tail of synchrotron radiation is expected even steeper. This is demonstrated in Fig. 8 where the broad-band SEDs of radiation initiated by gamma-rays in a source at $z = 0.186$ are...
shown. It is assumed that gamma-rays in the frame of the jet moving with a Lorentz factor $\gamma_J = 10$ have a power-law distribution with an exponential cut-off at 1 TeV, $dN/\Delta E \propto E^{-3/2} \exp(-E/1\text{ TeV})$. It is also assumed that $\delta J = \gamma J$ (i.e. the viewing angle is $\theta \approx 6^\circ$). The calculations are performed for two temperatures of the radiation field through which the jet propagates $-T = 5 \times 10^4$ and $5 \times 10^5$ K, assuming that in both the cases the optical depth inside the moving gamma-ray production region (the blob) with a homogeneous magnetic field is $\tau_{\text{max}} = 3$. Finally, for the intergalactic absorption, a ‘template’ EBL spectrum is assumed with a normalization at 2.2 $\mu$m at the level of 16 $\text{mW m}^{-2} \text{s r}$. The impact of the temperature on both the spectrum of arriving gamma-rays and the synchrotron radiation of secondary electrons is clearly seen. Note that while below 100 GeV the deformation of the primary gamma-ray spectrum is caused mainly by internal absorption, the sharp cut-off at energies above 10 TeV is due to the severe intergalactic absorption. In the intermediate-energy range between 100 GeV and 10 TeV, the internal and intergalactic photon–photon interactions ‘operate’ together resulting in a quite specific broad-band SEDs. The discussion of implications of these results for specific astrophysical objects is beyond the scope of this paper. We note only that our preliminary studies show that the suggested model, in general, can satisfactorily explain the observed broad-band SEDs of TeV blazars.

4 DISCUSSION

The energy spectra of VHE gamma-rays from blazars, after correction for intergalactic absorption, generally appear very hard, even for the minimum flux level of EBL determined by the integrated light of resolved galaxies at optical (Hubble) and IR (Spitzer) wavelengths. A slight deviation from the robust lower limits of EBL leads to unusually hard intrinsic gamma-ray spectra which cannot be easily explained within the standard particle acceleration and radiation models. In this paper, we suggest a scenario which can lead to the formation of intrinsic gamma-ray spectra of arbitrary hardness without introducing modifications in the particle acceleration models. The main idea is that the gamma-rays before they leave the source suffer significant internal energy-dependent absorption due to the interactions with the ambient low-frequency photons. The existence of dense radiation fields of different origin in blazars (see e.g. Urry & Padovani 1995; Celotti, Fabian & Rees 1998), combined with the large photon–photon pair production cross-section, makes this scenario quite natural and effective, in particular in the compact cores of blazars. For the formation of hard VHE gamma-ray spectra, the target radiation field must have a rather narrow-spectral distribution or a sharp low-energy cut-off, with a typical energy of photons of about 1 to 10 eV. Formally, for a very large optical depths, this process can provide an arbitrary hardness of gamma-ray spectra, though at the expense of a significant increase in the required non-thermal energy budget. However, as long as the current blazar models require relativistically moving gamma-ray production regions with large Doppler factors, $\delta J \geq 30$, and perhaps even more (Aharonian et al. 2007b; Begelman et al. 2008), the available energy budget seems to be not a critical issue. Moreover, even a rather moderate internal absorption is sufficient to provide a significant hardening effect (see Fig. 3).

The unavoidable feature of the proposed model is the radiation of secondary electrons via synchrotron or IC scattering. If the optical depth inside the gamma-ray production region is small, $\tau \ll 1$, e.g. the gamma-ray source is much smaller than the external source of optical photons, the secondary electrons are produced and radiate mainly outside the gamma-ray production region. Even in the case of heavy absorption of gamma-rays, the secondary radiation of secondary electrons can hardly be detected. Indeed, since the intrinsic gamma-ray luminosity is relatively modest, and the absorbed energy is re-radiated as an isotropic source, the lost of the beaming factor dramatically reduces the signal compared to the primary (Doppler-boosted) radiation.

The picture is dramatically changed when the gamma-ray source moves through a very dense photon field, such that the optical depth inside the source becomes larger than 1. In this case, the main fraction of the absorbed energy is released in the form of secondary electrons inside the gamma-ray production region, and thus the radiation of the secondary electrons profits, as the primary gamma-radiation does, from the Doppler boosting. The secondary electrons are cooled through synchrotron and/or IC channels. The latter in fact proceeds via development of pair cascades as long as the typical energies of electrons or gamma-rays and the energy of target photons $\varepsilon E_{\gamma'} \gg m_e^2 c^2$. The cascade, however, diminishes the energy-dependent absorption features, thus the model becomes effective when the electrons are cooled predominantly via synchrotron radiation, i.e. $B^2/8\pi \tau \geq u_e u_\gamma^2$ (here, $u_e$ is the energy density of target photons in the lab frame). The energy density of the radiation $\varepsilon = \delta n_{\text{ph}}$ with an average energy of target photons of about $\bar{\varepsilon} \sim 1$ eV may be linked to the value of $\tau_{\text{max}}$, thus for the effective suppression of the cascade

$$B \geq \left( \frac{40 \pi \delta \tau_{\text{max}} \gamma_{\gamma'}^2}{\sigma T R} \right)^{1/2} \approx 0.5 \text{ G} \left( \frac{\tau_{\text{max}}^{1/2} \gamma_{\gamma'}}{10} \right) \left( \frac{R}{10^{18} \text{ cm}} \right)^{-1/2}. \quad (4)$$

Thus, the magnetic field exceeding 1 G should be sufficient to prevent the cascade. For such magnetic fields, the synchrotron radiation of secondary electrons appears in the optical to hard X-ray energy bands. Depending on the optical depth, the synchrotron peak can be higher than the gamma-ray peak. Interestingly, unlike the classical ‘synchrotron/IC models’, where the ratio of the synchrotron to IC peak is determined by the ratio of $u_e/u_\gamma$; in the ‘internal gamma-ray absorption’ scenario, the synchrotron peak does not strongly depend on the magnetic field. Whether this scenario can be applied to the broad-band SEDs of gamma-ray blazars, is an interesting issue which requires special dedicated studies.

Finally, we want to discuss briefly the radiation mechanisms of primary gamma radiation. Generally, the model does not give a preference to the leptonic or hadronic origin of radiation, unless the magnetic field exceeds the estimate given by equation (4). In this case, the synchrotron-to-IC flux ratio produced by directly accelerated electrons would be too high, especially after the internal absorption of gamma-rays, contrary to the detected SEDs of most of the TeV blazars.

Large magnetic fields in the gamma-ray production region, typically $B \geq 1$ G, would favour gamma-ray production by relativistic protons, with all advantages and disadvantages common for hadronic models. The basic problem of hadronic models is linked to the low-interaction rates which do not allow the most natural explanation of the observed fast gamma-ray variability of blazars in terms of radiative cooling. For example, in the case of interactions of protons with the ambient plasma with number density $n$, the characteristic time of $pp$ interactions with production of $\pi^0$-mesons is

2 Unless the electrons are produced in an environment with a very low magnetic field, and thus are cooled via IC scattering before any notable deflection.
\( t_{pp} \approx 10^{15} \text{s} \). Thus, in order to explain the variability of gamma-rays as short as several minutes like the TeV flares observed from PKS 2155–304 and Mkn 501, the density of plasma should be as large as \( 5 \times 10^2 \delta_i^2 \text{cm}^{-3} \) which implies a very large source and correspondingly huge kinetic energy \( E_{kin} = (4/3)\pi l^2 m_p c^2 \gamma_j \approx 10^{50} \text{erg} \) (here, we assume that \( \delta_0 / \gamma_j \)). One may invoke alternative explanations of the variability of blazars, for example, due to the adiabatic losses or escape of particles from the source, but this assumption leads to dramatic reduction of radiation efficiency, and to increase the energy requirements to the accelerated protons.

A similar problem faces the photomeson processes at interactions of protons with the ambient radiation fields. Actually in the ‘internal gamma-ray absorption’ scenario, this mechanisms seems a quite natural choice because the same background photons which absorb gamma-rays can play a role of the target for photomeson interactions. However, because of the small cross-section, the efficiency of this process appears quite low. The interaction time of protons with energy, \( E \geq 200 \text{MeV}/(\epsilon/\gamma_j) \approx 2 \times 10^{16} (\epsilon/1 \text{eV})^{-1} (\gamma_j/10^{-1})^{-1} \text{eV} \) (in the frame of the moving source with a Lorentz factor \( \gamma_j \)) is estimated \( t_{pp} \approx l/1(f \sigma_{pp}/\hbar c) \) (\( \sigma_{pp}/\sigma_\gamma \approx 1/\gamma_j^2 \gamma_j^2 \gamma_j = \approx \sigma_{ph}/r_{\text{max}} \approx 10^{-28} \text{cm}^2 \) is the average cross-section and \( f \approx 0.2 \) is the multiplicity of the process). Thus, we can see that during the passage of the source of optical photons of size \( R \), the protons transfer only \( \sigma_{pp}/\sigma_\gamma \approx 10^{-3} \) fraction of their energy to gamma-rays. If such a low energy can be compensated by very large Doppler boosting (e.g. assuming \( \delta_j / 100 \)), this channel can provide very large fluxes of neutrinos, which unlike gamma-rays do not suffer internal and extragalactic absorption. In the case of attenuation of VHE gamma-ray fluxes by two to three orders of magnitude, the expected fluxes of neutrinos from TeV blazars can be as large as the detection threshold of the \( km^2 \) volume high-energy neutrino telescopes, \( F_{\nu} (\geq 1 \text{ TeV}) \approx 10^{-11} \text{neutrinos cm}^{-2} \text{s}^{-1} \).

It is interesting to note that, because of the threshold of photomeson production, the interactions of protons of arbitrary distribution with a narrow-band radiation with a characteristic energy \( \epsilon \), result in a differential gamma-ray spectrum which below the energy \( \approx 10^{10} (\epsilon/1 \text{TeV})^{-1} \text{eV} \) is extremely hard, \( dN/dE = \text{constant} \), thus this process itself can provide very hard gamma-ray spectra independent of the spectrum of parent protons.

Despite certain attractive features, this mechanism faces the same problem as \( pp \) interactions – a low radiation efficiency. Therefore, it can work only under conditions of extremely large Doppler boosting of radiation. The efficiency of VHE gamma-ray production can be much higher in the case of synchrotron radiation of protons, provided that the acceleration of protons proceeds at a rate close to the fundamental limit, and the magnetic field in the proton accelerator well exceeds \( 10 \text{ G} \). In particular, in the magnetic field of the order of \( 100 \text{ G} \), protons can be accelerated to energies \( 10^{20} \text{eV} \) and thus can produce VHE synchrotron gamma-rays on time-scales of \( 10^4 \) s. Although due to the self-regulated synchrotron cut-off (Aharonian 2000), the spectrum of gamma-rays is limited by subGeV energies, an observer detects Doppler-boosted gamma-radiation extending to multi-GeV energies. The characteristic features of this mechanism are the very large electromagnetic energy contained in the blob, \( l B^2 / 6 \approx 2 \times 10^{48} \text{erg} \) (here \( l \) is the linear size of the blob), hard X-ray emission of the secondary (pair-produced) electrons and negligible fluxes of neutrinos.

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