On the origin of highest energy gamma-rays from Mkn 501

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Abstract. The spectra of very high energy γ-radiation observed from distant extragalactic objects suffer significant deformations during the passage of primary γ-rays through the intergalactic medium. The recently reported fluxes of diffuse infrared background radiation indicate that we detect, most probably, heavily absorbed TeV radiation from BL Lac objects Mkn 421 and Mkn 501, especially at energies above 10 TeV. This implies that the source spectrum of Mkn 501 corrected for the intergalactic absorption may contain a sharp pile which generally contradicts to the predictions of current models of TeV emission of BL Lac objects, and thus leads to the so-called “IR-TeV crisis”. To overcome this difficulty, in this paper we study two possibilities assuming that (i) the TeV γ-rays from Mkn 501 have a secondary origin, i.e. are formed during development of electron-photon cascades in the intergalactic medium initiated by primary γ-rays; (ii) the pile-up in the source spectrum is a result of comptonization (in deep Klein-Nishina regime) of ambient optical radiation by the ultrarelativistic cold conical outflow (jet) with bulk motion Lorentz factor Γ₀ ≥ 3.3 × 10⁷. We show that the first hypothesis cannot reproduce the spectral shape of the TeV emission from Mkn 501. At the same time we demonstrate that the inverse Compton radiation of the ultrarelativistic cold jet hypothesis can quite satisfactorily explain the unusual spectral features of the “reconstructed” TeV radiation. We briefly discuss the astrophysical implications of this hypothesis.

Key words. galaxies: BL Lacertae objects: individual: Mkn 501 – cosmology: diffuse radiation – gamma rays: observations – gamma rays: theory

1. Introduction

The cosmic background radiation (CBR) at infrared to ultraviolet wavelengths carries crucial cosmological information about the galaxy formation epochs. It is believed that this radiation basically consists of two emission components produced by stars and partly absorbed and re-emitted by dust during the entire history of evolution of galaxies. Consequently, two distinct bumps in the spectrum of red-shifted radiation at near infrared (NIR) λ ~ 1 – 2 µm and far infrared (FIR) λ ~ 100 – 200 µm wavelengths, and a mid infrared (MIR) “valley” between these bumps are expected (?, see e.g. ) dwek/::iv:1998, primack/:1999, pei/:1999, silk/devriendt:2000, malkan/stecker:2000, hauser/dwek:2001,franceschini/:2001.

Direct measurements of CBR contain large uncertainties because of heavy contamination caused by foregrounds of different origin (? for review see) hauser/dwek:2001. Gamma-ray astronomy offers a complementary approach to derive information about CBR. Although this method requires certain model assumptions about the primary (un-absorbed) spectrum of γ-rays, it has an adequate potential for robust conclusions concerning the absolute flux and the spectrum of CBR. Moreover, the study of angular and spectral properties of γ-radiation from predicted giant electron-positron halos surrounding powerful nonthermal extragalactic objects like AGN and radiogalaxies with known redshifts (?) can provide a unique tool to “measure” unambiguously the broad-band spectrum and the absolute flux of CBR at different cosmological epochs, and thus to probe the evolution of galaxies in past.

The spectra of high energy (E ≥ 10 GeV) γ-radiation observed from distant extragalactic objects suffer significant deformation during their passage through the intergalactic medium due to interactions of primary γ-rays with CBR (??). The absorption features in the γ-ray spectra depends on the flux of CBR, thus the study of such features from extragalactic objects with firmly established distances could yield important constraints on CBR. Strictly speaking, this approach requires good understanding of the source spectra of γ-rays from ensemble of sources located at different cosmological distances.
Otherwise, the conclusions based merely on $\gamma$-ray observations from a single source would be essentially model-dependent, and therefore would permit different interpretations concerning both the intrinsic $\gamma$-ray spectrum, and the flux of CBR.

Presently we do face such an ambiguity, when trying to interpret the multi-TeV $\gamma$-ray emission of Mkn 501 observed during its remarkably strong and long flare in 1997 (??). The only definite conclusion which can be drawn from these observations is that we see, most probably, significantly absorbed TeV radiation, especially at energies above 10 TeV, for which the optical depth could be as large as 10 (??). Moreover, a non-negligible absorption may take place already at low, sub-TeV energies (??). However, the analysis of the intergalactic absorption at sub-TeV and multi-TeV parts of the spectrum of Mkn 501 leads to two essentially different conclusions. The absorption-corrected $\gamma$-ray spectrum at low energies, based on the CBR fluxes reported at 2.2 and 3.5 $\mu$m (???) and on the current theoretical predictions for NIR (??, see e.g.,)primack/2001, is in a general agreement with the Synchrotron-self-Compton (SSC) model of X- and TeV radiation of Mkn 501 (??, see e.g.,)guy/2000, krawczynski/coppi/2000, primack/2001. On the other hand, the corrections to the $\gamma$-ray spectrum at energies above 10 TeV based on the unexpectedly large CBR fluxes detected by COBE at 140 and 250 $\mu$m (???) result in an "unreasonable" source spectrum. Namely it implies a source spectrum which sharply curves up above 10 TeV, unless we assume that the CBR flux at MIR between 10 and 50 $\mu$m is quite low (a few nW/m²sr), and at longer wavelengths it increases rapidly ($\nu F_\nu \propto \lambda^\alpha$ with $s \geq 2$) in order to match the COBE points (??). Even so, the large DEBRA fluxes at 140 and 250 $\mu$m imply very flat "reconstructed" source $\gamma$-ray energy distributions (SED), $\nu S_\nu = E^\alpha \frac{dN}{dE} = E^{2-\alpha}$ with photon indices $\alpha \leq 2$. Such flat source spectra extending beyond 10 TeV require, within SSC models, rather unconventional jet parameters, namely very large Doppler factors and very small magnetic fields (H. Krawczynski and P. Coppi, private communication: J. Kirk, private communication).

A real trouble arises, however, when we take into account the recent claims about detection of CBR flux at 100 $\mu$m (??), and especially at 60 $\mu$m (??). If we refer the reported fluxes to the truly diffuse extragalactic background radiation, then a little room would be left for speculations concerning the spectral shape of CBR in order to prevent the "unreasonable" $\gamma$-ray source spectrum. This implies that we should accept the existence of a sharp pile-up in the spectrum of TeV radiation. Motivated by such a non-standard spectral shape of TeV-radiation, recently several extreme assumptions have been made in order to overcome the "IR background – TeV gamma-ray crisis" (??). In particular, (?) suggested an intriguing hypothesis that the HEGRA highest energy events are due to Bose-Einstein condensations interacting with the atmosphere, and proposed a test to inspect this hypothesis by searching for peculiar features of showers detected by HEGRA in the direction of Mkn 501. Subsequently, the HEGRA collaboration has demonstrated (?) that the detected shower characteristics are in fact in good agreement with the predictions for the events initiated by ordinary $\gamma$-rays. Another, even more dramatic hypothesis – violation of the Lorentz invariance – has been proposed by several authors (??, see e.g.)coleman/glashow:1999, kifune:1999, kluzniak:1999, alonso/camelia/piran:2001, protheroe/meyer:2000 to solve this problem. We may add to the list of "exotic" solutions of the "IR background – TeV gamma-ray crisis" a less dramatic, in our view, hypothesis, assuming that Mkn 501 is located at a distance significantly less than 100 Mpc – a good news for the advocates of non-cosmological origin of some of AGN and quasars (??, see e.g.)hoyle/burbidge:1996, arp/1997.

Although very fascinating, it seems to us too premature to invoke such dramatic revisions of essentials of modern physics and astrophysics. The nature of the FIR isotropic emission detected by COBE is not yet firmly established, and it is quite possible that the bulk of the reported flux, especially below 100 $\mu$m, is a result of superposition of different local backgrounds. Needless to say, that this would be the simplest solution of the problem (??). In this paper we adopt, however, that the reported FIR fluxes have universal (extragalactic) origin. This implies that we adopt the existence of a pronounced pile-up in the $\gamma$-ray spectrum of Mkn 501 above 10 TeV, but try to find an explanation of this spectral feature within the framework of new but yet conventional astrophysical scenarios. In this paper we propose and study two potential ways to overcome the "IR background – TeV gamma-ray crisis":

(1) TeV $\gamma$-rays from Mkn 501 are not direct representatives of primary radiation of the source, but have a secondary origin, i.e. they are formed during the development of high energy electron-photon cascades in the intergalactic medium initiated by interactions of primary $\gamma$-rays with diffuse extragalactic photons. This hypothesis implies a rather extreme assumption concerning the strength of the intergalactic magnetic field on $\geq 1$Mpc, $B \leq 10^{-18}$ G.

(2) The "reconstructed" source spectrum of Mkn 501 with a flat (almost constant) SED below 10 TeV, and a pile-up beyond 10 TeV, is partly or entirely produced by monoenergetic ultrarelativistic beam of electrons due to the inverse Compton scattering in deep Klein-Nishina regime. In order to avoid significant radiative (synchrotron and Compton) losses, which otherwise would result in an equilibrium, $E^{-2}$ type differential spectrum of electrons, we assume that such a beam of electrons in fact is a cold, conical kinetic-energy dominated ultrarelativistic wind with the bulk Lorentz factor $\Gamma_0 \sim 4 \times 10^7$ formed beyond the accretion disk of the central black hole. Apparently this hypothesis implies non-acceleration origin of highest energy $\gamma$-rays detected from Mkn 501.
2. Absorption of gamma-rays in CBR

The reported fluxes and flux upper/lower limits of CBR from optical/UV to far IR wavelengths are shown in Fig. 1. The reliability and the implications of these measurements are discussed in the recent review article by [?]. The level of the spectral energy distribution (SED) of CBR at optical/NIR wavelengths with the “best guess estimate” between 20 and 50 nW/m²sr is comparable with the overall energy flux of FIR of about 40-50 nW/m²sr (?). This indicates that an essential part of the energy radiated by stars is absorbed and re-emitted by dust in a form of thermal sub-mm emission. Currently the information at mid-infrared wavelengths is very limited. The only available measurement at 6 and 15 µm on Fig. 1 derived from the ISO CAM source counts (?) shown in Fig. 1 should be treated as a lower limit. In Fig. 1 we show also a slightly higher flux estimate at 15 µm reported by (?). Therefore the flux estimate at the level of ≃ 2–3nW/m²sr (?) as well as the lower limits based on the IRAS counts at 25-100 µm (?) do not allow firm conclusions about the depth of the MIR “valley” dominated by radiation of the warm dust component. Consequently, it does not provide sufficient information for definite predictions regarding the slope of the spectrum in the most crucial (from the point of view of absorption of ≥ 10 TeV γ-rays) MIR-to-FIR transition region.

As long as the available measurements of CBR do not allow a quantitative study of the effect of absorption of γ-rays in the intergalactic medium, we can rely only on model predictions or on the “best guess” shape of the CBR spectrum. In this regard we notice that the reported high FIR fluxes present a common problem for all current CBR models. Therefore, if one adopts that the reported FIR fluxes have truly diffuse extragalactic origin, an essential revision of the CBR models is needed in order to match the data. Such an attempt has been made recently by (?), who showed that their semi-analytical approach, with a reasonable adjustment of some model parameters, and using the empirical dust emission templates of (?), can match the reported FIR fluxes.

In Fig. 1 we present a template of the CBR spectrum which fits all reported fluxes or upper/lower limits of CBR (including, within 2-σ uncertainty, the 60 µm point), and the same time has a general shape close to the prediction of the current theoretical models in all 3 principal – optical/NIR, MIR and FIR – bands of CBR. Actually this idealized smooth template of CBR spectrum (hereafter Model III; the dashed line in Fig. 1) is quite similar to the CBR spectrum shown in Fig. 1 of (?) based on their reference model for IR galaxy evolution, as well as to some of the recent theoretical models of (?). It has a rather flat shape in the MIR- to-FIR transition region, νFν ∝ λα with s ≤ 1. This results in short mean free paths of γ-rays above 10 TeV (L ≤ 50 Mpc; see Fig. 2), and consequently in a sharp pile-up in the reconstructed γ-ray source spectrum (see Fig. 3) determined as:

\[ J_\text{obs}(E) = J_\text{obs}(E) \exp[\tau(E)], \]

where \( J_\text{obs} \) is the observed γ-ray spectrum, \( \tau(E) = d/L(E) \) is the intergalactic optical depth, and \( d \) is the distance to the source.

If we adopt that the reported FIR fluxes correctly describe the level of truly diffuse background radiation, only two ways are left for reduction of the effect of attenuation of ≥ 10 TeV γ-rays: (i) an ad hoc assumption of the CBR flux at wavelengths between 10 and 60 µm at the marginally acceptable (i.e. the ISO CAM low-limit) level, but with very rapid rise beyond 60 µm in order to match the reported fluxes at FIR, and (ii) adopting for the Hubble constant \( H_0 \approx 100 \text{ km/s Mpc} \), i.e. the assuming the smallest possible distance to Mkn 501 \( d = cz/H_0 = 102 \text{ Mpc} \) (\( z = 0.034 \)).

In Fig. 1 we show 2 other model spectra of CBR (solid line – Model I, dotted line – Model II) which fit the data at NIR and FIR, but at the same time allow minimum intergalactic γ-ray absorption, because both spectra are forced to be at the lowest possible level at MIR- to-FIR transition region set by the ISO CAM lower limit at 15 µm. At optical/NIR wavelengths we assumed for both models an approximation which coincides with the Model - III.

The CBR fluxes above 140 µm are approximated by the function suggested by (?). Below 140 µm for both I and II Models we assume the same spectral shape described by Planckian distribution. Such spectra should be considered as a lower limit, because in the most critical MIR-FIR transition region near 60µm it is essen-

![Fig. 1. Cosmic background radiation. The reported fluxes are shown with filled symbols: (?) – diamonds, (?) – circles, (?) – squares, (?) – triangles. The low limits are shown by open symbols: (?) – diamonds, (?) – triangle, (?) – circles, (?) – squares. The CBR models are shown by solid line – Model I, by dotted line – Model II, by dashed line – Model III, by dot-dashed line – Model IV (for details see the text).](image-url)
Fig. 2. Mean free path of $\gamma$-rays for 4 different models of the CBR spectrum: solid line – Model I, dotted line – Model II, dashed line – Model III, dot-dashed line – Model IV. The horizontal lines indicate the distances to Cen A, M87, Mkn 501, and 3C 273 ($H_0 = 60$ km/s Mpc).

Fig. 3. Spectral Energy Distribution (SED) of Mkn 501. The experimental points (filled circles) correspond to the time-averaged spectrum of Mkn 501 during the flare in 1997 (?). The heavy line corresponds to the fit to this data in the form of Eq. (2). The star correspond to the flux in the highest energy bin around 21 TeV obtained after the reanalysis of the same data set but with improved energy resolution (?). The vertical line at 17 TeV indicates the edge of the spectrum of Mkn 501 measured by HEGRA with high statistical significance. The solid, dotted, dashed and dot-dashed lines represent the reconstructed (absorption-corrected) spectra of $\gamma$-rays for the CBR Models I, II, III and IV, respectively ($H_0 = 60$ km/s Mpc).

1 Note that somewhat different CBR models with more complex spectral shapes can also result in a flat, $E^{-2}$ type power-law absorption-corrected $\gamma$-ray spectrum (?), see e.g.) coppi/aharonian:1999, konopelko/:1999.
CBR, as well as the FIR spectra of nearby galaxies, if we take into account that the bulk of the integrated extragalactic background most probably have been generated recently, at \( z < 1 \) (??). In particular, the shape of the Model II contradicts to the average SED of the ISOCAM sources which not only contribute a dominant fraction in the CBR at MIR, but are likely are major contributors to CBR at longer wavelengths (?).

All current CBR models fail to explain the the reported flux at 60 µm. If this point, however, represents the truly diffuse flux, we must assume a spectrum close to the model - I shown in Fig. 1 by the solid line. It should be noticed that the Model I assumes a very steep slope between 30 and 60 µm; a steeper spectrum (i.e. steeper than the Wien tail of the black-body radiation) in this narrow wavelength band hardly could be physically justified. Moreover, already 60 µm photons have sufficient energy for effective interaction with \( \geq 10 \) TeV \( \gamma \)-rays, therefore we cannot suppress anymore the severe \( \gamma \)-ray absorption by speculating about the spectral shape of CBR. This is demonstrated in Fig. 4.

Finally, in Fig. 1 we show one more possible shape of CBR (dot-dashed curve – Model IV) which assumes by a factor of 2-3 higher flux at 15 µm compared with the reported flux based on the ISOCAM source count, and smoothly passes through the low edges of the error bars of the reported fluxes at 100 and 140 µm. Surprisingly such a high at MIR spectrum does not result in an unusual \( \gamma \)-ray spectrum as long as it concerns the energy region below 10 TeV. Namely, at these energies we obtain an almost single hard power-law \( \gamma \)-ray source spectrum with photon index less than 2. Above 10 TeV we again observe a pile-up which however in this case is less pronounced than in the case of Models I and III.

A \( \gamma \)-ray photon with energy \( E \) propagating trough isotropic photon field can interact, via electron-positron pair production, with ambient photons of energy \( \epsilon \geq \epsilon_{\text{th}} = (m_e c^2)^2/E \simeq 0.26 (E_{\gamma}/\text{1 TeV})^{-1} \) eV or of wavelength \( \lambda = 4.8 (E_{\gamma}/\text{1 TeV}) \) µm. The latter relation is shown in Fig. 4 by solid line. The cross-section of \( \gamma \gamma \) interactions averaged over the directions of background photons peaks at \( \epsilon_{\text{max}} \simeq 3.5 \epsilon_{\text{thresh}} \) with \( \sigma_{\gamma\gamma}^{\text{max}} \simeq (1/4) \sigma_{\gamma} \) (?, see, e.g.)/vassiliev:2000.

Therefore, even for broad, e.g. power-law spectra of background photons, the most contribution to the optical depth \( \tau \) comes from a narrow spectral band of CBR within \( \epsilon_{\text{max}} \pm \Delta \epsilon \) with \( \Delta \epsilon \sim 1/2 \epsilon_{\text{max}} \). However, for typical spectra of CBR with two distinct NIR and FIR bumps and a MIR “valley”, the relative contributions of different spectral intervals of CBR to the optical depth \( \tau_0 \) significantly depend on the energy of the primary \( \gamma \)-ray photon. It is convenient to describe this dependence by the ratio \( \kappa(E, \lambda) = \tau(E, \lambda)/\tau_0(E) \), where

\[
\tau(E, \lambda) = \int_{\lambda}^{\lambda_{\text{th}}} \sigma_{\gamma\gamma}(E, \lambda) n_{\text{CBR}}(\lambda) \, d\lambda,
\]

and \( \tau_0 = \tau(E_{\gamma}, \lambda = 0) \) is the optical depth integrated over the entire spectral range of CBR \( n_{\text{CBR}}(\lambda) \) above the threshold \( \lambda_{\text{th}} \simeq 4.8 (E_{\gamma}/1 \text{ TeV}) \) µm.

In Fig. 4 the contour map of the function \( \kappa(\lambda, E) \). The solid, dotted and dashed lines show the levels of \( \kappa(\lambda, E) \) for the CBR Models I, II, and III, respectively. The heavy solid line represents the threshold of \( \gamma\gamma \) pair production.

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In Fig. 4 the contour map of the function \( \kappa(\lambda, E) \) is shown for 3 different models of CBR in the spectral range of \( \gamma \)-rays from 1 to 100 TeV, and for the CBR photons from 1 to 500 µm. For the given energy of \( \gamma \)-ray photon \( E_0 \), the spectral region of CBR responsible for the fraction \( \xi \) of the total optical depth \( \tau_0 \) is \([\lambda_{\xi}, \lambda_{\text{th}}]\), where \( \lambda_{\xi} \) and \( \lambda_{\text{th}} \) are the abscissas of the points where the horizontal line \( E = E_0 \) intersects the corresponding level curve, and the threshold line, respectively. In Fig. 4 four levels for \( \xi = 10, 50, 90, \) and 99\%, are shown. By definition, \( \xi = 0 \) corresponds to the threshold boundary \( E_{\text{Th}} = 0.21 \lambda_{\gamma} \).

It is seen that at \( E_0 = 17 \) TeV approximately 50 per cent of the total optical depth \( \tau_0 \) is contributed by background photons with wavelengths longer than 50µm. Therefore even the sharp cutoff of the CBR flux below 50µm cannot prevent the large optical depth of 17 TeV \( \gamma \)-rays, as far as we accept that the 60µm flux has a cosmological origin, and reflects the level of CBR at these wavelengths. This is the case of Model I for which the free path of 17 TeV \( \gamma \)-rays is about 20 Mpc, and therefore for the distance to the source of 170 Mpc \((H_0 = 60 \text{ km/s Mpc})\) the optical depth \( \tau_0 \approx 8.5 \). The corresponding absorption factor is so large \((\exp(-8.5) \approx 2 \times 10^{-4})\) that the sharp file-up in the absorption-corrected spectrum becomes unavoidable.

Since the exponent in the absorption factor is very large, even relatively small reduction of the optical depth \( \tau_0 \) may lead to a dramatic suppression of the \( \gamma \)-ray attenuation. In particular, the Model III which has a more
realistic spectral shape at mid infrared wavelengths, and fits the FIR data above 100 \( \mu m \), allows a bit larger (25 per cent or so) free paths at highest energy \( \gamma \)-rays. This makes the pile-up less pronounced, but still cannot eliminate it completely. Only the Model II gives a conventional, \( E^{-2} \) type spectrum.

We may reduce the absorption effect furthermore, assuming a larger, although presently less favored value for the Hubble constant, \( H_0 = 100 \text{ km/s Mpc} \). The latter makes smoother the pile-up for the Model I, and almost eliminates it for the Models III and IV. Therefore we may conclude that it is possible, in principle, to avoid the “unwanted” sharp turn-up in the intrinsic \( \gamma \)-ray spectrum of Mkn 501, if we adopt for CBR a model like the Model III, and assume a very large value for the Hubble constant.

Below we discuss, however, possible solutions which allow accommodation of both higher CBR fluxes and more realistic value for the Hubble constant.

3. The effect of cascading in the intergalactic photon fields

Generally, the propagation of high energy \( \gamma \)-rays through a low frequency photon field cannot be reduced to the simple effect of \( \gamma \gamma \) absorption. When a \( \gamma \)-ray is absorbed its energy in fact is not lost. The secondary electrons and positrons create new \( \gamma \)-rays via inverse Compton scattering; the second generation \( \gamma \)-rays produce new \((e^+, e^-)\) pairs, thus an electromagnetic cascade develops. Actually, in the intergalactic space this process is inevitable, and it may significantly contribute to the isotropic (extragalactic) \( \gamma \)-ray background radiation (protheroe/stanev:1996, coppi/aharonian:1997). It is interesting to note that in the energy region of interest the \( \gamma \)-rays and electrons interact with photon fields of different origin. Although the energy density of the 2.7 K cosmic microwave background radiation (CMBR) significantly exceeds the density of other (“starlight” and “dust”) components of background radiation (see Fig. 1), because of the kinematic threshold of the reaction \( \gamma \gamma \rightarrow e^+ e^- \) the \( \gamma \)-rays with energy less than several hundred TeV interact mostly with the infrared and optical background photons. The inverse Compton scattering of electrons does not have kinematic threshold, therefore the electrons interact predominantly with CMBR.

For intrinsic \( \gamma \)-ray spectra harder than \( E^{-2} \) extending to energies \( E \geq 100 \text{ TeV} \), the cascade spectrum at lower energies could well dominate over the primary \( \gamma \)-ray spectrum. On the other hand, the cascade spectrum typically has a standard shape which slightly depends on the primary \( \gamma \)-ray spectrum. This makes rather attractive the idea of interpretation of one of the most remarkable features of the TeV radiation of Mkn 501, namely the surprisingly stable spectral shape of the source in high state, despite dramatic variation of the absolute flux on timescales less than several hours (??)\(^2\). Moreover, as it was noticed by ??, the shape of the TeV spectrum of Mkn 501 given by Eq. (2) reminds the \( \gamma \)-ray spectrum formed during the cascade development in the photon field. Therefore, the quantitative study of this effect presents a definite interest.

We should note, however, that the interpretation of the observed TeV emission from Mkn 501 in terms of the intergalactic cascade radiation requires an extremely low intergalactic magnetic field. Indeed, for the field exceeding \( 10^{-12} \text{ G} \), the \( \gamma \)-rays of the cascade origin should be observed in a form of an extended emission from a giant isotropic pair halo with an angular radius more than several degree (??). Both the detected angular size and the time variability of the TeV radiation from Mkn 501 excludes such a possibility (??). For lower magnetic fields, the cascade \( \gamma \)-rays penetrate almost on a straight line, thus the first argument based on the detected angular size becomes less stringent. Note however that for the distance to the source \( d \geq 100 \text{ Mpc} \) even tiny deflections of the secondary (cascade) electrons by the intergalactic magnetic field lead to non-negligible time delays of arriving \( \gamma \)-rays (??):

\[
\Delta t_{\gamma} \simeq 10(d/170\text{Mpc})(E/1\text{TeV})^{-2}(B/10^{-18}\text{G})^2 \text{ h}
\]  

(4)

This would smear out the observed time variation of the TeV flux on timescales less than several hours (??), unless \( B \leq 10^{-18} \text{ G} \). Although very dramatic, this assumption could not be \textit{a priori} ruled out, especially if we take into account that the typical scale of the so-called intergalactic voids, where the magnetic field could be extremely small, is estimated as \( \sim 120(H_0/100 \text{ km/s/Mpc})^{-1} \text{ Mpc} \) (??), i.e. comparable or larger than the distance to Mkn 501.

For such a low intergalactic magnetic field, we have studied the spectral properties of electromagnetic cascades generated by the primary multi-TeV radiation of Mkn 501 in the intergalactic medium, using a fast numerical method based on the solution of adjoint cascade equations (??). Two processes have been taken into account: electron-positron pair production and inverse Compton scattering. The details of calculations and astrophysical implications will be published elsewhere.

The idea behind the attempt to interpret TeV radiation of Mkn 501 by the intergalactic cascade is the fol-

\(^2\) Note that the spectral change during the strong April 16, 1997 flare reported by the CAT collaboration (??), as well as the noticeable steepening of the spectrum in a low state of Mkn 501, found by the HEGRA collaboration (??) do not contradict to this statement. These effects, in fact, could be caused by variations of the ratio of the “cascade” component to the overall (“unabsorbed” plus “cascade”) flux of \( \gamma \)-rays due to, for example, the increase of the maximum energy in the primary spectrum during strong flares.

\(^3\) Actually, due to non-zero (\( \sim m_e c^2/E \)) emission angles of the secondary products in the \( \gamma \gamma \rightarrow e^+ e^- \) and \( e^+ \rightarrow e^+ \gamma \) reactions, we should expect a non-negligible broadening, and consequently time delays of the cascade radiation even at the absence of magnetic field (??).
The cascade development initiated by primary monoenergetic \(\gamma\)-rays with energy (a) \(E_0 = 10^4\) TeV and (b) \(E_0 = 10^2\) TeV for the CBR Model I. The curves show the number of cascade \(\gamma\)-rays in different energy intervals as a function of the penetration depth.

The number of photons in a given energy band of the cascade spectrum could essentially exceed the number of \(\gamma\)-rays in the absorbed primary \(\gamma\)-ray spectrum. The \(\gamma\)-rays of highest energies during their propagation through the intergalactic photon fields initiate cascade, which produce many lower energy photons, i.e. transfer the energy from the primary highest energy photons to lower energy \(\gamma\)-rays. Thus, the cascade somewhat "move" the source closer to the observer. In order to illustrate this effect, in Fig. 5 and 6 we show the number of cascade \(\gamma\)-rays in 5 energy bands as a function of the penetration depth. In the case of a cascade initiated by monoenergetic primary \(\gamma\)-rays of energy \(E_0\) (Fig. 5), the number of photons in all energy bands sharply increases and reaches its maximum at some distance \(R_*\) which is approximately determined by the condition \(\tau(E_0) \sim 1 \) or \(R_* \simeq L(E_0)\), where \(L(E_0)\) is the mean free path of primary photons. Beyond \(R_*\) the cascade develops more slowly. This stage is characterized by 'competition' between production and absorption processes. While the low energy (0.1 - 0.3 TeV) \(\gamma\)-rays continue to (slowly) grow, the number of higher energy (10-30 TeV) \(\gamma\)-rays drops beyond 10 Mpc, the reason being the lack of the “fuel”, i.e. highest energy particles, which could support further development of the cascade at these energies.

It is interesting to note that the overall picture slightly depends on energy of the primary photon (compare curves in Fig. 5 calculated for \(E_0 = 10^4\) and \(10^2\) TeV). This explains why the spectrum of an well-developed cascade is almost independent of the primary \(\gamma\)-ray spectrum.

The case of the cascade initiated by a broad-band spectrum of primary \(\gamma\)-ray photons is more complicated because the observer detects a mixture of the primary (unabsorbed) and secondary (cascade) \(\gamma\)-rays. Two example of cascades triggered by a \(E^{-2}\) type primary \(\gamma\)-ray spectrum with \(E_{\text{max}} = 10^2\) TeV (dashed lines) and \(E_{\text{max}} = 10^4\) TeV (dot-dashed lines) are shown in Fig. 6. In order to demonstrate the photon excess caused by the cascade development, we show also the evolution of the number of photons calculated for the case of a simple absorption effect, i.e. 

\[
J(E) = J_0 \exp \left[-R/L(E)\right].
\]

In Fig. 7 we show the spectra of cascade \(\gamma\)-rays from Mkn 501, calculated for the Hubble constant \(H_0 = 60\). The spectrum of the source was assumed to be power-law \(J_0(E) \propto E^{-\alpha}\) with \(\alpha = 2\). For softer source spectrum (\(\alpha > 2\)) the most power is radiated in the lower energy band, therefore the cascade has small impact on the resulting spectrum, in particular at low energies around 1 TeV. The optical depth in this spectral range is less than 1, and therefore the detected spectrum near 1 TeV would have a form steeper than \(E^{-2}\); this contradict to observations (???). For hard source spectrum (\(\alpha < 2\)) the most power is radiated in the high energy range, and therefore the resulting spectrum is dominated by the “cascade” component. At energies below 1 TeV, the spectrum of the cascade radiation is very hard with a photon index \(\approx 1.5\). This
The cascade spectra significantly underestimate the both CBR models allow rather good fits below 10 TeV, of TeV radiation of Mkn 501, at least for the CBR Model. Indeed, the high quality data of HEGRA obtained during the high state of the source rule out the “intergalactic cascade” hypothesis, without a need of implementation of the cascade effects. Thus the “intergalactic cascade” hypothesis loses, to a large extent, its significance, given the high price we have to pay for that – the dramatically low (≤ 10^{-18} G) intergalactic magnetic field.

Fig. 7. Cascade spectra initiated by primary γ-rays from Mkn 501. The solid, dotted, and dashed lines correspond to the Model I, Model II, and Model III of CBR, respectively (H_0 = 60 km/s Mpc). The experimental fluxes and the heavy solid line are the same as in Fig. 3.

also contradicts to the observed spectrum of Mkn 501. Therefore in order to fit the TeV spectrum of Mkn 501 by the intergalactic cascade radiation, the primary γ-ray spectrum should have a form close to $E^{-2}$ in order to avoid the strong dominance of the cascade component in the overall spectrum at low energies.

For a narrow, e.g. Planckian type spectrum of field photons, the γ-ray spectrum of (well-developed) cascade radiation has a standard shape with a power low photon index 1.5 at energies $E \ll E^* \simeq 4 m_e^2 c^4/\epsilon$ (where $\epsilon \simeq 3 kT$), and sharp cutoff beyond $E^*$. In the case of broader spectrum of background photons the spectral shape of CBR does play a non-negligible role in formation of the cascade spectrum, especially in the region of the cutoff, the details of which are determined by the function $\tau(E)$. This is seen in Fig. 7, where the presented cascade spectra are calculated for 3 different models of CBR shown in Fig. 1.

The comparison of the cascade spectra with the detected spectrum of Mkn 501 shows that despite the general similarity none of the calculated spectra satisfactorily fit the details of the observed spectrum. Indeed, the high quality data of HEGRA obtained during the high state of the source rule out the “intergalactic cascade” hypothesis of TeV radiation of Mkn 501, at least for the CBR Model I (solid curve) and Model III (dashed curve). Actually both CBR models allow rather good fits below 10 TeV, but the cascade spectra significantly underestimate the γ-ray fluxes above 10 TeV. Calculations show that for the Hubble constant $H_0 = 100$ km/s Mpc, the cascade gives smoother γ-ray spectra in the cutoff region, but at the same time it predicts a flat, $E^{-2}$ type spectrum up to 10 TeV which contradict the HEGRA measurements.

The cascade spectrum calculated for the Model II of CBR (dotted line) marginally agrees with the HEGRA points, given the 15 per cent uncertainty on the energy scale throughout the entire energy range from 0.5 to 20 TeV, and up to factor of 2 statistical and systematic uncertainties in flux estimates above 10 TeV. Thus, formally we cannot completely rule out the cascade origin of TeV radiation. Nevertheless we should note that this is true only for the Model II type spectrum of CBR which does not explain the 60 μm flux (see Fig. 1). Moreover, such a model of CBR allows a reasonable absorption-corrected γ-ray spectrum, without a need of implementation of the cascade effects. Thus the “intergalactic cascade” hypothesis loses, to a large extent, its significance, given the high price we have to pay for that – the dramatically low (≤ 10^{-18} G) intergalactic magnetic field.

4. Gamma-radiation produced by ultrarelativistic unshocked jets

As it follows from Eq. (4), even a tiny magnetic field of about $10^{-17}$ G would lead to the delay of arrival of TeV γ-rays, compared with associated low energy photons, e.g. X-rays, more than 1 month. This obviously contradicts the observed strong X/TeV correlations, observed in particular during the strong outburst of Mkn 501 in 1997 (e.g. j.pian/:1998, catanese/:1997, krawczynski/coppi/:2000). Therefore, for the intergalactic magnetic field exceeding $10^{-17}$ G the absorption-corrected spectrum of γ-rays given by Eq. (1) appropriately represent the source spectrum in the high state. If so, we face a difficulty with the current common belief that the source spectrum of γ-rays should have a “decent” shape, i.e. be in accord with the predictions of conventional astrophysical scenarios suggested for blazars. Indeed, none of the models of blazars, in general, and of Mkn 501 in particular, allow the striking feature which appears unavoidably in the absorption-corrected spectrum of Mkn 501 above 10 TeV (see Fig. 3), if we adopt that the reported high FIR fluxes are due to the truly extragalactic background radiation. All versions of both electronic and hadronic models, suggested until now, predict smooth broad-band γ-ray spectra with characteristic (gradual or sharp) steepening above 10 TeV.

Formally, it is possible to “reproduce” a γ-ray spectrum with sharp pile-up assuming very narrow features in the distribution of accelerated particles. It is interesting to note in this regard that almost all particle acceleration models predict power-law distributions with high energy cut-offs. While the cutoff energy $E_0$ can be estimated, generally quite confidently, from the balance between the particle acceleration and the energy loss rates, the shape of the resulting particle spectrum in the cutoff region depends on many specific mechanisms of acceleration and energy dissipation. Remarkably, even within the “ordinary”
shock acceleration scenarios we may expect not only spectral cutoffs, but also pronounced pile-ups preceding the cutoffs (e.g. ???, see however ???)

Within the proton-synchrotron model of blazars, such a pile-up would result in a pronounced bump in the synchrotron TeV emission at $\simeq 0.3\eta^{-1}D_j$ TeV (?), where $\eta \geq 1$ is the so-called gyrofactor. However, the location of the bump at $E \geq 17$ TeV would require very large Doppler factor $D_j \geq 50 \eta$. In the leptonic models the pile-up in the electron spectrum would result in corresponding features in the synchrotron X-ray and inverse Compton TeV $\gamma$-ray spectra. The absorption-corrected spectra of Mkn 501 shown in Fig. 3 require very sharp pile-up in the electron spectrum. Whether such a pile-up could be formed in realistic particle acceleration models of small (sub-pc) jets of blazars is a question of future detailed studies. Below we offer a different, non-acceleration scenario which postulates that the TeV radiation of Mkn 501 is a result of comptonization of the ambient low-frequency radiation by ultrarelativistic jet-like outflow with a Lorentz factor of bulk motion of about $\Gamma \simeq (3 - 4) \times 10^7$.

The relativistically moving plasma outflows in forms of jets or winds, are common for many astrophysical phenomena on both galactic or extragalactic scales (?), see e.g.[mirabel2000]. Independent of the origin of these relativistic outflows, the concept of the jet seems to be the only successful approach to understand the complex features of nonthermal radiation of blazars, microquasars and GRBs. The Lorentz factor of such outflows could be extremely large. In particular in the Crab Nebula the Lorentz-factor of the MHD wind is estimated between $10^6$ and $10^7$ (???). The conventional Lorentz-factors of jets in the inverse Compton models of $\gamma$-ray blazars, are rather modest, $\Gamma \sim 10$. However there are no apparent theoretical or observation arguments against the bulk motion with extreme Lorentz-factors (see e.g. discussion by ?) on Mkn 421). ? have shown that in the context of cosmological GRBs the magnetically dominated jet-like outflows from stellar mass black holes may attain extreme bulk Lorentz factors exceeding $10^8$. We are not aware of similar calculations (and conclusions) concerning the massive black holes - the engines of AGN. Therefore we will limit our discussion by postulating existence of the outflow in Mkn 501 moving, at least at initial stages of its propagation in the vicinity of the central black hole, with an extreme bulk Lorentz factor $\geq 10^7$. If true, it is almost obvious that the outflow should have MHD origin, the energy being extracted from the rotating black hole through the Blandford-Znajek type mechanism (see ? for a recent review). In proximity of the accretion disk the outflow most probably should be Poynting-flux dominated in order to avoid the Compton drag. Furthermore, we assume that at relatively large distances from the central object, where the photon density is significantly reduced, an essential part of the electromagnetic energy is transfered to the kinetic energy of bulk motion, i.e. may become kinetic-energy-dominated (KED) jet with the so-called sigma-parameter (the ratio of the electromagnetic energy density to the particle kinetic energy density) $\sigma \leq 1$. In the case of the cold relativistic outflow (like the wind in the Crab) we hardly could expect noticeable synchrotron radiation. Indeed, although the energy of electrons in the frame of observer can be as large as 10 TeV, they move together with magnetic field, and thus they do not emit synchrotron photons. Nevertheless the cold ultrarelativistic outflow is not invisible. It could be revealed due to the inverse Compton $\gamma$-radiation of wind electrons. The suggested scenario is quite similar to the inverse Compton $\gamma$-radiation from unshocked winds in isolated (?) or binary (?) pulsars. Apparently, in this scenario the dense ambient photon target field is the second important ingredient, in addition to the ultrarelativistic cold wind, for effective production of $\gamma$-rays. Remarkably, even in the case of relatively week BL Lac objects there are several important sources of infrared and optical emission within the inner sub-parsec region of the central source - IR emission from the dust torus, broad-line emission from fast moving clouds, starlight, etc. It is easy to show that the Compton optical depth $\tau_C$ in this region could be as large as 1. We refer the reader to the paper by ? where the authors discuss the optical depth of (quite similar) pair-production process for TeV $\gamma$-rays in Mkn 421. Actually we have to introduce some additional conditions to avoid the destruction of the jet due to the Compton drag. On the other hand, since for $\tau_C \leq 1$ the $\gamma$-ray luminosity is proportional to the product $L_j \times \tau_C$, the optical depth should not be much less than 1 in order to have modest energy assumptions concerning the jet power $L_j$. Obviously, the most favorable value for $\tau_C \leq 1$ lies between 0.1 and 1. Due to extremely large bulk Lorentz factor $\Gamma \geq 10^7$, the Compton scattering on the ambient optical photons with energy more than 1 eV proceeds in deep Klein-Nishina regime; therefore the $\gamma$-radiation should have a very narrow distribution with energy $E \approx E_E = mc^2T$. Meanwhile, the IC scattering on far IR photons still takes place in the Thomson regime, resulting in a smooth broad-band spectrum.

In Figs 8 and 9 we demonstrate that the overall absorption-corrected spectrum of Mkn 501 can be satisfactorily interpreted in the terms of bulk inverse Compton emission of the jet, assuming a specific ambient radiation field consisting of two - narrow (Planckian) type radiation with temperature $kT \sim 1$ eV (curve I) and broader IR radiation, which formally could be presented in a power-law form $n(\epsilon) \propto \epsilon^{-m}$ with $m \approx 1.8$ (curve II). More specifically, the best fit for the CBR Model I is achieved for $kT = 2$ eV and $\epsilon = 1.8$, with the ratio of the energy densities of two components of about $r = w_1/w_2 = 163$. The CBR Model III requires similar, although slightly different parameters: $kT = 0.2$ eV and $\epsilon = 1.8$, and $r = 9.5$. In both cases the bulk Lorentz factor $\Gamma = 3.33 \times 10^7$ is assumed.

The $\gamma$-ray component caused by inverse Compton scattering of the jet electrons on relatively “hot” narrow photon distribution presents the prime interest because this component provides the most critical part of the spec-
Fig. 8. Inverse Compton spectrum of cold unshocked ultrarelativistic jet with bulk motion Lorentz factor $\Gamma = 3.33 \times 10^7$. The radiation component associated with comptonization of ambient optical photons with narrow spectral distribution is shown by the dashed line I. The IC spectrum on ambient photons with broad-band spectral distribution is shown by the dashed line II. The heavy solid line represents the superposition of these two components. Formally, the dashed line II could be treated as residual of the total TeV source emission after subtraction of the unshocked wind component I, and therefore can be referred to the IC radiation of blobs in shocked jet (see Fig. 10). Fits to the observed flux of Mkn 501 are shown by thin solid lines. Curve 1 corresponds to the fit given by Eq.(2) and curve 2 – to the steepest possible spectrum above 17 TeV based on the reanalysis of Mkn 501 HEGRA data (??). Absorption-corrected spectrum of Mkn 501 for CBR Model I is shown by dotted lines $1'$ and $2'$ for the fits to the observed spectrum 1 and 2 respectively.

Fig. 9. The same as Fig. 8, but for CBR Model III.

factor of about 10-30, and the magnetic field of about 0.1-1 Gauss (?????). The difference is that in the two-stage scenario of jet radiation suggested here, we solve the problem of the pile-up referring the latter to the first stage of radiation of the (unshocked) wind. Such a two-stage scenario is illustrated in Fig. 10.

5. Discussion

It is believed that the diffuse extragalactic infrared background radiation may have dramatic impact on the models of TeV blazars. In particular, the recently reported high CBR fluxes, both at NIR and FIR bands, imply that we detect significantly absorbed TeV radiation even from relatively nearby objects like Mkn 421 and Mkn 501. Due to the energy-dependent mean free path of $\gamma$-rays in the intergalactic medium, the detected spectra of TeV emission from extragalactic objects at cosmological distances significantly deviates from the source spectra. It is important to note that the intergalactic absorption does not simply imply spectral cutoffs, but rather modulates the primary spectrum over the broad energy band from sub-TeV to multi-TeV energies. For some CBR models, the “high-state” TeV spectrum of Mkn 501 after correction for the intergalactic absorption becomes very hard (Fig. 3), $dN/dE \propto E^{-2}$ (??, e.g., [coppi/aharonian::SSC:1999,konopelko::1999 or even flatter (???)], if the CBR density at relatively flat part of the spectrum at mid infrared wavelengths exceeds $10^{-3}$ eV/cm or $\nu F_\nu \geq 3.8$ nW/m$^2$/sr (??). Although formally such spectra can be described within the conventional SSC models, the detailed treatment of the problem within the one-zone SSC model requires quite unconventional jet parameters, in particular very large Doppler
factor $\delta_1$ exceeding 100, and very weak magnetic field $B \leq 0.01$ G. If so, this perhaps would require alternative models for TeV emission like the proton-synchrotron model which can satisfactorily fit the data of Mkn 501 and Mkn 421 even for quite high CBR fluxes (Aharonian 2000). Another interesting possibility could be a scenario like “cascade in the radio jet” which assumes that the $dN/dE \propto E^{-1.5}$ type spectrum is a result of cascade development in the jet initiated by $E \geq 100$ TeV photons produced at the base of the jet (J. Guy, private communication).

However all these models fail to explain the sharp pile-up which appears at the end of the “reconstructed” spectrum of Mkn 501, if the reported FIR fluxes correctly describe the level of the diffuse cosmic background radiation. Remarkably, such a pile-up appears unavoidably not only due to the reported extremely high flux at 60$\mu$m, which obviously needs further confirmation, but also, albeit in a less distinct form, due to the fluxes at longer wavelengths $\lambda \geq 100\mu$m reported by several independent groups. To avoid such an unusual shape of $\gamma$-radiation, recently several dramatic assumptions have been proposed concerning the origin of the detected signals (Bose-Einstein condensations instead of $\gamma$-rays) or validity of one of the fundamental physics laws (the Lorentz invariance). Also, the pile-up in the source spectrum of Mkn 501 could be avoided speculating that the source is located much closer to us than it follows from the Hubble law, i.e., assuming non-cosmological origin of the redshift $z = 0.034$.

The aim of this study was to investigate some other possible ways which would allow us to overcome the “IR background – TeV gamma-ray crisis” with less dramatic assumptions. In particular, we studied two possibilities, namely (i) assuming that the observed TeV spectrum of $\gamma$-rays from Mkn 501 is formed due to the cascade initiated by primary $\gamma$-rays in the intergalactic medium, and (ii) assuming that the detected highest energy $\gamma$-rays are result of bulk-motion comptonization of the ambient optical photons by the ultrarelativistic unshocked conical wind emerging from the central source.

The cascade development in the extragalactic photon fields results in a non-negligible increase of the effective mean free path of $\gamma$-rays, assuming extremely low, $\leq 10^{-18}$ G, intergalactic magnetic fields. This extreme (but not completely unreasonable) condition is necessary in order to avoid the time delays which would contradict to the observed time correlations in different energy bands. However, the results of our numerical calculations show that this hypothesis is not able to reproduce the observed spectrum of Mkn 501.

The second hypothesis seems to be more promising in the sense of quite satisfactorily explanation of the shape of the sharp pile-up at the end of the reconstructed $\gamma$-ray spectrum above 10 TeV. Although the assumption about the existence of such a wind with extreme bulk motion Lorentz factor $\Gamma \sim 3.5 \times 10^7$ is somewhat unusual and perhaps even provocative (at least it has not been discussed in the literature before), it cannot be a priori ruled out. Moreover, a similar scenario most probably takes place, although on significantly smaller scales, in environments of pulsars. The rotation–powered pulsars eject plasma in the form of relativistic winds which carry off bulk of the rotational energy. At a distance $d \leq 1$ pc the wind is terminated by a strong standing reverse shock which accelerates particles and randomizes their pitch angles. This results in formation of strong synchrotron and inverse Compton nebulae. On the other hand, it is generally believed that the region between the pulsar magnetosphere and the shock is invisible because the electrons move together with magnetic field and thus do not emit synchrotron radiation. However, recently it has been argued that such winds could be directly observed through their inverse Compton emission, the low-frequency seed photons for comptonization being provided by the neutron star in the case of radiopulsars like Crab or Vela (?) or by the optical companion star in the case of binary pulsars like PSR B1259-63 (?).
relativistic conical wind can indeed be produced in the proximity of the central rotating black hole (e.g. through the Blandford-Znajek mechanism), because of existence of dense photons fields in the inner sub-parsec region, it could be very powerful emitter of inverse Compton $\gamma$-radiation. The later however would not be accompanied by noticeable synchrotron radiation.

The possibility to disentangle the multi-TeV emission with a characteristic sharp pile-up at the very end of the spectrum, $E_{\gamma} \approx m_{e}c^{2}\Gamma$ associated with the unshocked jet, from the sub-10 TeV emission associated with the shocked structures (e.g. blobs) in the jet (see Fig. 10), not only solves the “IR background – TeV gamma-ray crisis” but also allows more relaxed parameter space for interpretation of X-rays and the remaining low energy ($\leq$ 10 TeV) $\gamma$-rays within the conventional SSC scenario. Consequently, this offers more options for interpretation of X-ray/gamma-ray correlations both on small ($t \leq$ several hours) and large (weeks or more) timescales. If the overall TeV radiation of Mkn 501 indeed consists of two, unshocked and shocked jet radiation components (curves I and II in Figs. 8, 9), we may expect essentially different time behaviors of these radiation components. In particular, the “unshocked jet” $\geq$ 10 TeV radiation should arrive earlier than the SSC components of radiation consisting of synchrotron X-rays and sub-10 TeV $\gamma$-rays. Generally, all principal parameters of blobs like the magnetic field $B$, the maximum energy of electrons $E_{\text{max}}$, the radius of the blob, etc., which determine the spectra and absolute fluxes of synchrotron X-rays and IC TeV $\gamma$-rays, may dramatically evolve in time ($?$. Therefore we should expect strong X/TeV correlations, especially during strong flares of the source. These correlations may be realized in quite different forms, i.e. it could vary from flare to flare depending on the time-evolution of specific parameters of blobs. At the same time the IC radiation of the unshocked jet significantly depends only on the Lorentz factor of the jet $\Gamma$. If the latter during short flares remains unchanged, we should expect rather stable spectral shape of the $\geq$ 10 TeV emission, despite strong variations of the SSC radiation (X- and $\gamma$-ray) components. It should be noticed that because of possible external broad-band infrared radiation fields, the unshocked jet radiation component may significantly contribute to the low energy TeV radiation as well (see Sect. 4). If so, it would enhance correlations between high and low energy bands of TeV radiation. On the other hand, it would reduce and make more complicated correlations between the low energy TeV $\gamma$-rays and synchrotron X-rays.

On larger time-scales, e.g. in a low state of the source which could last weeks or months, the bulk motion Lorentz factor of the unshocked jet may be smaller than in high states. This would not only reduce the luminosity of all components of nonthermal radiation, but also would make softer the overall $\gamma$-ray spectrum above several TeV.

The straightforward prove of the suggested model would be detection of TeV $\gamma$-ray spectra with characteristic sharp high energy pile-up. Apparently this requires nearby objects within 100 Mpc, thus the main fraction of $\geq$ 10 TeV $\gamma$-rays would arrive without significant intergalactic absorption. However, all currently known BL Lacs are located beyond 100 Mpc. This significantly limits the chances for direct detection of sharp pile-ups in the spectra of BL Lacs or other type of blazars, unless the initial Lorentz factors of ultrarelativistic outflows in some objects do not exceed $\Gamma \leq 10^{7}$.

Important tests of the suggested two stage (pre-shock plus post shock) scenario of the TeV radiation of jets can be provided also by the search for correlations (or lack of such correlations) of high energy (multi-TeV) $\gamma$-radiation with both the low energy (e.g. 1-3 TeV) $\gamma$-rays and synchrotron X-rays. The low statistics of (heavily absorbed) $\gamma$-rays above 10 TeV makes the search for such correlations rather difficult, and requires ground-based instruments with very large, $\gg 10^{5}$ m$^{2}$ detection areas in this energy domain. The new generation imaging Cherenkov telescope arrays like CANGAROO-3, H.E.S.S. and VERITAS should be able, hopefully, to perform such correlation studies.