Extragalactic background light absorption signal in the $0.26 - 10$ TeV spectra of blazars.

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Abstract. Recent observations of the TeV $\gamma$-ray spectra of the two closest active galactic nuclei (AGNs), Markarian 501 (Mrk 501) and Markarian 421 (Mrk 421), by the Whipple and HEGRA collaborations have stimulated efforts to estimate or limit the spectral energy density (SED) of extragalactic background light (EBL) which causes attenuation of TeV photons via pair-production when they travel cosmological distances. In spite of the lack of any distinct cutoff-like feature in the spectra of Mrk 501 and Mrk 421 (in the interval $0.26 - 10$ TeV) which could clearly indicate the presence of such a photon absorption mechanism, we demonstrate that strong EBL attenuation signal (survival probability of $10$ TeV photon $\sim 10^{-2}$) may still be present in the spectra of these AGNs. This attenuation could escape detection due to a special form of SED of EBL and unknown intrinsic spectra of these blazars. Here we show how the proposed and existing experiments, VERITAS, HESS, MAGIC, STACEE and CELESTE may be able to detect or severely limit the EBL SED by extension of spectral measurements into the critical $100 - 300$ GeV regime.

Introduction

It has long been thought [1] that the detection of attenuation effect in the TeV spectra of extragalactic sources caused by pair production $\gamma + \gamma \rightarrow e^+ + e^-$ with the EBL would be of great value for the understanding of cosmology and many aspects of the astrophysics of the Universe. Finding the cutoff feature in the high energy end of the Markarian 501 (Mrk 501) spectrum ($> 10$ TeV), reported during this workshop [2], may well be a long awaited signature of such extinction of the highest energy photons. In the presentation [3] during this workshop, the claim has been made that the found cutoff is well explained by a semi-empirically derived EBL prediction [4] and by the simple power-law spectrum intrinsic to the source with an exponent close to two spanning from 0.2 to 20 TeV. The latter implies that the EBL attenuation mechanism below 10 TeV should rather be weak which seems to be confirmed intuitively by the absence of a distinguishable feature in this part of the spectra for both Mrk 501 ($z = 0.03$) and Mrk 421 ($z = 0.03$) blazars (Fig. 1, [5]).

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We might now ask, whether the proposed SED of EBL is uniquely consistent with experiment, in order to begin its interpretation in terms of astrophysical constraints, or even if the lack of the feature in the low energy part of the TeV AGN spectra does prove an absence of the EBL absorption. Here I argue that we are not yet ready to make such statements neither on theoretical nor experimental basis, and due to ironic coincidence there is still a substantial degree of freedom in the definition of the SED of EBL. In this talk I consider a peculiar degeneracy which allows a certain type of SED of EBL to avoid “apparent” detection in currently available experimental data below 10 TeV due to the unknown properties of intrinsic spectra of the sources. The conclusions which I draw at the end of this talk will show how we can narrow down the existing possibilities even if we use spectral data of only these two AGN which may become available in the near future with the introduction of new γ-ray instruments, such as VERITAS or STACEE.

The EBL

Any contemporary theoretical consideration of the SED of EBL predicts two well pronounced peaks (Fig. 2). One at $\sim 1 \mu m$ due to the starlight emitted and redshifted through the history of the Universe, the other at $\sim 100 \mu m$ generated by re-processing of the starlight by dust, its extinction and reemission. Theoretical modeling of the spectral evolution of the EBL field involve complex astrophysics with many unknown input parameters which specify cosmology, number density and evolution of dark matter halos, distribution of galaxies in them, mechanisms of converting cold gas into stars, the star formation rate (SFR), stellar initial mass
function (IMF), supernovae feedback, and the mechanisms by which light is absorbed by dust and reemitted at longer wavelengths [6]. Semi-Analytical modeling of these processes show that the dominant factors shaping SED of EBL in the region $1 - 10 \mu m$ are IMF, which provides a source of the UV light, generated mostly by the high mass stars and is therefore dependent on their fraction, and dust extinction which functions as a sink of UV light [7]. The region from 1 to 10 $\mu m$ is primarily determined by the type of cosmology and the SFR. Allowing partial degeneracy between these two factors leads to an ambiguity in the interpretation of the actual SED of EBL [8]. It is also possible that a non-negligible contribution from a number of pregalactic and protogalactic sources may exist in this interval [9].

This EBL fraction is usually not considered in the EBL evolution models nor in semi-empirical EBL estimates. The long wavelength region, from approximately a few $\mu m$ to 100 $\mu m$, is currently predicted with the largest uncertainty, due to poorly defined dust extinction and re-radiation mechanisms, which are crucial ingredients for modeling EBL in this band. In addition, it has been suggested recently [10], that a substantial energy in this wavelength interval may come from quasars. Most of their radiation should be absorbed in the dust and gas of the accretion disk and re-emitted later in the far-infrared. Up to now this contribution has been considered as negligible, but failure to explain existing X-ray background suggests a presence of a large population of the faint quasars generating this diffuse radiation field [11].

These sources, visible only in X-ray and far-infrared, are expected to be probed by the Chandra mission. Energy ejected into the surrounding media by supernovae and re-radiated later may also be concealed in this wavelength interval [12].

At present, the degree of the uncertainty of various theoretical considerations of the SED of EBL is about the same as the distance between current upper and lower experimental limits. Fig 2 shows a compilation [13] of various EBL detections and limits as well as several theoretical [12] and semi-empirical [4] estimates of the SED of EBL. In the current situation a preferential choice of a particular prediction based solely on a theoretical background seems unjustified. We do expect, however, that the SED of EBL is likely to be a function with complex behavior. If we take into account that attenuation of extragalactic TeV $\gamma$-rays is an exponential effect, one would intuitively expect appearance of the structures in the observable spectra of AGNs, such as cutoff, for example. Non-existence of any peculiar features in $0.25 - 10$ TeV spectra of AGNs should then indicate a very weak absorption effect. The problem, however, is more subtle than it first appears. There is a whole class of non-trivial solutions for the SED of EBL (see [13]), shown in Fig. 3, which may well describe starlight peak expected in the $0.1 - 10 \mu m$ region. The important property of such SEDs is that they do not produce any peculiar change in the observable AGN spectrum. The only effect to be seen is change of the overall attenuation factor, change of the power-law spectral index, and slight change of the spectral curvature. All three of these potentially detectable EBL indicators are perfectly masked by the unknown intrinsic spectrum of the source. The existence of such SED solutions, which have been hinted in [14], is due to slow, power-law-like, change of an attenuation coefficient when the SED is proportional to energy.
FIGURE 3. Three examples of “invisible” SED of EBL are marked 1, 2, and 3 [13].

FIGURE 4. Predicted change of the Mrk 421 and Mrk 501 power-law spectral index due to attenuation of TeV photons on EBL [12].

of the infrared photon with logarithmic accuracy. Such a case seems to take place in the $1 - 10 \, \mu m$ region to which observations in $0.25 - 10$ TeV interval are most sensitive. It is an ironic coincidence that current observational window of TeV γ-ray astronomy coincided with the region of a special behavior of SED which makes EBL attenuation effect “invisible.” If we were to move γ-ray observational window to lower or higher energies we would be sensitive to the bands in the EBL spectrum where the SED is rapidly falling. This would produce an exponential effect on the observable spectra of AGNs, such as one detected by the HEGRA collaboration in the region $10 - 25$ GeV [2].

Since there are a number of upper and lower limits for the SED of EBL in the $0.1 - 10 \, \mu m$ interval, established by various experiments, it becomes possible to constrain the EBL attenuation effect in the spectra of Mrk 421 and Mrk 501 using an explicit form of “invisible” SEDs. Such considerations [13] lead to the conclusions that the optical depth for 10 TeV photons is bounded within the interval $0.85 - 4.43$, the EBL contribution to the power-law spectral index at photon energy 1 TeV can be in the range $0.19 - 0.94$, and spectral curvature does not exceed 0.22 (the Hubble constant used is 65 km s$^{-1}$ Mpc$^{-1}$). Analogous constraints derived from the EGRET measurements of the spectral indices of these sources [15,16] provide similar upper limit for spectral index change due to the EBL attenuation effect ($< 1.0$). Source luminosity arguments [2] suggest that if the optical depth at 1 TeV exceeds $\sim 3$ then the intrinsic γ-ray luminosity of Mrk 501 is an order of magnitude larger than the luminosity in all other wavelengths which is difficult to explain with realistic parameters of the jet. This places approximately the same upper bound on the absolute value of the γ-ray absorption. Finally, a lack of the curvature in the spectrum of Mrk 421 provides upper limit of 0.3 which is no stronger at the...
moment than the direct EBL constraints.

The large degree of the uncertainty which still exists in an experimental detection of EBL signal via observations of $\gamma$-ray attenuation is due to the, as yet, undetermined initial conditions in the region approximately from 100 to 300 GeV. Although EBL induced attenuation of $\gamma$-rays in this interval is rather small for $z=0.03$, the absorption effect must produce a jump in the spectral index and curvature here. In Fig. 4 I show a derivative of the optical depth with respect to the logarithm of energy, which characterizes the change of the spectral index. Two examples shown correspond to the predictions made in [12] for Salpeter and Scalo IMFs. Note that the region from 100 GeV to 500 GeV is characterized by a rapid change in the spectral index. This result is, of course, hardly surprising since it is produced by a rapid fall of the SED of EBL in UV band. The subsequent dip above 1 TeV is due to a very low prediction of the models for EBL field in the region around 10 $\mu$m. Such a low estimate is not currently supported by the lower bound on EBL from ISO measurements at 15 $\mu$m [17]. Absence of the EBL signature in the spectra of Mrk 421 and Mrk 501 in the 0.3 – 10 TeV interval suggests that the behavior of the derivative of optical depth should likely be linear function of the logarithm of photon energy (curve marked “Example” in Fig. 4). The measurements of the AGN spectra in the region 100 – 300 GeV are of crucial importance then to experimentally determine two parameters of this curve and therefore unfold a unique SED “invisible” solution [13]. The expected change of spectral index, 0.19 – 0.94, of Mrk 501 and Mrk 421 between 100 GeV and 1 TeV due to the EBL absorption is a measurable effect. If the opacity of the Universe to TeV $\gamma$-rays is large, most of this change should occur below 300 GeV since such an effect has not been detected in the AGN spectra above this energy [5]. This would produce a “knee-like” feature in the spectra of these blazars in the 100 – 300 GeV interval. If the attenuation effect is small though, it is possible that the derivative of optical depth remains the same linear function in this energy band generating only a logarithmically small EBL footprint in the AGN spectra. In the latter case, a small curvature, $1/2 \frac{d^2 \tau}{d \ln(E)^2} \sim 0.1$, in 0.1 – 1 TeV energy range would be the only indicator of EBL presence.

Conclusions

1. The featureless spectra of the two closest AGNs in the 0.25 – 10 TeV energy band does not guarantee a low attenuation of TeV $\gamma$-rays via pair-production with EBL. The large class of “invisible” SED solutions exists [13] which change only overall attenuation factor, spectral index, and spectral curvature of the observable AGN spectrum. Behavior of these SEDs is consistent with the theoretically expected starlight EBL peak at 1 $\mu$m, but due to the unknown intrinsic properties of the sources such an attenuation effect cannot be unambiguously isolated based only on the data from this energy interval. The EBL spectral density suggested in [3] for explanation of spectral properties of Mrk 501 is, therefore, only one of many possibilities.
2. Even by observing only two known extragalactic TeV sources, Mrk 501 and Mrk 421, we can hope to constrain or possibly detect SED of EBL if spectral measurements are extended into the 100 − 300 GeV region where change of the spectral index would indicate a turn on of the absorption effect. Detection of this feature by future γ-ray observatories, for example VERITAS or STACEE, will provide a missing piece of information for proper unfolding of the SED of EBL in the wavelength interval above 0.1 µm. Of course, a certain ambiguity of spectra interpretation due to unknown properties of the sources will remain, the presence of a similar feature, which is static in time, in both spectra may allow to disentangle or severely limit intergalactic γ − γ extinction effect.

3. It turns out that the most important constraints for limiting or unfolding the SED of EBL may be provided by accurate measurements of the curvature (better than ∼ 0.1 per decade in energy) in the spectrum of Mrk 421 through the interval 250 − 10 TeV. At the moment the spectrum of this source during high flaring state has been found consistent with a pure power-law [5]. If the source cooperates, an improved statistics may give EBL upper limits in the region around a few micrometers lower than the currently available DIRBE results.

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