

Breaks in gamma-ray spectra of distant blazars and transparency of the Universe¹⁾

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Submitted 3 July 2014

Resubmitted 13 August 2014

Energetic gamma rays scatter on soft background radiation when propagating through the Universe, producing electron-positron pairs (A. I. Nikishov, *Sov. Phys. JETP* **14**, 393 (1962)). Gamma rays with energies between 100 GeV and a few TeV interact mostly with infrared background photons whose amount is poorly known experimentally but safely constrained from below by account of the contribution of observed light from known galaxies (R. C. Keenan, A. J. Barger, L. L. Cowie, and W.-H. Wang, *Astrophys. J.* **723**, 40 (2010); arXiv:1102.2428). The expected opacity of the intergalactic space limits the mean free path of TeV gamma rays to dozens of Megaparsecs. However, TeV photons from numerous more distant sources have been detected (S. P. Wakely and D. Horan, <http://tevcat.uchicago.edu/>). This might be interpreted, in each particular case, in terms of hardening of the emitted spectrum caused by presently unknown mechanisms at work in the sources (S. Archambault et al. (VERITAS and Fermi LAT Collaborations), *Astrophys. J.* **785**, L16 (2014); arXiv:1403.4308). Here we show that this interpretation is not supported by the analysis of the ensemble of all observed sources. In the frameworks of an infrared-background model with the lowest opacity (R. C. Gilmore, R. S. Somerville, J. R. Primack, and A. Dominguez, *Mon. Not. Roy. Astron. Soc.* **422**, 3189 (2012); arXiv:1104.0671), we reconstruct the emitted spectra of distant blazars and find that upward spectral breaks appear precisely at those energies where absorption effects are essential. Since these energies are very different for similar sources located at various distances, we conclude that the breaks are artefacts of the incorrect account of absorption and, therefore, the opacity of the Universe for gamma rays is overestimated even in the most conservative model. This implies that some novel physical or astrophysical phenomena should affect long-distance propagation of gamma rays. A scenario in which a part of energetic photons is converted to an inert new particle in the vicinity of the source and reconverts back close to the observer (M. Simet, D. Hooper, and P. Serpico, *Phys. Rev. D* **77**, 063001 (2008); arXiv:0712.2825; M. Fairbairn, T. Rashba, and S. Troitsky, *Phys. Rev. D* **84**, 125019 (2011); arXiv:0901.4085) does not contradict to our results. This new axion-like particle appears in several extensions of the Standard Model of particle physics (J. Jaeckel and A. Ringwald, *Ann. Rev. Nucl. Part. Sci.* **60**, 405 (2010); arXiv:1002.0329) and may constitute the dark matter (P. Arias et al., *JCAP* **1206**, 013 (2012); arXiv:1201.5902).

DOI: 10.7868/S0370274X14180015

Modern instruments of gamma-ray astronomy, namely atmospheric Cerenkov telescopes and the Fermi spaceborn observatory, continue to discover very-high-energy (VHE, energies larger than 100 GeV) gamma radiation from more and more distant sources [1–3]. The optical depth of the Universe for VHE photons is large because of the pair production on the extragalactic background light (EBL) [4]. One therefore expects additional suppression of the VHE flux from distant sources with respect to that of similar astrophysical objects located relatively nearby. Indeed,

the suppression has been observed recently in the Fermi data [5].

However, a precise amount of the suppression is hard to predict theoretically because of the lack of information about the EBL density (for reviews, see e.g. Refs. [6, 7]). Indeed, the relevant target photons are mostly infrared, and the extragalactic infrared background can hardly be determined by measurements within the Solar system because of contamination by the so-called Zodiacal light.

Every particular EBL model allows one to reconstruct the emitted gamma-ray spectrum of the source by correcting the absorbed spectrum for the pair-production suppression. Since, for particular distant sources, the observed spectra are reasonably described

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by a power-law falloff of intensity with energy, the deabsorbed spectra often exhibit hardening, or upward breaks, because the suppression is energy-dependent: the mean free path of GeV photons is of order of the size of the visible part of the Universe while that of TeV photons does not exceed 100 Mpc.

All observed distant sources are blazars, that is belong to a certain class of active galactic nuclei whose relativistic jets point to the observer. While the mechanism of high-energy emission of blazars is disputable, the bulk of their spectral energy distribution is well described by two wide bumps. The low-energy bump is formed by the synchrotron radiation of relativistic electrons while the high-energy one is often attributed to photons which gain their energies by means of the inverse Compton scattering. The overall shape of the distribution is to a large extent determined by the position of the synchrotron peak which sets up the energy scale of the electron population. One often distinguishes two large classes of blazars, namely flat-spectrum radio quasars (FSRQs) with the peak in the radio to infrared and BL Lac type objects (BLLs) with the peak in optical to X -ray bands. However, deabsorbed spectra of distant blazars often exhibit high-energy hardening which is not seen in nearby objects. Even a visual inspection of the deabsorbed blazar spectra leads to a conclusion that both the position and the strength of the spectral hardening differ for blazars located at different distances, see Fig. 1 for an example. In what follows, we quantify this

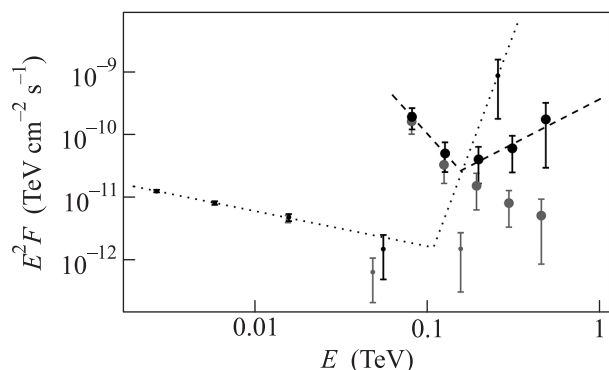


Fig. 1. Example of two spectra with breaks: 3C 279 (redshift $z = 0.536$, large points) and PKS J0730-1141 (redshift $z = 1.591$, small points). Both objects are FSRQs and have similar spectral energy distributions in the optically thin part. However, spectral breaks in the gamma-ray band are located at the energies where the absorption becomes significant, different for the two sources. Grey points represent the observed spectrum, dark points are corrected for the EBL absorption with the most conservative model

observation by a statistical analysis of a large sample of blazars detected in VHE.

To begin with, we formulate three simple hypotheses to be tested which might explain unusual high-energy breaks in (otherwise smooth and universal) deabsorbed blazar spectra:

(i) the breaks in the emitted spectra have a physical, source-related origin. This most natural explanation suggests that positions and sizes of the breaks should depend on the physical conditions in the sources, which are to a large extent parametrized by the synchrotron peak position, and should not depend on the distance;

(ii) the spectral shape of the assumed EBL density is incorrect, so that the absorption is overestimated for some particular energy. This would result in unphysical breaks always located close to this energy but becoming stronger for more distant sources;

(iii) the overall absorption is uniformly overestimated, for instance, as a result either of incorrect normalization of the assumed EBL density or of ignorance of some other phenomena which decrease the opacity of the Universe. This option would manifest itself in unphysical breaks located at the energy where the absorption becomes essential for a given distance; the breaks should be stronger for more distant sources.

To study the effect quantitatively, we need a sample of blazars located at various distances with fluxes measured beyond the energies where absorption on EBL is significant. We compile the sample from published data of atmospheric Cerenkov telescopes by making use of the TeVCat catalog [8] and supplement it with a set of more distant objects observed by Fermi. The selection criteria and the procedure of the sample construction are described in the Supplementary Information (SI) section [9]. The resulting list of objects is given in [9]. For each of the objects in the sample, we construct a deabsorbed spectrum as described in the SI section. The results we report here are based on the most conservative (i.e., the lowest absorption) EBL model consistent with lower bounds, the “fiducial” model of Gilmore et al. [10]. For comparison, we performed the same procedure for a popular model of Franceschini et al. [11] and obtained similar results.

For the first preliminary test, we fit each spectrum with a power law and, independently, with two power laws with a break, keeping the break position arbitrary. We select these (few) objects for which the fit with a break is better than without it (as determined by the R^2 statistics) and the break corresponds to a spectral hardening (it is not so for a few nearby sources). Then we compare the break positions with the values of energy at which the absorption is expected to be signifi-

icant (namely, with the energy E_0 for which the optical depth due to pair production $\tau = 1$). The results are shown in Fig. 2, where we plot the positions

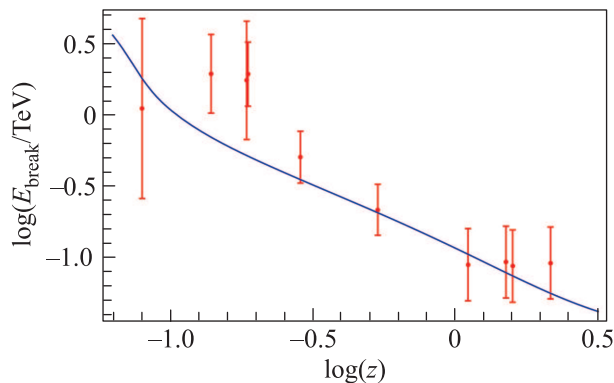


Fig. 2. Positions of individual significant upward breaks versus redshift z . The line represents the energy $E_0(z)$ at which the optical depth with respect to the pair production $\tau = 1$

of these significant upward breaks versus the redshift of spectral lines z , which is the measure of distance at cosmological scales. The breaks happen, on average, at $\log_{10}(E/E_0) = 0.18 \pm 0.32$, statistically consistent with $E = E_0$. This observation favours the option (iii) and suggests that a more statistically solid test of the hypothesis should be performed.

This kind of a test, to which we turn now, constitutes the main part of our study and results in our principal conclusion. We assume now that the position of the break is fixed at $E = E_0$, perform the corresponding fits and study how the strength of the break, determined as the difference $\Delta\Gamma$ between power-law indices below and above the break, depends on z . In this approach, we use the information from all sources, even if their individual breaks are not statistically significant. The results are presented in Fig. 3, together with the best-fit approximation, $\Delta\Gamma = (5.08 \pm 0.37) \log_{10} z + (4.05 \pm 0.29)$. For the best fit, $\chi^2 \simeq 9.9$ for 18 degrees of freedom (upper limits in Fig. 3 correspond to the objects for which there is no significant flux measurement above the assumed break; we do not include them in the fit). For the hypothesis of the absence of breaks, $\Delta\Gamma = 0$, the corresponding $\chi^2_0 \simeq 217.5$ (20 d.o.f.); the assumption of a distance-independent break, $\Delta\Gamma = \text{const}$, results in $\chi^2_C \simeq 201.0$ (19 d.o.f.). These results mean that, speaking in terms of the Gaussian distribution, the absence of distance-dependent spectral hardening is excluded at the 12.4 standard deviations (12.4σ) level. This is the principal result of our work, and it gives a serious argument in favour of the (iii) hypothesis formulated above.

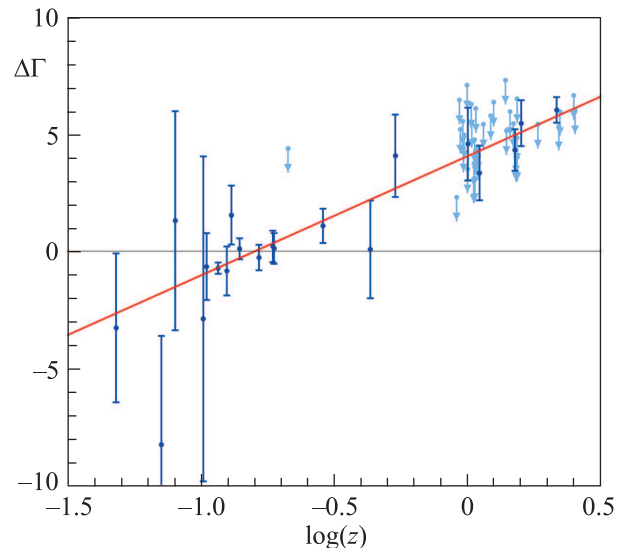


Fig. 3. Value $\Delta\Gamma$ of the break in the spectrum deabsorbed with the most conservative model, assumed to happen at $E = E_0$, versus redshift z . The line gives the best fit; its slope is non-zero at the 12σ significance

However, one should worry about potential systematic errors and statistical biases which might affect the result. The sample of blazars we use is by no means complete (which objects are observed by Cerenkov telescopes is determined by the choice of their teams). We discuss a number of potential problems in SI and conclude that it is unlikely that they might affect our result. However, a detailed quantitative study of the biases and systematics is hardly possible without a complete sample of sources, which unfortunately is not expected to be available, at least in relatively near future.

Among previous studies of gamma-ray blazars in the context of the EBL opacity, two groups went beyond the discussion of individual objects and used a sample, like we do here. The first one is the Fermi LAT collaboration [5] which discovered a spectrum suppression by comparison of BLL spectra grouped in large redshift bins. This result was interpreted as the effect of the EBL absorption. Since the bulk of the data they used correspond to the energies for which the opacity is low, this effect was seen in stacked samples only. This result does not contradict to ours because it does not exclude the opacity below the lowest model and even favours it for high energies, cf. Fig. 1 of Ref. [5]. Horns and Meyer [12] concentrated on the sample of blazars detected at very large optical depths, $\tau \geq 2$, and found a 4-sigma evidence for the pair-production anomaly which lead them to conclusions similar to ours. The differences of our approach, which lead to a 12-sigma result, from Ref. [12], are in the choice of the sample (they used only 7 objects for which significant fluxes have been detected for

$\tau \geq 2$ and did not use Fermi-LAT data), in the use of simultaneous data only (they stacked data points obtained at different epochs and by different instruments into a single spectrum, which might result in considerable smoothing of the effect because of a high degree of intrinsic variability of blazars, both in the flux and in the spectral index, and of possible relative systematics in the energy scale between the instruments), and the method of the analysis. They also did not take into account the shift of the mean energy in the bin in the de-absorbed versus observed spectrum, important at large opacities.

Having established that the most conservative EBL model is likely to overestimate the absorption, we turn now to possible implications of the effect we observed. The probability of the pair-production process cannot be questioned: it is calculated in quantum electrodynamics at the center-of-mass energies where no unknown effects are expected to contribute, and has been measured experimentally. The downward change in the amount of target photons is hardly acceptable because the EBL model we use is already the lowest-opacity one and is saturated by lower limits of Ref. [13]. We have checked that the artificial reduction of the EBL density 2.1 times below the lower limit, which is far beyond reasonable, reduces the significance of the effect down to $\sim 2\sigma$; however, the reduction is caused by the depletion of the sample (harder to satisfy the criterion 2 [9]) and not by the disappearance of breaks. Therefore, one should consider new processes which affect the observed photon flux and are not accounted for in the absorption model which takes into account pair production only. Several models of this kind have been suggested; they invoke either new physical processes or very unusual astrophysical assumptions. A quantitative study of these models in the context of our result is beyond the scope of the present paper (G.R. and S.T., work in progress); however, we give here a brief overview of possible explanations and present very rough estimates for some models. We consider three approaches; as we will see, they can be distinguished by the assumed value of the (presently unknown) intergalactic magnetic field.

Two quite different scenarios invoke similar extensions of the particle-physics Standard model, the so-called axion-like particles (ALPs; see Ref. [14] for a review and a list of references and Ref. [15] for a dark-matter connection). In external magnetic fields, these hypothetical particles may convert to photons and vice versa. Applied to our problem, this conversion may happen [16] in intergalactic magnetic fields provided they are sufficiently strong ($> 10^{-9}$ G). In this regime, VHE photons convert to ALPs and back during propa-

gation in a way similar to neutrino oscillations. Since the photon state produces pairs but the ALP state does not, this effectively makes the mean free path of a photon longer. In a rough approximation and for the maximal possible photon/ALP mixing, the path becomes longer by a factor of $\sim 3/2$ because there are two photon polarization states and one ALP state in the beam. Using the optical thickness of $2\tau/3$ instead of τ in our analysis, we obtain the reduction in significance of the distance dependence of breaks from $\sim 12\sigma$ to $\sim 6\sigma$ which suggests that this scenario may not explain the entire observed effect, though a detailed analysis is required for a firm conclusion.

In the second scenario, intergalactic magnetic fields are assumed to be weaker, $\lesssim 10^{-10}$ G, and therefore insufficient for the photon/ALP transitions which may happen instead in the regions of stronger field around both the source and the observer. The conversion may happen on magnetic fields of galaxies [17], galaxy clusters or superclusters [18]. A qualitative picture of the effect is that $\sim 1/3$ of original photons convert to ALPs near the source and travel unattenuated, to produce $\sim 2/3 \cdot 1/3 = 2/9$ photons reconverted back in the vicinity of the observer. The rest of the photons attenuate on the EBL in a usual way. Account of this mechanism in our study reduces the effect to $\sim 2\sigma$ thus making it insignificant. We conclude that our result may be explained in this scenario.

The third option [19] does not require new physics beyond the Standard Model; however, it invokes some non-conventional astrophysical assumptions. In this approach, a competitive source of VHE photon *production* along the path from the source to the observer feeds the photon flux which is, in parallel, absorbed in the usual way. These additional photons may be created in interactions of ultra-high-energy cosmic protons, which are assumed, in this model, to be produced in the very same source, with the background radiation. It is not possible to perform a simple rough test of this model in our study because this scenario is necessarily based on rather arbitrary parameters of the hypothetical proton flux. We just note that the assumption that all TeV blazars accelerate the required amount of energetic cosmic protons should be used with a degree of care. Also, the viability of this scenario requires very low values of the intergalactic magnetic fields, $\lesssim 10^{-14}$ G, otherwise charged particles would be deflected and secondary photons would not point back to the source.

While detailed tests of these scenarios versus our results will be presented elsewhere, our preliminary considerations thus favour the ALP conver-

tion/reconversion scenario [17, 18] for the explanation of the effect we observe.

The authors are indebted to Oleg Kalashev for discussions. This work was supported in part by the RFBR grant # 13-02-01293 (G.R. and S.T.), by the Dynasty foundation (G.R.), by the grants of the President of Russia MK-1170.2013.2 (G.R.), and NS-2835.2014.2 (G.R. and S.T.). We acknowledge the use of data and software provided by the Fermi Science Support Center.

1. S. Archambault et al. (VERITAS and Fermi LAT Collaborations), *Astrophys. J.* **785**, L16 (2014); arXiv:1403.4308.
2. E. Aliu et al. (MAGIC Collaboration), *Science* **320**, 1752 (2008); arXiv:0807.2822.
3. Y.T. Tanaka, C.C. Cheung, Y. Inoue, L. Stawarz, M. Ajello, C.D. Dermer, D.L. Wood, and A. Chekhtman, *Astrophys. J.* **777**, L18 (2013); arXiv:1308.0595.
4. A.I. Nikishov, *Sov. Phys. JETP* **14**, 393 (1962).
5. M. Ackermann et al. (Fermi-LAT Collaboration), *Science* **338**, 1190 (2012); arXiv:1211.1671.
6. M.G. Hauser and E. Dwek, *Ann. Rev. Astron. Astrophys.* **39**, 249(2001); astro-ph/0105539.
7. L. Costamante, *Int. J. Mod. Phys. D* **22**, 1330025 (2013); arXiv:1309.0612.
8. S.P. Wakely and D. Horan, <http://tevcat.uchicago.edu/>.
9. See Supplemental Material at (URL to be inserted by publisher).
10. R.C. Gilmore, R.S. Somerville, J.R. Primack, and A. Dominguez, *Mon. Not. Roy. Astron. Soc.* **422**, 3189 (2012); arXiv:1104.0671.
11. A. Franceschini, G. Rodighiero, and M. Vaccari, *Astron. Astrophys.* **487**, 837 (2008); arXiv:0805.1841.
12. D. Horns and M. Meyer, *JCAP* **1202**, 033 (2012); arXiv:1201.4711.
13. R.C. Keenan, A.J. Barger, L.L. Cowie, and W.-H. Wang, *Astrophys. J.* **723**, 40 (2010); arXiv:1102.2428.
14. J. Jaeckel and A. Ringwald, *Ann. Rev. Nucl. Part. Sci.* **60**, 405 (2010); arXiv:1002.0329.
15. P. Arias et al., *JCAP* **1206**, 013 (2012); arXiv:1201.5902.
16. A. De Angelis, O. Mansutti, and M. Roncadelli, *Phys. Lett. B* **659**, 847 (2008); arXiv:0707.2695.
17. M. Simet, D. Hooper, and P. Serpico, *Phys. Rev. D* **77**, 063001 (2008); arXiv:0712.2825.
18. M. Fairbairn, T. Rashba, and S. Troitsky, *Phys. Rev. D* **84**, 125019 (2011); arXiv:0901.4085.
19. W. Essey and A. Kusenko, *Astropart. Phys.* **33**, 81 (2010); arXiv:0905.1162.