Indications for a cascade component in γ-ray blazar spectra

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We present a very brief overview of some recent γ-ray observations of selected blazars to reveal an indication for a considerable or even dominant contribution of secondary γ-rays from electromagnetic cascades to the observable spectra in the 1–500 GeV energy range.

I. INTRODUCTION

The Universe is filled by light. There are two principal sources of such photons — the cosmic microwave background (CMB) and the extragalactic background light (EBL). While CMB properties are quite well measured and theoretically understood for more than 20 years (e.g. [1]), many EBL models with widely different parameters were developed [2]–[10]; for instance, the total EBL intensity for these models differs by more than a factor of two [11]. Comparatively recently, however, some of these EBL models started to converge, at least in the 0.5–10 nm wavelength region (e.g., [4] and [9]).

High-energy γ-rays with primary energy $E_0 > 0.25(1[eV]/\epsilon)[TeV]$ get absorbed [12]–[13] ($\gamma\gamma \rightarrow e^+e^-$) on EBL and CMB photons with energy ϵ, reaching maximum cross section at $E_0 \approx (1[eV]/\epsilon)[TeV]$ [9]. Therefore, the improved reliability of EBL models allows for more detailed studies of this fundamental quantum electrodynamics process in the γ-ray energy range of about 500 GeV– 10 TeV, and of extragalactic γ-ray propagation effects in general.

Using the CMB for such studies is, in principle, also possible [14], but at present is not feasible due to several factors. Indeed, the typical mean free path L of a $\sim 10^{15}$ eV= 1 PeV γ-ray on the CMB is $\sim$10 kpc; for such high energies there is still no discovered sources, while using lower energies is not convenient either as in the E_0 <100 TeV energy region the $L(E_0)$ dependence is very strong: L falls for about an order of magnitude for every 10 % of E decrease. Therefore, extremely well knowledge of experimental systematics on primary γ-ray energy would be crucial while using CMB photons at E_0 <100 TeV as a probe of the $\gamma\gamma \rightarrow e^+e^-$ process.

In the present conference contribution we emphasize on the potential importance of the development of electromagnetic cascades on the EBL/CMB to the interpretation of observations in the high energy (HE, E=100 MeV–100 GeV) and the very high energy (VHE, E=100 GeV–100 TeV) ranges. This short paper does not pretend to claim great originality; most of its basic ideas were already discussed and most of its main results were already presented in [15]–[19].

II. EXTRAGALACTIC γ-RAY PROPAGATION: ANOMALIES AND MODELS

A. Absorption-Only Model

Soon after the discovery of the first TeV extragalactic γ-ray source [20], the first γ-astronomical constraints on the EBL density were obtained [21]–[22], accounting for only the pair-production process as the main cause of transformation of the primary γ-ray spectrum (for very distant sources, it is necessary to include adiabatic losses). This model we call "the absorption-only model". Since 1993, almost every year several papers appear, assuming the absorption-only model, sometimes at a rate of a dozen a year or more.

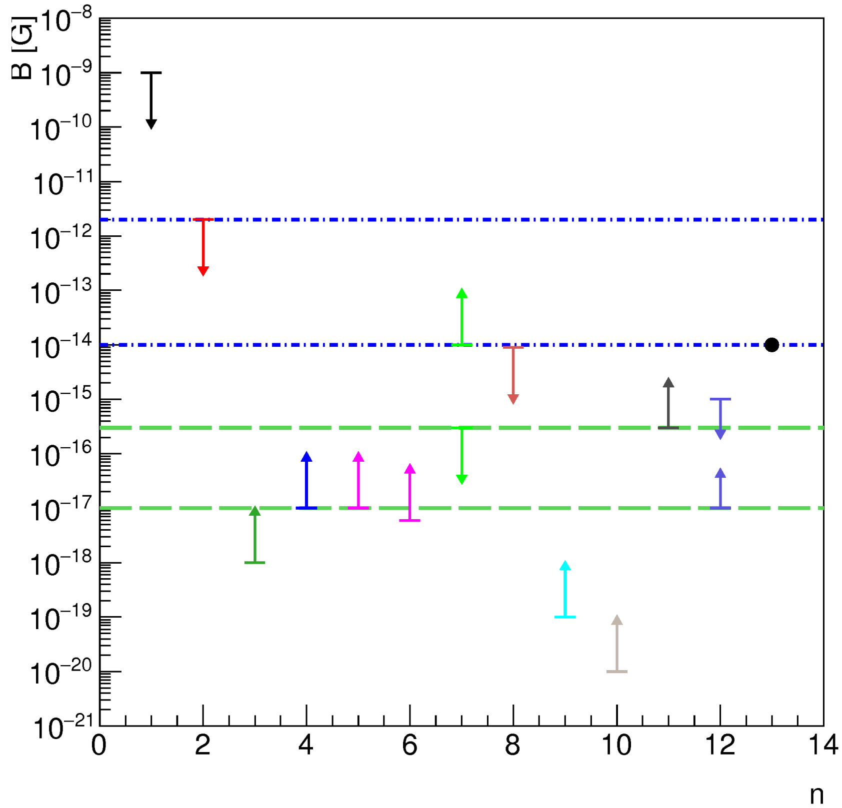

FIG. 1. Some constraints on the EGMF strength in voids (a figure from [19]).

B. Anomalies

In what follows, any significant deviations from the absorption-only model are called "anomalies", even if they do not fall beyond the conventional physics. Several such anomalies were reported [23]–[27], with a statistical significance not overwhelming in every single case, but together they indicate that the absorption-only model is incomplete and must be modified in some way (see [15] for more details).

C. Extragalactic Magnetic Field

Secondary electrons and positrons (hereafter simply "electrons") produced in the $\gamma\gamma \rightarrow e^+e^-$ process radiate cascade γ-rays by means of the Inverse Compton (IC) process; these γ-rays may contribute to the observable spectrum of an extragalactic source. Therefore, besides the properties of background photon fields (EBL/CMB), another very important factor is the strength and structure of the extragalactic magnetic field (EGMF). Some selected constraints on the EGMF strength B in voids of the large scale structure (LSS), most of them assuming correlation length of the field L_c= 1 Mpc, are shown in Figure 1. There are two regions of B values that satisfy most of these constraints: 10^{-14} G < B <$2{\cdot}10^{-12}$ G and 10^{-17} G < B <$3{\cdot}10^{-16}$ G. The first case corresponds to the absorption-only model regime: for such a strong EGMF secondary electrons are, as a rule, strongly deflected and delayed so that cascade photons do not contribute to the point-like image of the source. On the other hand, for the case of the second option such a contribution is still possible, at least in the VHE energy range. The lower bound on the B value, 10^{-17} G, is highly uncertain [28]-[29]. Very recently a paper [30] appeared, disfavouring a narrow range of values around B= 10^{-14} G for L_c= 1 Mpc.

D. Electromagnetic Cascade Model

Let us assume for a moment the following simple two-phase model of the EGMF. LSS voids with $B = 0$ fill a fraction of the total volume $0 < V < 1$, while the rest is occupied by the comparatively strong ($B > 10^{-14}$ G) EGMF with $L_c \sim 1$ Mpc. Figure 2 shows several fits to the observed spectral energy distribution (SED) of blazar 1ES 0229+200 ([31] for the four lowest-energy bins shown in black and [32] for other bins) assuming this model with various values of V. Cascade component dominates at low energies (E <300–500 GeV). Details of simulations corre-

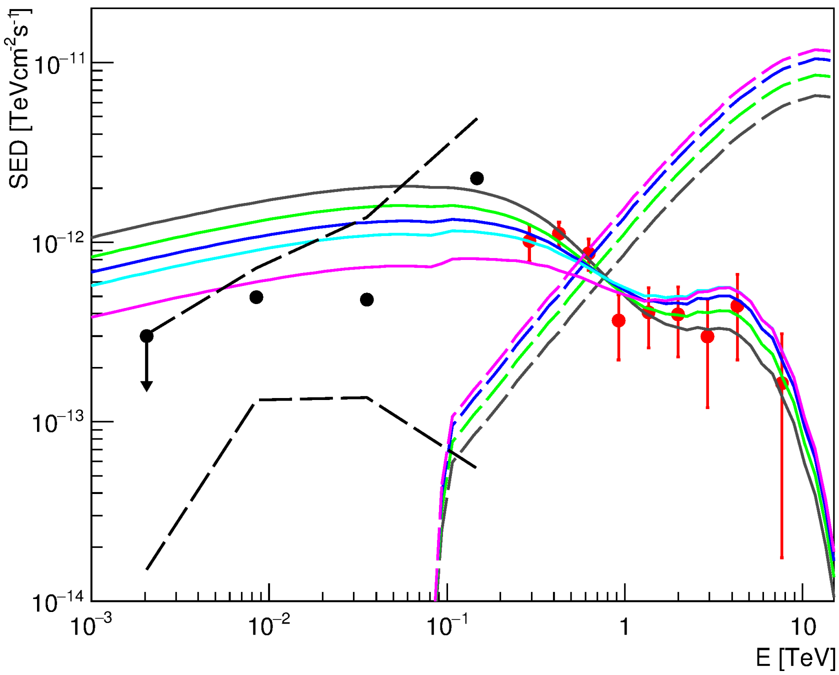

FIG. 2. Several fits (solid curves) to the spectrum of blazar 1ES 0229+200 [31]–[32] obtained in the framework of the intergalactic electromagnetic cascade model. Black curve denotes $V = 1$, green curve — $V = 0.6$, blue — $V = 0.4$, cyan — $V = 0.3$, magenta — $V = 0.2$. Primary (intrinsic) spectra for each case are also shown by the same colors (dashed curves in the right part of the graph). Full uncertainty for the four lowest-energy bins is shown by black dashed lines.

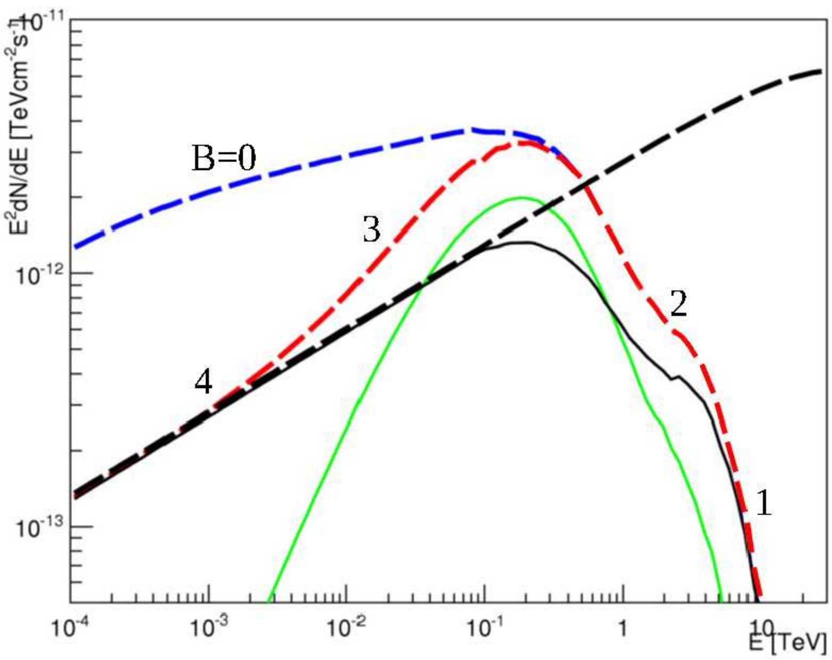

FIG. 3. The main spectral signatures of the electromagnetic cascade model (a figure from [35]).

spond to the case of Figure 15 of [15]. Reasonable fits in the energy range 30 GeV − 10 TeV may be obtained for the case of V between 0.4 and 0.6. However, below 30 GeV the model intensity exceeds the observed one. This may be explained either by the deflection and/or delay of cascade electrons while travelling the EGMF [33]–[34] or by additional (with respect to IC) electron energy losses [29].

Figure 3 depicts the main spectral signatures of the electromagnetic (EM) cascade model: 1) high-energy cutoff, similar to the absorption-only model, 2) an ankle at the intersection of the primary and cascade components (in fact, this signature is also visible in Figure 2), 3) a low-energy cutoff for the case of a non-zero EGMF value ("magnetic cutoff"), and 4) a "second ankle" at the low-energy region of the spectrum.

E. Explanation of anomalies in the EM Cascade Model

We argue that all above-mentioned anomalies may be interpreted within the framework of the EM cascade model, namely:
1. The apparent excess of observed γ-rays in the highest-energy bins claimed in [23]–[24] was discussed by [15]. A prominent ankle (signature 2 in Figure 3) may account for this effect.
2. The unusual spectral hardening towards lower energies [25] is explained by the existence of a "magnetic cutoff" (signature 3 in Figure 3), as the authors of [25] themselves note (however, see [36] and [25] itself for other possible explanations).
3. The same spectral feature (a prominent magnetic cutoff) may account for the result of [26], as discussed in [35].
4. Finally, "halos" observed around some blazars also may be explained in the context of the EM cascade model [27].
Thus, the EM cascade model appears to be the simplest extragalactic γ-ray propagation scenario that coherently explains all these anomalies. Other, more exotic models that could account for a part of these anomalies do exist [37]–[38]; the main difficulties of these scenarios were discussed by us in [15],[18].

III. CONCLUSIONS

Recent observations of some blazars in the 1 GeV – 10 TeV energy region seem to indicate that the secondary component of cascade γ-rays may constitute a considerable contribution to the observable flux in the E =1–500 GeV energy range.

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