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Constraints on the Intergalactic Magnetic Field

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Abstract: High energy particles interacting with the extragalactic photon background initiate electromagnetic pair cascades. We discuss the resulting constraints on the intergalactic magnetic field (IGMF) for time-variable sources. In particular, we show that the non-observation of 1ES 0229+200 by Fermi-LAT requires that magnetic fields fill at least 60% of space. Thus the (non-) observation of GeV extensions around TeV blazars probes the extragalactic magnetic field in voids and puts strong constraints on the origin of IGMF, favoring a primordial origin. We present also a new public code for the calculation of electromagnetic cascades.

Keywords: galaxies, gamma rays, magnetic fieds, electromagnetic cascade, intergalactic space.

1 Introduction

At present stage very little is known about the magnetic fields in the intergalactic space [1, 2]. The relatively strong (μG scale) fields in galaxies and galaxy clusters are generally assumed to result from an amplification of much weaker magnetic seed fields. However, both the origin and the structure of such magnetic seeds still remain a mystery. They could have been created in the early universe, e.g. during phase transitions, being further amplified by plasma processes [3]. Alternatively, an early population of starburst galaxies or active galactic nuclei (AGN) could have generated the seeds of intergalactic magnetic fields (IGMF) at high reshifts, before galaxy clusters formed as gravitationally bound systems [4, 5]. A quite different possibility is that the ejecta of AGNs magnetized the intracluster medium only at low reshifts, in which case magnetic fields would be confined within galaxy clusters, thus filling only a small fraction of space.

While only weak upper limits have been established on the IGMF strength, based on Faraday rotation measurements, an alternative approach to obtain information on IGMF properties is based on studies of photon spectra of TeV-bright gamma-ray sources. The initial γ-ray flux from distant blazars is strongly attenuated by pair production on the infrared/optical extragalactic background light (EBL). On the other hand, the pair-produced electrons and positrons emit secondary photons via the inverse Compton scattering (ICS) process, thus contributing to the development of electromagnetic (e/m) cascades in the intergalactic medium. The charged component of the cascades is deflected by magnetic fields and delayed with respect to the direct photon signal. This leads to potentially observable effects, like delayed "echoes" of multi-TeV gamma-ray flares [6, 7] or the appearance of extended emission around initially point-like sources [8, 9, 10, 11, 12], which could be used to infer IGMF properties.

A somewhat different way to derive lower limits on the IGMF strength has been proposed recently in [13, 14], based on non-observation of GeV γ-ray signal from TeV-bright blazars. Generally, for distant sources characterized by a hard TeV photon spectrum and a low intrinsic GeV emission one expects the GeV γ-ray flux to be dominated by the above-discussed cascade contribution. Hence, the absence of the signal in the GeV range can be naturally explained by the cascade deflection in relatively strong magnetic fields: the final photons appear to be spread over a large extended "halo" while contributing very little to the point-like image. The analysis of the *Fermi*-LAT observations of distant blazars, notably of 1ES 0229+200, has resulted in the lower bound $B_{\rm IGMF} \gtrsim 10^{-15}$ G [13, 14]. However, as stressed in [15], the obtained limits depend strongly on the assumption that the source emission remains stationary on large time scales. Another open question concerns the influence of the IGMF structure on the GeV γ-ray fluxes.

1.1 Calculation method

We choose to address the problem describing the development of e/m cascades in the intergalactic medium with the help of Monte Carlo methods. We use the program

ELMAG[1] which provides an efficient cascade simulation, taking into account the relevant physical processes, as the e^+e^--pair production, inverse Compton scattering, and synchrotron losses of charged particles, and treats angular deflections of electrons and positrons by IGMF and the related time-delays using the small angle approximation, as discussed in more detail in [16].

For small $\theta_{\rm obs}$, the cascade geometry can be approximated by a triangular configuration, providing simple relations between the observation angle $\theta_{\rm obs}$, the cascade deflection angle $\theta_{\rm defl}$, and the jet opening angle of the source $\theta_{\rm jet}$ [10]:

$$\theta_{\rm jet} + \theta_{\rm obs} = \theta_{\rm defl} \tag{1}$$

$$\theta_{\rm obs} \simeq x/L\, \theta_{\rm defl}, \tag{2}$$

with L being the distance to the source, x – the distance from the source to the emission point of the final photon, and with $\theta_{\rm defl}$ obtained as the squared average of partial $e^\pm$ deflections in the cascade chain: $\theta_{\rm defl} = \sqrt{\sum_i \theta^2_{{\rm defl}(i)}}$. Here $\theta_{{\rm defl}(i)}$ is proportional to the distance $\Delta x_e^{(i)}$ travelled by i-th electron (positron) between its production and emission of the next photon in the given cascade branch:[2]

$$\theta_{{\rm defl}(i)} \propto B_{\rm IGMF}\, \Delta x_e^{(i)}. \tag{3}$$

For the photon time delay one thus obtains

$$\Delta\tau \simeq \frac{2x}{c}\,(1 - x/L)\,\theta^2_{\rm defl}, \tag{4}$$

with c being the speed of light. While average values for x and $\Delta x_e^{(i)}$ are defined respectively by the TeV photon mean free pass in the EBL $l_{\gamma\gamma_{\rm b}} \sim 100$ Mpc and the electron cooling length $l_e^{\rm cool} \sim$ few $\times$ 100 kpc (for the energy range of interest), the obtained distributions of $\theta_{\rm obs}$ and $\Delta\tau$ prove to be very sensitive to fluctuations of the above quantities, which are naturally accounted for by the Monte Carlo procedure. In particular, photons produced close to the source are observed under small angles [c.f. Eq. (2)], thus contributing to the point-like image. On the other hand, i-th $e^\pm$ emits first few photons on the length scale of its mean free pass in the EBL $l_{e\gamma_{\rm b}} \sim$ few kpc $\ll l_e^{\rm cool}$, which results in pronounced tails of the time-delay distributions, with characteristic values of $\Delta\tau$ being few orders of magnitude smaller than the average values.

2 Results for stationary source emission

We concentrate on the gamma-ray emission from the blazar 1ES 0229+200 which provided the most stringent limits on the IGMF strength in the previous studies [13, 14]. We follow essentially the same assumptions about the source and the sensitivity of the *Fermi*-LAT instrument as in Ref. [14], using in particular a hard photon injection spectrum $\mathcal{F} \sim E^{-2/3}$ consistent with *Swift* observations [17], with a cutoff at $E_{\rm max} = 20$ TeV, and a jet opening angle $\theta_{\rm jet} = 6^{\rm o}$. We describe EBL using the best-fit model of Ref. [18] and calculate point-like flux of the source in the GeV range summing all photons with arrive within the angle θ_{95} characterizing the point-spread function (PSF) of *Fermi*-LAT while using $\theta_{95} = 0.11^{\rm o}$ above 300 GeV (as the typical angular resolution of Cherenkov telescopes).

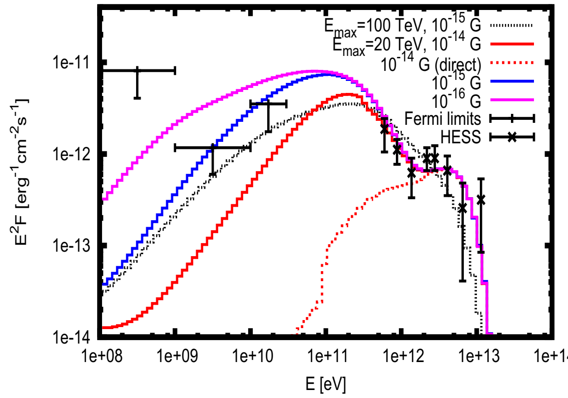

Figure 1: Fluence contained within the 95% confidence contour of the PSF of Fermi-LAT as a function of energy together with Fermi-LAT upper limits and HESS observations for a uniform magnetic field with strengths (from top to bottom) $B = 10^{-16}, 10^{-15}, 10^{-14}$ G with $E_{\rm max} = 20$ TeV (solid lines) and $B = 10^{-15}$ G with $E_{\rm max} = 100$ TeV (dotted line). The direct component for $B = 10^{-14}$ G is also shown by a dashed line.

The calculated γ-ray fluence of 1ES 0229+200 within the 95% confidence contour of the PSF of *Fermi*-LAT is shown in Fig. 1 for different values of the IGMF strength in comparison with HESS data [19] and the *Fermi*-LAT upper limits derived in [14]. Here, like in [13, 14], we assumed the source to be stationary and the magnetic field to be uniform in space. The obtained results agree qualitatively with the ones of the previous studies, resulting in the limit $B_{\rm IGMF} \gtrsim 10^{-15}$ G on the IGMF strength. However, the obtained spectral shapes differ substantially from the ones in [14]. In particular, for the relatively low cutoff energy $E_{\rm max} = 20$ TeV, one observes a spectral shoulder in the TeV range, which is also indicated by the HESS data. This due to the fact that only direct photons (i.e. photons arriving to the observer without interacting on EBL) contribute to the TeV γ-ray spectra in that case, while the cascade photon contribution strongly dominates at sub-TeV energies.

How will the above results change if the magnetic field is concentrated inside cosmological structures like filaments rather than filling uniformly all the space? We investigate such a case using the simple top-hat profile for the EGMF structure: assuming a strong magnetic field $B = 10^{-10}$ G in filaments which occupy a fraction f of space, being separated by $D = 10$ Mpc (as the typical distance between large scale structures), and setting the field strength to ze-

1. URL: `http://elmag.sourceforge.net/`

2. For small coherence scale of IGMF, $L_{\rm coh} \ll \Delta x_e^{(i)}$, one rather obtains $\theta_{{\rm defl}(i)} \propto \sqrt{B_{\rm IGMF}\, \Delta x_e^{(i)}}$.

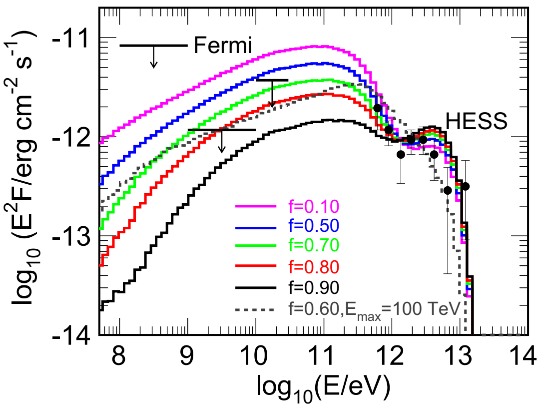

Figure 2: Fluence contained within the 95% confidence contour of the PSF of Fermi-LAT as a function of energy for the top-hat profile of the extragalactic magnetic field with the filling factor (from top to bottom) $f = 0.1, 0.5, 0.7, 0.8, 0.9$ for $E_{\max} = 20$ TeV (solid lines) and with $f = 0.6$ for $E_{\max} = 100$ TeV (dashed line).

ro in voids. The obtained results for the fluence contained within the PSF of *Fermi*-LAT are shown in Fig. 2. It is easy to see that the consistency with the *Fermi*-LAT upper limits requires that sufficiently strong magnetic fields fill most of space ($\gtrsim 80\%$). The obtained limit is practically independent on the field strength for $B \gtrsim 5 \times 10^{-15}$ G and is only slightly reduced (to $\sim 60\%$) when using a higher cutoff $E_{\max} = 100$ TeV for the injection spectrum.

The obtained results can be easily understood when we keep in mind that the mean free pass of TeV γ-rays through the EBL is much larger than the sizes of both the filaments and the voids, $l_{\gamma\gamma_b} \gg D$, while the opposite is true for the electron cooling length: $l_e^{\rm cool} \ll \min\{f, 1-f\}\, D$. Taking into account that for the energies considered the dominant contribution to the final spectra comes from simple two-step e/m cascades ($\gamma \to e^{\pm} \to \gamma$), we have two possible cases:

1. With the probability f, the initial γ-ray interacts in a filament. The produced $e^{\pm}$ also propagates in the filament, being strongly deflected by the magnetic field (Fig. 3). Hence, the final photon can arrive to the observer under large angle only, thus giving no contribution to the point-like flux.

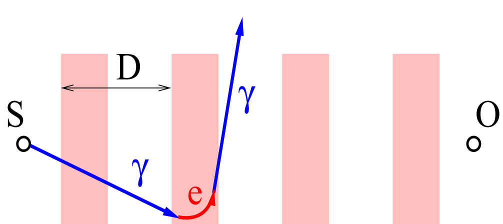

Figure 3: Case 1: primary photon interacts in a filament.

2. With the probability $(1-f)$, an $e^{\pm}$ is produced in a void and remains undeflected until it emits the final photon, the latter going straight to the observer (Fig. 4).

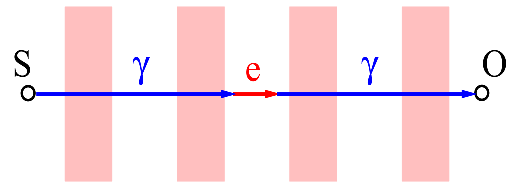

Figure 4: Case 2: primary photon interacts in a void.

Therefore, the observed γ-ray flux has a simple relation to the one expected in the absence of any magnetic field:

$$\text{observed flux}(f, B \to \infty) = (1-f) \times \text{flux}(B=0). \quad (5)$$

For higher $E_{\max}$, a non-negligible contribution comes from multi-step cascades, in which case all the intermediate $e^{\pm}$-pairs in a given cascade branch have to be produced in the voids – in order to have the final photon undeflected. This results in a somewhat stronger suppression of γ-ray fluxes compared to the case $B = 0$, hence, a slightly weaker bound on the IGMF filling factor f has been obtained for $E_{\max} = 100$ TeV.

Similar limits on the cumulative space filling by IGMF have been obtained when using realistic IGMF profiles resulting from cosmological MHD simulations [20].

3 Effect of time delays

As blazars are generally variable objects, the suppression of the GeV γ-ray flux from 1ES 0229+200 may also be caused by the time-delay of the cascade signal with respect to the direct TeV photons measured by HESS – if the source was active for a relatively short time [15]. To check the influence of the potential variability of the source, we calculated the γ-ray fluence contained within the PSF of *Fermi*-LAT for different time-delay bins, as shown in Fig. 5(left) for $B_{\rm IGMF} = 10^{-17}$ G. Additionally, in Fig. 5(right) we show the corresponding fluxes for cumulative time-binning. It is easy to see from Fig. 5(left) that the stability of the source on a few years scale is sufficient to set the lower bound on the IGMF strength $B_{\rm IGMF} \gtrsim 10^{-17}$ G for a uniformly distributed field. As the time delay scales with B as $\Delta\tau \propto B^2$ [c.f. Eqs. (3-4)], the above-quoted limit $B_{\rm IGMF} \gtrsim 10^{-15}$ G requires the source to be stationary on a scale of few $\times\, 10^4$ yr.

At the same time, the conclusion that non-zero magnetic fields have to fill most of space remains unmodified – due to the relation (5) for the corresponding fluxes. The source life-time impacts the limits on the IGMF strength but has no influence of the IGMF filling factor – as far as the field is stronger than $\sim 5 \times 10^{-15}$ G, as illustrated in Fig. 6.

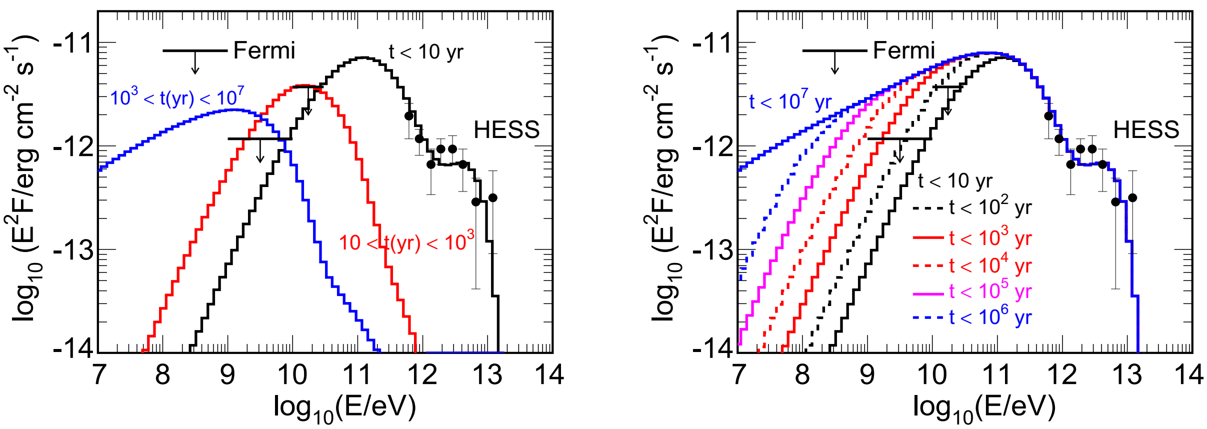

Figure 5: Fluence contained within the 95% confidence contour of the PSF of Fermi-LAT as a function of energy for $B = 10^{-17}$ G and $E_{\max} = 20$ TeV: for different time-delay bins (left) and for cumulative time-binning (right).

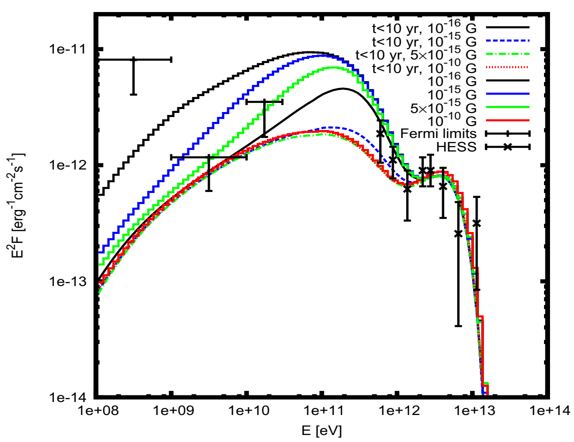

Figure 6: Fluence contained within the 95% confidence contour of the PSF of Fermi-LAT as a function of energy for $E_{\max} = 20$ TeV, $f = 0.8$, and $B = 10^{-16}, 10^{-15}, 5 \times 10^{-15}, 10^{-10}$ G: for stationary sources – solid histograms (from top to bottom) and for $\tau_{\rm source} < 10$ yr – solid, dashed, dot-dashed, and dotted lines correspondingly.

4 Conclusions

We have calculated the fluence of 1ES 0229+200 as seen by Fermi-LAT using a Monte Carlo simulation for the cascade development. We have discussed the effect of the IGMF structure on the resulting suppression of the point-like flux seen by Fermi-LAT. Since the electron cooling length is much smaller than the mean free path of the TeV photons, a sufficient suppression of the point-like flux requires that extragalactic magnetic fields fill a large fraction of space along the line-of-sight towards 1ES 0229+200, $f \gtrsim 0.6$. The lower limit on the magnetic field strength in this volume is $B \sim \mathcal{O}(10^{-15})$ G, assuming that the source is stable at least for few $\times 10^4$ yr, weakening as $\propto \sqrt{\tau_{\rm source}}$ for a shorter life-time of the source. These limits put very stringent constraints on the origin of IGMFs: either the seeds for IGMFs have to be produced by a volume filling process (e.g. primordial) or very efficient transport processes have to be present which redistribute magnetic fields that were generated locally (e.g. in galaxies) into filaments and voids with a significant volume filling factor.

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