Constraints on the intergalactic magnetic field from gamma-ray observations of TeV blazars

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Abstract. We discuss different approaches to infer the properties of the intergalactic magnetic field (IGMF) from gamma-ray observations of blazars. In particular, we investigate constraints on the IGMF strength and spacial distribution, resulting from studies of TeV blazars by imaging atmospheric Cherenkov telescopes and the *Fermi*-LAT instrument. We demonstrate that the non-observation of GeV gamma-rays from powerful TeV blazars indicates that more than 60% of space is filled by magnetic fields with stength $\gtrsim 10^{-15}$ G, favoring the primordial IGMF origin.

1. Introduction

At present stage very little is known about 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 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 redshifts, before galaxy clusters formed as gravitationally bound systems [4]. A quite different possibility is that the ejecta of AGNs magnetized the intracluster medium only at low redshifts, 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 way to study intergalactic magnetic fields is based on observations 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 process. Thus, an electromagnetic (e/m) cascade develops 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 [5, 6] or the appearance of extended emission around initially point-like sources [7, 8, 9, 10, 11], which could be used to infer IGMF properties (see [12] for experimental limits on extended emission).

A different way to derive lower limits on the IGMF strength has been proposed 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, the obtained limits depend strongly on the assumption that the source emission remains stationary on large time scales [15, 16]. Another open question concerns the influence of the IGMF structure on the GeV γ-ray fluxes.

2. Calculation method

We employ a Monte Carlo description for the development of e/m cascades in the intergalactic medium. We use the program ELMAG [17] 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.

For small $\theta_{\rm obs}$ we are interested in, one obtains a simple relation between the observation angle $\theta_{\rm obs}$ and the cascade deflection angle $\theta_{\rm defl}$ [9]: $\theta_{\rm obs} \simeq x/L\, \theta_{\rm defl}$, with L being the distance to the source, x is the distance from the source to the emission point of the final photon, and with $\theta_{\rm defl}$ obtained as a 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 $\Delta x_e^{(i)}$ traveled by i-th electron (positron) between its production and the emission of the next photon in the given cascade branch:[1]

$$\theta_{{\rm defl}(i)} \propto B_{\rm IGMF}\, \Delta x_e^{(i)}. \tag{1}$$

Similarly, for the cascade photon time delay with respect to the primary emission one obtains

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

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 path 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, thus contributing to the point-like image. On the other hand, each $e^{\pm}$ emits first few photons on the length scale of its mean free path in the EBL $l_{e\gamma_b} \sim$ 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.

3. Results for stationary source emission

We concentrate on the gamma-ray emission from the blazar 1ES 0229+200, positioned at redshift $z = 0.14$, 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 $\mathcal{F}{\sim}E^{-2/3}$, 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 which 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 imaging atmospheric Cherenkov telescopes (IACTs).

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

Assuming the source to be stationary and the magnetic field to fill uniformly the space, we obtained the same limit on the IGMF strength, $B_{\rm IGMF} \gtrsim 10^{-15}$ G, as in the previous studies [13, 14]. To investigate a more realistic case, when magnetic fields are concentrated inside cosmological structures like filaments, we use a top-hat profile for the spacial structure of IGMF: 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 zero in voids. The obtained results for the fluence contained within the PSF of *Fermi*-LAT are shown in Fig. 1. It is easy to see that the consistency with *Fermi*-LAT upper bounds requires that sufficiently strong magnetic fields fill most of space ($\gtrsim 80\%$). The obtained limit is practically independent on the field strength for $B \gtrsim 5\times10^{-15}$ G and is only slightly reduced (to $\sim 60\%$) when using a higher cutoff $E_{\rm max} = 100$ TeV for the injection spectrum.

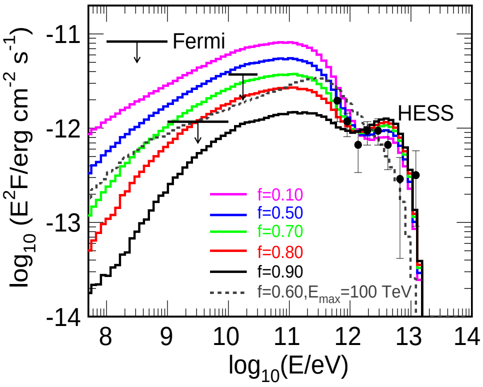

Figure 1. Fluence contained within the PSF of *Fermi*-LAT as a function of energy for the top-hat profile of magnetic field with the filling factor (from top to bottom) $f = 0.1, 0.5, 0.7, 0.8, 0.9$ for $E_{\rm max} = 20$ TeV (solid lines) and with $f = 0.6$ for $E_{\rm max} = 100$ TeV (dashed line). *Fermi*-LAT upper bounds derived in [14] and HESS data [19] are also shown.

The obtained results can be easily understood when we keep in mind that the mean free path of TeV γ-rays through the EBL exceeds significantly the spacial scale for the IGMF distribution, $l_{\gamma\gamma_b} \gg D$, 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:

(i) With the probability f, the initial γ-ray interacts in a filament; produced $e^\pm$ also propagate in the filament, being strongly deflected – Fig. 2 (left). Hence, the final photon can arrive to the observer under large angle only, thus giving no contribution to the point-like flux.

(ii) 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. 2 (right).

The observed γ-ray flux is thus related to the one expected in the absence of magnetic fields as

$$\text{observed flux}(f, B \to \infty) = (1-f) \times \text{flux}(B = 0). \tag{3}$$

For higher $E_{\rm max}$, 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 stronger suppression of γ-ray fluxes, hence, a slightly weaker bound on the IGMF filling factor f has been obtained for $E_{\rm max} = 100$ TeV.

Similar limits on the cumulative space filling by IGMF have been obtained when using realistic IGMF profiles resulting from cosmological MHD simulations [15].

Figure 2. Case 1 (left): primary γ-ray interacts in a filament; produced $e^\pm$ are strongly deflected by IGMF. Case 2 (right): primary γ-ray interacts in a void; produced $e^\pm$ remain undeflected.

4. 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 direct TeV photons – if the source was active for a relatively short time [16]. 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 for $B_{\rm IGMF} = 10^{-17}$ G, as shown in Fig. 3. Clearly, the stability of the source on a few years scale is sufficient to set the lower bound $B_{\rm IGMF} \gtrsim 10^{-17}$ G for a uniformly distributed field, a similar result obtained in [20]. As the time delay scales as $\Delta\tau \propto B^2$ [c.f. Eqs. (1-2)], 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. On the other hand, the conclusion that non-zero magnetic fields have to fill most of space remains unmodified due to the relation (3). The source life-time thus impacts limits on the IGMF strength, not on the filling factor.

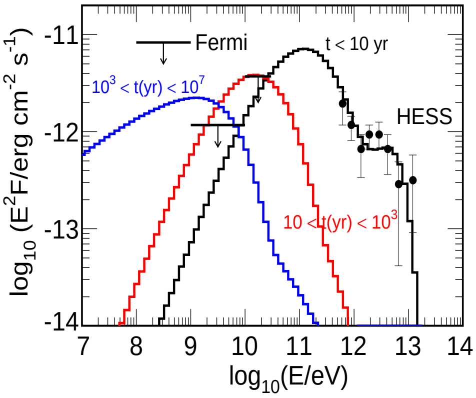

Figure 3. Fluence contained within the PSF of Fermi-LAT as a function of energy for $B = 10^{-17}$ G and $E_{\rm max} = 20$ TeV for different time-delay bins.

In conclusion, simultaneous observations of powerful blazars by IACTs and *Fermi*-LAT have large potential for studying the IGMF properties. In particular, presently available data, notably on 1ES 0229+200, imply that extragalactic magnetic fields fill a large fraction of space, $f \gtrsim 0.6$. 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 (e.g. primordial) mechanism 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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