Large-Scale Diffuse Intergalactic Magnetic Fields Constraints with the Cherenkov Telescope Array

Paramita Barai¹, Elisabete M. de Gouveia Dal Pino¹ (on behalf of the CTA Collaboration)

¹Instituto de Astronomia, Geofísica e Ciências Atmosféricas - Universidade de São Paulo (IAG-USP), Rua do Matão 1226, São Paulo, 05508-090, Brazil
email: paramita.barai@iag.usp.br

Abstract. Magnetic fields of the order of $\mu$-Gauss are observationally detected in galaxies and galaxy clusters, which can be (at least) in part originated by the amplification of much weaker primordial seed fields. These fields should be carried out by strong galactic outflows, magnetically enriching the InterGalactic Medium (IGM). However direct observation of magnetic fields in the IGM is scarce. This talk will give a review of how Intergalactic Magnetic Field (IGMF) can be constrained using gamma-ray observations. High-energy TeV photons emitted by distant blazars can interact with the cosmic extragalactic optical/infrared/microwave background light, producing electron-positron pairs, and initiating electromagnetic cascades in the IGM. The charged component of these cascades is deflected by IGMFs, thereby reducing the observed point-like TeV flux, and creating an extended image in the GeV energy range, which can potentially be detected with $\gamma$-ray telescopes (Fermi-LAT, HESS, CTA). Studies (e.g., Nerov & Vovk 2010, Dolag et al. 2011) have put lower limits on the IGMF strength of the order of $10^{-16} - 10^{-15}$ G, and filling factors of 60%. This talk will describe the constraints which the Cherenkov Telescope Array sensitivity is expected to give (CTA Consortium 2018).

Keywords. magnetic fields, instrumentation: high angular resolution, methods: data analysis, (galaxies:) BL Lacertae objects: general, intergalactic medium, gamma rays: observations

1. Introduction

Magnetic Fields (MF) of the order of (1–10)$\mu$G are observed (e.g., Berkhuijsen et al. 2003) in galaxies and galaxy clusters. These fields are understood to be created from the amplification of much weaker primordial seed fields, by turbulent dynamo effects and baryonic processes. The origin of these tiny seed fields is unknown (e.g., Widrow 2002). There are 2 classes of concordance models for the generation of primordial seed fields. One is Cosmological origin: where the seed fields are produced in the early primordial Universe (e.g., Grasso & Rubinstein 2001). The other is Astrophysical origin: where the seed fields are produced by plasma motions from baryonic processes (star-formation, supernovae, black holes) in galaxies (e.g., Ryu et al. 2012).

A potentially relevant component of cosmic MF, of which very little is known yet, is the Intergalactic Magnetic Field (IGMF) existing in the low-density InterGalactic Medium (IGM), or the space between galaxies not related to gravitational collapse. The MFs inside galaxies are dragged out by powerful galactic outflows generated by energy feedback from baryonic processes with time, and dispersed into the IGM. Over cosmological epochs these IGMFs permeate the turbulent IGM, and may be even amplified by turbulent dynamo action (e.g., de Gouveia Dal Pino 2011), at the same time influencing large scale structure formation (e.g., Dolag 2006, Barai 2008).
The knowledge of IGMF distribution is crucial in understanding the cosmological versus astrophysical origin of cosmic MF. It is challenging to directly observe the IGMF, because they are diffuse and weak in intensity. An upper limit: $B_{\text{IGM}} < (10^{-8} - 10^{-9}) G$, is provided by standard constraints: Big Bang nucleosynthesis, Cosmic Microwave Background (CMB) anisotropy (e.g., Durrer et al. 1998), Faraday rotation measures of polarized radio emission from quasars (e.g., Pshirkov et al. 2016). Here we will overview how IGMF can be constrained using $\gamma$-ray observations, which provide lower limits for it.

2. IGMF Constraints using $\gamma$-ray Observations of Blazars

A novel technique to constrain the IGMF’s strength and filling factor uses Very-High-Energy (VHE) $\gamma$-ray emission from distant blazar sources. Blazars are Active Galactic Nuclei (AGN) with the central supermassive black hole jet pointed toward our line of sight, and present rapid variability (e.g., Aharonian et al. 2007). The observed spectral energy distributions of blazars (e.g., Bonnoli et al. 2015) are fitted to models, where the TeV $\gamma$-ray emission comes from the jet base. There, relativistic electrons ($e^-$) upscatter, by Inverse Compton (IC), lower-energy ambient photons to the TeV. Relativistic protons can also have a contribution, by emitting direct synchrotron radiation, or by the creation of secondary pions, which decay into TeV photons.

The VHE primary TeV photons ($\gamma_{\text{VHE}, 1}$) emitted by distant blazars undergo the following interactions, as they travel 100s-of-Mpc intergalactic space before reaching Earth:  

$$
\gamma_{\text{VHE}, 1} + \gamma_{EBL} \rightarrow e^-_1 e^+_1,
\quad e^-_1 + \gamma_{CMB} \rightarrow \gamma_{\text{VHE}, 2} + e^-_2.
$$

Firstly, the $\gamma_{\text{VHE}, 1}$ interact with optical/infrared/microwave Extragalactic Background Light (EBL), and cause $e^- e^+$ pair production. These very-energetic electrons undergo IC scattering off CMB photons and produce secondary $\gamma$-rays ($\gamma_{\text{VHE}, 2}$) in the GeV energy range, as shown in Fig. 1 (Sol et al. 2013a). The $e^- e^+$ pair electromagnetic cascades are deflected by IGMF present in the intervening space, and the secondary GeV $\gamma_{\text{VHE}, 2}$ are strongly attenuated as they appear on Earth. These attenuated secondary GeV components can be detected with our $\gamma$-ray telescopes (Fermi-LAT, HESS, CTA), as either:

- **Pair Halo**: Spatially-extended GeV emission around primary TeV $\gamma_{\text{VHE}, 1}$ signal. These are expected for $B_{\text{IGM}} > \sim 10^{-16} G$, and involve imaging analysis searches for extended pair halos around blazars. (Larger IGMFs produce larger deflections, resulting in a weaker pair halo flux, that can make it undetectable with current instruments.)

- **Pair Echo**: GeV emission with a time delay relative to the primary. These are expected for $B_{\text{IGM}} < 10^{-16} G$, and involve time-resolved spectral analysis of pair echoes. Studies usually model the $e^- e^+$ pair cascade development using Monte-Carlo simula-
tions, compute the simulated pair halo and/or pair echo assuming some IGMF configuration, compare with observations (e.g., Fermi data on blazars), and derive IGMF constraints (e.g., Alves Batista 2017). However, several studies have inferred a non-detection of secondary components, which nevertheless provide lower limits on $B_{\text{IGM}}$, assuming that the suppression of GeV flux is due to the deflection of $e^- e^+$ pairs by IGMF. E.g. Neronov & Vovk (2010) found a lower limit of $B_{\text{IGM}} \geq 3 \times 10^{-16} \text{G}$. Dolag et al. (2011) inferred that IGMF fills at least 60% of space with fields stronger than $B_{\text{IGM}} \geq 10^{-16} - 10^{-15} \text{G}$. Considering a coherence length $> 1 \text{Mpc}$ for the IGMF and persistent TeV emission, Taylor et al. (2011) inferred a $B_{\text{IGM}} > (10^{-17} - 10^{-15}) \text{G}$.

A first hint for the existence of pair halos (extended emission around a point-source) has been found by Chen et al. (2015), by the stacking analysis of 24 blazars at $z < 0.5$ using Fermi-LAT data. It implies a magnetic field strength of $B_{\text{IGM}} \sim 10^{-17} - 10^{-15} \text{G}$, using a Bayesian statistics.

3. $\gamma$-ray Pair Halo to be Observed by the Cherenkov Telescope Array

The Cherenkov Telescope Array (CTA) is a planned next-generation ground-based $\gamma$-ray observatory (CTA Consortium 2018). CTA will provide the deepest insight into the non-thermal VHE Universe ever reached, probing the physical conditions of cosmic accelerators like black holes and supernovae. It will consist of an array of around 100 imaging atmospheric Cherenkov telescopes of various sizes. CTA foresees a factor of 5–10 improvement in sensitivity in the energy domain ($\sim 100 \text{ GeV} - 10 \text{ TeV}$) of current Cherenkov telescopes: HESS, MAGIC, and VERITAS. It is also expected to extend the observable VHE range to below 100 GeV and above 100 TeV, and have unprecedented angular and energy resolution, as well as a wider field-of-view. A Northern site (Canarias Islands) and a Southern site (Chile) are planned for a full sky coverage.

Elyiv et al. (2009) performed Monte Carlo simulations of 3D electromagnetic cascades (described in §2). One of the cases they simulated is a blazar source at a distance 120 Mpc, and $B_{\text{IGM}} = 10^{-14} \text{G}$. The expected geometry of Pair Halo from this blazar is presented in Fig. 2- left panel. The sky Field-of-View (FoV) of 1.5° is indicated by the blue-dashed circle, which is equal to the radius of the FoV of the MAGIC telescope. And a 2.5° FoV is denoted by the red-solid circle, which corresponds to the size of the FoV of the HESS telescope. These would perfectly fit into the much larger FoV of CTA.

Sol et al. (2013b) estimated the pair halo flux using a theoretical model of differential angular distribution of a pair halo at $z = 0.129$ with $E_\gamma > 100 \text{ GeV}$ (Eungwanichavapant & Aharonian 2009), and assuming an observation time of 50 hours. The pair halo emission is displayed in Fig. 2- right panel, as the dashed curve. The CTA sensitivity curves are overplotted as the solid lines: the CTA South (North) site is labeled as I (NB). Hence CTA should well observe pair halos in the energy range ($0.1 - 5$) TeV.

4. Conclusions

The observational detection of IGMF (extremely tiny magnetic fields permeating the cosmos on the largest scales) can shed light on the origin of seed fields in the Universe. Current results of VHE $\gamma$-ray astronomy conclude to the existence of a non-zero IGMF: $10^{-17} \text{G} < B_{\text{IGM}} < 10^{-14} \text{G}$, mostly based on the non-detection of expected secondary GeV $\gamma$-rays. Future theoretical studies need to take into account possible additional effects in the IGM, e.g. energy losses by cosmic rays, plasma effects. Observationally the positive detection of Pair Halos and Pair Echos are needed with detailed data on cascade signatures, which the CTA with its improved sensitivity is expected to observe.
Figure 2. Left panel: Open black circles indicate the arrival directions of primary and secondary \( \gamma \)-rays from a blazar (details in \( \S \)), with the circle sizes proportional to the photon energies (as labeled in TeV at the bottom of the figure). Sky FoVs of 1.5\(^\circ\) and 2.5\(^\circ\) are shown by the blue-dashed and red-solid circles. Figure from Elyiv et al. (2009). Right panel: Estimated flux for the expected pair halo emission compared to the CTA sensitivity curves for the southern (I) and northern (NB) sites. Figure from CTA Consortium (2018), originally from Sol et al. (2013b).

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