PROCEEDINGS OF SCIENCE

Intergalactic magnetic field studies by means of the gamma-ray emission from GRB 190114C

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The origin of the large-scale magnetic fields in the Universe is one of the long-standing problems in cosmology. To discriminate among the different explanations it is crucial measuring the intergalactic magnetic field (IGMF) in the voids among the galaxies. Gamma-rays coming from extragalactic sources can be used to constrain the IGMF due to their interaction with the intergalactic medium. Particularly, strong transients allow to constrain very weak magnetic fields. We used CRPropa 3 to propagate the measured VHE (Very High Energy, E>100 GeV) spectrum from GRB 190114C in the intergalactic medium. We then computed the expected cascade emission in the GeV domain for different IGMF settings and compare it with the *Fermi*-LAT limits for different exposure times.

7th Heidelberg International Symposium on High-Energy Gamma-Ray Astronomy (Gamma2022)
4-8 July 2022
Barcelona, Spain

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PoS(Gamma2022)085

1. Introduction

The origin of the large-scale magnetic field is one of the longstanding problems in cosmology. There is a general agreement that magnetic fields in galaxies originate from the amplification of pre-existing weak seed fields with unknown origin. Two different scenarios can be identified, considering either an astrophysical or a cosmological origin (see e.g [1] for a recent review). The main difference between the two scenarios is in the fact that, in case of cosmological origin, a non-negligible magnetic field in the voids in between the galaxies is expected. Indeed, although the contamination of the intergalactic medium by winds or outflows is possible, this contribution is limited and the seed fields far away from the structures should remain in their original form (see e.g. [2] and [3]). To discriminate between the two scenarios, it is crucial looking for signatures of magnetization in regions devoid of structures, the cosmic voids.
Contrary to the magnetic fields in galaxies and clusters of galaxies, the intergalactic magnetic field (IGMF) has never been detected. Only limits with different techniques have been derived so far (see e.g. Fig. 1 in [1]). In the simplest settings, the IGMF configuration can be characterized by two parameters: the field strength B, and the correlation length λ_B, the scale length within which the magnetic field can be considered uniform and constant. This means that all limits on the IGMF derived from observations can be presented in the so-called exclusion plot (B, λ_B). Due to the difficulties of direct detection, the observation of extragalactic γ-ray sources is a powerful instrument that can allow to study and constrain the IGMF. Very-high energy (VHE, $E > 100$ GeV) gamma-rays cannot propagate over large distances (~ Gpc) because they interact, via γ-γ pair production, with the extragalactic background light (EBL, [4]). For this reason the VHE spectra of extragalactic sources are affected by the EBL absorption which is stronger for more distant sources and more energetic source photons. The created pairs, during their travel in the intergalactic medium, interact with the cosmic microwave background (CMB) via Inverse Compton (IC) producing secondary γ-rays at lower energies with respect to the primary VHE photons. Typically $E \simeq 70(E_0/10\ \text{TeV})^2$ GeV where E the energy of the cascade IC photon and E_0 is the source primary photon [5]. In case of a non-negligible IGMF the pairs can be deviated, and because of the longer path length, the secondary GeV γ-rays result in a "pair-echo" delayed with respect to the primary emission from the source. The delay of the cascade signal can be used to constrain the IGMF because it depends on the IGMF configuration.
In this contribution we used the VHE emission of GRB 190114C to predict the lightcurves and the spectral energy distributions (SEDs) with Monte Carlo simulations for different IGMF configurations. We then compared these observables with the *Fermi*-LAT limits obtained for different observation times.

2. Simulation of pair echo emission

In order to model the cascade emission we used the Monte Carlo Code CRPropa 3 [7]. The code allows, given a particular primary VHE photon spectrum, to trace the development of the cascade in the intergalactic medium. In this framework the source is placed at the centre of a sphere with radius equal to the co-moving distance of the Earth to GRB 190114C (~1.6 Gpc). The source is assumed to emit VHE photons uniformly within a cone of 10° and as target photon

fields for γ-γ and IC interactions, we used the CMB and the Franceschini et al. [8] model for the EBL background. A photon that hits the sphere and has an energy larger than 0.05 GeV represents a particle arriving and being detected at Earth. The magnetic field is considered to be turbulent with a Kolmogorov spectrum between a minimum scale length of 1 Mpc and a maximum scale length of 25 Mpc. Such a configuration corresponds to $\lambda_B \simeq 5$ Mpc. It is defined in a cubic grid periodically repeated to cover the whole volume between the GRB the the Earth. We used CRPropa to inject 10^6 primary VHE photons with energies in the range 0.2–10 TeV. All particles are traced with a minimum step size of 10^{-4} pc, which is sufficient to reproduce the arrival time delay with an accuracy better than 3 hours. We calculate the time delay as the difference between the arrival time of the simulated cascade photon and the time that a particle moving at c would require to cover the luminous distance D to the GRB.
The shape of the intrinsic VHE spectrum is a crucial point of this work. We decided to infer the VHE spectral shape from a GRB model used to reproduce the multiwavelength SED. For this reason, we estimated the best-fit spectral parameters for GRB 190114C assuming a log-parabola in the energy range 0.2–10 TeV and in the first temporal bin 68–110 s of [9]:

$$F_E^{GRB} \propto \left(\frac{E}{E_0}\right)^{-2.5-0.2\log(E/E_0)} . \quad (1)$$

Since MAGIC started to observe the GRB at T_0+62 s (being T_0 the burst trigger time), we used the VHE lightcurve to extrapolate the flux up to T_0+6 s when the powerlaw of the afterglow likely started. The extrapolated VHE flux is about five times larger than the one published by MAGIC Collaboration. Finally we looked for the echo emission after $T_0 + 2 \times 10^4$ s to exclude all photons associated with the GRB afterglow in the GeV domain.

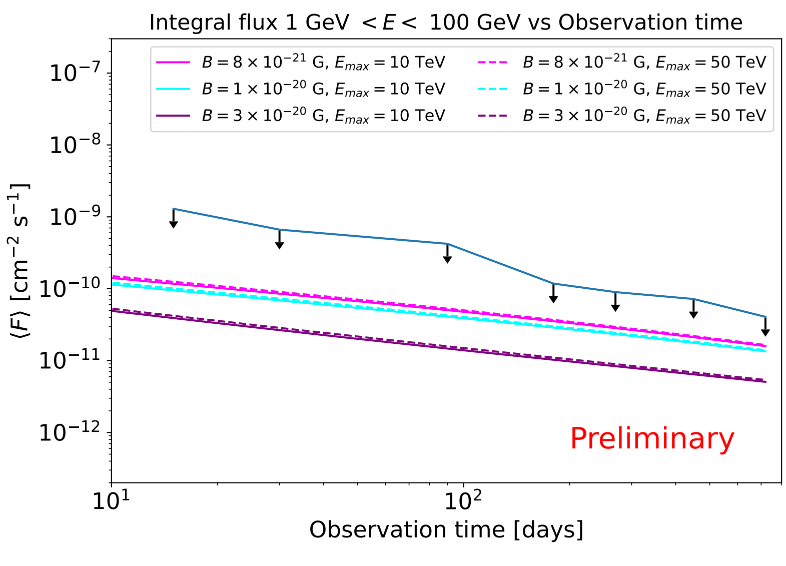

Figure 1: Expected echo daily lightcurves between 1 GeV and 100 GeV for different IGMF strengths and maximum primary energies. The lightcurves are plotted together with the *Fermi*-LAT upper limits.

We obtained upper limits above 1 GeV using P8R3 *Fermi*-LAT data after T_0+ 2×10^4 s for different exposure times. We performed our analysis in a $10^\circ \times 10^\circ$ region of interest, modelling a the background with 4FGL-DR2 catalog sources and the standard Galactic and isotropic diffuse models. We assumed the source to be point-like, since the cascade extension falls well within the point-spread function of the instrument for the time scales explored. To take into account the dilution in time of the echo flux both the SEDs and lightcurves have been averaged over the corresponding time window. The pair-echo lightcurves have been computed in the energy range 1-100 GeV and they are plotted in Fig. 1 together with the *Fermi*-LAT upper limits derived for 15 days, 1, 3, 6, 9, 15, and 24 months of observation time and for several IGMF strengths. In Fig. 2 the expected SED of the pair echo emission in the GeV domain are plotted together with the *Fermi*-LAT upper limits for several exposure times and IGMF strengths.

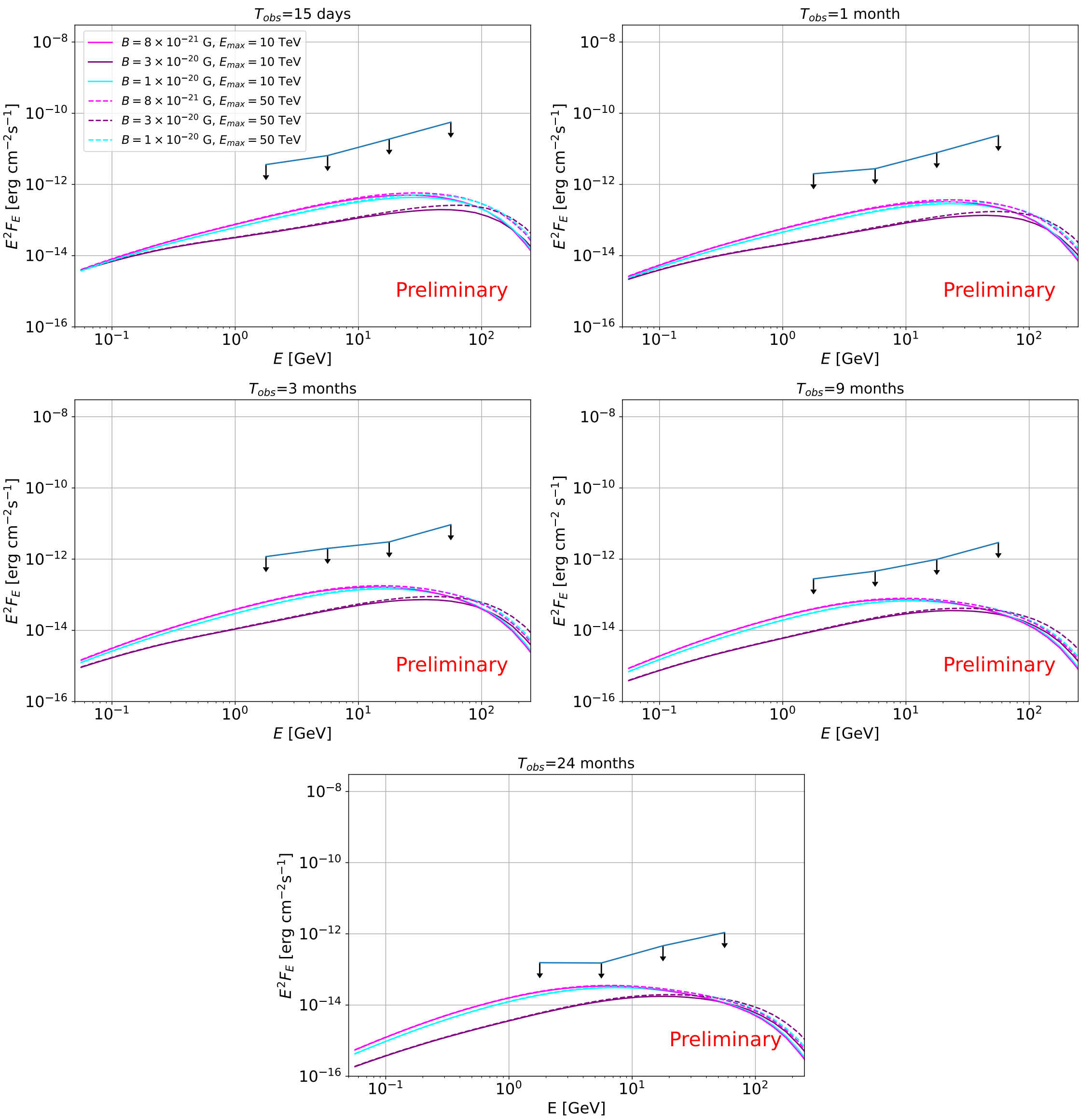

Figure 2: Expected SEDs for different IGMF strengths, observation times and for E_{max} = 10 and 50 TeV. The *Fermi*-LAT differential upper limits are also shown.

As we can see from the figures, we also tested whether a different choice of the maximum energy of the intrinsic VHE spectrum affects the results (E_{max}=10 and 50 TeV).

3. Conclusions

In this contribution, we used the γ-ray emission from GRB 190114C to infer the pair echo SEDs and lightcurves for different IGMF strengths. We used CRPropa 3 to simulate the cascade emission in the GeV domain originated by the interaction of the primary VHE GRB spectrum with the intergalactic medium. We then compared the simulated SEDs and lightcurves with the differential and integrated flux upper limits derived by analyzing the *Fermi*-LAT data. From both Fig. 1 and 2 we clearly see that no IGMF strengths can be constrained because the flux upper limits are well above the predicted cascade flux. This happens for both tested maximum energies of the intrinsic VHE spectrum E_{max}=10 and 50 TeV. Qualitatively the plots in Fig. 1 and 2 and can be explained in the following way: (1) The maximum cascade flux is contemporaneous to the afterglow. (2) Due to the decreasing flux of the signal with time, earlier times correspond to the maximum flux that we could probe. (3) On the other hand due to the limited observation time, the Fermi-LAT limits are also the least constraining. Increasing the observation time the Fermi-LAT limits improves, and the expected pair-echo signal decreases. (4) Concerning the behaviour under different magnetic fields, the larger B, the lesser is the cascade flux for a given time window.
Despite using a very promising GRB such as GRB 190114C, the IGMF remains unconstrained. The cascade flux is proportional the GRB time activity in the VHE band which is, in this case, around 5 hours. We would need the activity to be at least a factor of 5 larger (namely > 25 hours) in order to exclude IGMF strengths larger than 10^{-20} G for $T_{obs} > 9$ months.

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