Can we constrain the extragalactic magnetic field from very high energy observations of GRB 190114C?

T.A. Dzhatdoev
Federal State Budget Educational Institution of Higher Education,
M.V. Lomonosov Moscow State University, Skobeltsyn Institute of Nuclear Physics (SINP MSU),
1(2), Leninskie gory, GSP-1, 119991 Moscow, Russia and
Institute for Cosmic Ray Research, University of Tokyo, 5-1-5 Kashiwanoha, Kashiwa, Japan

E.I. Podlesnyi
Federal State Budget Educational Institution of Higher Education,
M.V. Lomonosov Moscow State University, Department of Physics,
1(2), Leninskie gory, GSP-1, 119991 Moscow, Russia and
Federal State Budget Educational Institution of Higher Education,
M.V. Lomonosov Moscow State University, Skobeltsyn Institute of Nuclear Physics (SINP MSU),
1(2), Leninskie gory, GSP-1, 119991 Moscow, Russia

(Dated: February 18, 2020)

Primary very high energy $\gamma$-rays from $\gamma$-ray bursts (GRBs) are partially absorbed on extragalactic background light (EBL) photons with subsequent formation of intergalactic electromagnetic cascades. Characteristics of the observable cascade $\gamma$-ray signal are sensitive to the strength and structure of the extragalactic magnetic field (EGMF). GRB 190114C was recently detected with the MAGIC imaging atmospheric Cherenkov telescopes, for the first time allowing to estimate the observable cascade intensity for various EGMF configurations. We inquire whether any constraints on the EGMF strength and structure could be obtained from publicly-available $\gamma$-ray data on GRB 190114C. We present detailed calculations of the observable cascade signal for various EGMF configurations. We show that the sensitivity of the Fermi-LAT space $\gamma$-ray telescope is not sufficient to obtain such constraints on the EGMF parameters.

I. INTRODUCTION

The recent detection of very high energy (VHE, $E > 100$ GeV) $\gamma$-rays from $\gamma$-ray bursts (GRBs) with imaging atmospheric Cherenkov telescopes (IACTs) MAGIC [1] and H.E.S.S. [2] have aroused great interest. Besides being important for the understanding of “intrinsic” physics of GRBs (e.g. [3–8]), these observations could in principle be used to constrain the spectrum of the extragalactic background light (EBL) as well as the strength and structure of the extragalactic magnetic field (EGMF). Primary VHE $\gamma$-rays escaping from the source are partially absorbed on EBL photons by means of the pair production (PP) process ($\gamma\gamma \rightarrow e^+e^-$) [9, 10]. This leads to a characteristic cutoff in the spectra of distant extragalactic sources [11]; the imprint of the EBL in the spectra of blazars was robustly detected with the Fermi-LAT space $\gamma$-ray telescope [12, 13] and IACTs (e.g. [14]). Secondary electrons get deflected in the EGMF and then produce cascade $\gamma$-rays; the parameters of the observable $\gamma$-ray flux are sensitive to the EGMF strength and structure [15, 17].

The first lower limits on the EGMF strength ($B \geq 3 \cdot 10^{-16}$ G) obtained with Fermi-LAT data on blazars using spectral information [17] were subsequently found to be subject to significant systematic effects including those related to the unknown duty cycle [18, 19] and poorly constrained spectral properties of the source, uncertainties of the EBL spectrum, etc. [20, 21]. In particular, [20] concluded that it is hard to rule out the zero-EGMF hypothesis. Under such circumstances, an independent channel of information is desirable such as that provided by GRB observations at very high energies [15, 22, 23].

In the present paper we perform detailed calculations of the observable intergalactic cascade signal from GRB 190114C taking into account statistical and systematic uncertainties of the intrinsic VHE $\gamma$-ray spectrum (i.e. the spectrum of $\gamma$-rays that have escaped into the intergalactic medium). This paper is organized as follows.

In Sect. II we reconstruct the intrinsic $\gamma$-ray spectrum of GRB 190114C. In Sect. III we present our results for the expected observable intergalactic cascade signal assuming various values of $B$. We conclude that the sensitivity of the Fermi-LAT telescope is not sufficient to constrain the EGMF (see Sect. IV). All graphs in the present paper were produced with the ROOT software toolkit [26].

Very recently, Wang et al. [27] (hereafter W20) found that observations of GRB 190114C with MAGIC and Fermi-LAT allow one to rule out $B < 3 \cdot 10^{-20}$ G [28]. Our results are significantly different from those of W20. In particular, in their Fig. 3 (middle panel) W20 present results for upper limits on the observed $\gamma$-ray spectral energy distribution (SED = $E^2dN/dE$, where $dN/dE$ is intensity) over the period of $\Delta T_{obs-LAT} = 1$ month obtained with Fermi-LAT. Additionally, they show model
results for observable $\gamma$-ray SEDs for three values of $B$: $10^{-19}$ G, $10^{-19.5}$ G, $10^{-20}$ G. Their curve corresponding to $B = 10^{-20}$ G overshoots the Fermi-LAT upper limits. Therefore, they draw out a conclusion that the hypothesis $B = 10^{-20}$ G is excluded. However, from the text of W20 it transpires that their model SEDs are instantaneous and not averaged over $\Delta T_{\text{obs-LAT}}$. These instantaneous SEDs are not directly comparable to the Fermi-LAT upper limits. In contrast, in this paper we present model results averaged over $\Delta T_{\text{obs-LAT}}$.

II. RECONSTRUCTED INTRINSIC SPECTRUM

The observable $\gamma$-ray intensity $dN/dE$ of GRB 190114C in the energy range of 0.2–1.1 TeV was measured with the MAGIC IACTs over the time period between $T_0 + T_1$ and $T_0 + T_2$ [1], where $T_0$ is the trigger time provided by the Burst Alert Telescope (BAT) onboard the Neil Gehrels Swift Observatory [29] and the $\gamma$-ray Burst Monitor (GBM) onboard the Fermi satellite [30]. $T_1 = 62$ s, and $T_2 = 2454$ s. The corresponding SED is shown in Fig. 1 together with its statistical uncertainties.

In what follows we assume that the intrinsic VHE $\gamma$-ray spectrum has a simple form $E^{-\gamma} \exp(-E/E_c)$. This is a reasonable assumption given the narrow energy range of the MAGIC spectrum (less than one order of magnitude). Assuming the EBL model of Gilmore et al. [31] (hereafter G12), we estimated the spectral parameters $\gamma$ and $E_c$ as follows. We assume the initial values of $(\gamma = 2, E_c = 10$ TeV) and calculate the observable intensity in all four bins of the MAGIC spectrum accounting for the effect of intergalactic absorption, dividing each of these bins to 21 parts in order to ensure small variation of the intergalactic $\gamma \gamma$ optical depth $\tau$ over any of these 84 new narrow bins. Then, varying the fitting parameters $(\gamma, E_c)$ and repeating the above-described procedure for every new set of these parameters, we minimize the chi-square form with the MINUIT package [32] integrated into the ROOT framework and determine the best-fit parameters. The corresponding best-fit observable spectrum is shown in Fig. 1 as black solid curve.

The intrinsic VHE $\gamma$-ray spectrum resulting from this procedure is also shown in Fig. 1 as black long-dashed curve. Finally, we account for the effect of redshift [33]; the resulting intrinsic VHE $\gamma$-ray spectrum in the source restframe is shown in Fig. 1 as black short-dashed curve. We repeat the whole procedure of the intrinsic spectrum reconstruction for three various normalizations of the EBL intensity, namely, those of 90 %, 80 %, and 70 % of the original EBL intensity according to the G12 EBL model. The results for these three runs of the optimization procedure are shown in Fig. 1 as black dashed curve, and for comparison, we also present the observable cascade SEDs for $B = 0$ calculated with the ELMAG 3 publicly-available code [36, 37] in the same figure (magenta long-dashed curve) [38]. All these curves are below the Fermi-LAT upper limits. Therefore, no constrains on the EGMF strength and/or structure could be set using these data. The account of the MAGIC systematics on the intrinsic $\gamma$-ray spectrum in the source restframe is shown in Fig. 1 as black short-dashed curve.

III. OBSERVABLE INTERGALACTIC CASCADE SIGNAL

Upper limits (95% C.L.) on the observable SED of GRB 190114C over the period of time $\Delta T_{\text{obs-LAT}}$ starting from $T_0 + 2 \cdot 10^4$ s according to W20 are shown in Fig. 2. Using the publicly-available code of Fitoussi et al. [34], we calculate the observable SED of intergalactic cascades over $\Delta T_{\text{obs-LAT}}$ assuming the intrinsic VHE $\gamma$-ray spectrum over $\Delta T_{\text{obs-MAGIC}} = T_2 - T_1$ for the “original” G12 EBL model intensity (shown as short-dashed black line in Fig. 1). The EGMF was modelled as a collection of domains with constant strength and random isotropic direction of the field in every domain. The size of each domain is 1 Mpc.

The resulting observable cascade SEDs are shown in Fig. 2 for four different values of $B = 10^{-20}$ G (black solid curve), $10^{-19}$ G (green solid curve), $10^{-18}$ G (blue solid curve), and $B = 0$ (magenta solid curve). For comparison, we also present the observable cascade SED for $B = 0$ calculated with the ELMAG 3 publicly-available code in the same figure (magenta long-dashed curve) [38]. All these curves are below the Fermi-LAT upper limits. Therefore, no constrains on the EGMF strength and/or structure could be set using these data. The account of the MAGIC systematics on the intrinsic spectrum normalization (about 50 %) would introduce an additional source of uncertainty (about a factor of two on the intensity).

We have also performed similar calculations for the modified EBL model with the normalization factor $K_{\text{EBL}}$.
the CTA experiment sensitivity for five hours of observation: zenith angle of $20^\circ$ (red triangles) and $60^\circ$ (blue diamonds).

For this case and $B=0$, the resulting cascade signal intensity is slightly lower than for $K_{\text{EBL}} = 1.0$ at $E = 100$ MeV, several times lower at $E = 1$ GeV, and about one order of magnitude lower at $E = 10$ GeV.

Finally, the sensitivity of the CTA IACT array [39, 40] for the time exposure of five hours is also shown in Fig. 2. The energy threshold of CTA appears to be too high to detect the cascade signal.

IV. CONCLUSIONS

The sensitivity of the Fermi-LAT $\gamma$-ray telescope is not sufficient to detect the intergalactic electromagnetic cascade signal from GRB 190114C over the time period of one month. The calculations for different values of $\Delta T_{\text{obs-LAT}}$ are straightforward; the results of these calculations will be reported elsewhere. Hopefully, future $\gamma$-ray detectors such as MAST [41] with much improved sensitivity will be able to probe the EGMF strength and structure for $B < 10^{-18}$ G.

ACKNOWLEDGMENTS

This work was supported by the Russian Science Foundation (RSF) (project no. 18-72-00083).

This research has made use of the CTA instrument response functions provided by the CTA Consortium and Observatory, see http://www.cta-observatory.org/science/cta-performance/ (version prod3b-v2) for more details.
J. D. Gropp et al., GCN Circulars 23688 (2019).  
R. Hamburg et al., GCN Circulars 23707 (2019).

R. C. Gilmore, R. S. Somerville, J. R. Primack, and A. Domínguez, Monthly Notices of the Royal Astronomical Society 422, 3189 (2012).

F. James and M. Roos, Computer Physics Communications 10, 343 (1975).

Here we ensure that the number of primary γ-rays is conserved.

T. Fitoussi, R. Belmont, J. Malzac, A. Mackowith, J. Cohen-Tanugi, and P. Jean, MNRAS 466, 3472 (2017).

W. B. Atwood, A. A. Abdo, M. Ackermann, W. Althouse, and B. Anderson et al., ApJ 697, 1071 (2009).

M. Blytt, M. Kachelriess, and S. Ostapchenko, arXiv:1909.09210 (2019).

M. Kachelriess, S. Ostapchenko, and R. Tomàs, Computer Physics Communications 183, 1036 (2012).

The normalization and the shape of the model curves for \( B = 0 \) calculated with the two different codes are slightly different, but still these results show a reasonable level of agreement between them.

B. Acharya, M. Actis, T. Aghajani, G. Agnetta, and J. Aguilar et al., Astropart. Phys. 43, 3 (2013).

The CTA Consortium, Science with the Cherenkov Telescope Array (World Scientific, 2018).

T. Dzhatdoev and E. Podlesnyi, Astroparticle Physics 112, 1 (2019).