PROCEEDINGS OF SCIENCE

Search for pair echo signatures in the gamma-ray light curve of GRB190114C

Ievgen Vovk[a,*]

[a] *Institute for Cosmic Ray Research, The University of Tokyo, 5-1-5 Kashiwa-no-Ha, Kashiwa City, Chiba, 277-8582, Japan*

E-mail: vovk@icrr.u-tokyo.ac.jp

The time delayed electromagnetic cascade "echo" model is applied to the gamma-ray burst GRB190114C, the first one observed simultaneously in high- and very high-energy gamma-ray bands. It is shown that even without intervening magnetic fields, the intrinsic cascade spread stretches the "echo" emission over a time span of $10^3 - 10^5$ seconds, depending on the energy. Considering the measured source flux in the $0.3 - 1$ TeV gamma-ray range, the predicted "echo" flux matches the lower-energy gamma-ray emission detected 10^4 seconds after the burst. However, within the measurement uncertainties, the "echo" emission remain indistinguishable from the intrinsic gamma-ray burst flux. Implications of these findings for intergalactic magnetic fields measurements with GRB190114C are discussed.

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

PoS(ICRC2023)712

1. Introduction

Very-high-energy (VHE; $\gtrsim$ 100 GeV) gamma rays traveling across vast cosmological distances are subject to partial absorption when interacting with extragalactic microwave and infrared/optical photon fields [1–3]. This absorption leads to the initiation of electromagnetic cascades, converting multi-TeV photons into lower-energy secondary gamma-ray "pair echo" emission [4–6]. In the presence of a significant intergalactic magnetic field (IGMF), the cascade and its associated secondary gamma-ray emission are spread out in time and angle, resulting in a reduction of observable secondary flux. Non-detection of such secondary emission from several hard-spectrum blazars has been earlier utilized to establish a lower limit on IGMF strength at redshift $z \sim 0.1$ [e.g. 7–12].

The presently uncertain nature of IGMF may be clarified if its evolution is traced to the redshifts $z \sim 1{-}2$, where fields of astrophysical origin would not have developed yet [13]. However, obtaining IGMF constraints at such redshifts is challenging due to the increased gamma-ray absorption on low-energy photon fields, which limits the number of detectable persistent gamma-ray emitters. Nonetheless, transient VHE sources such as gamma-ray bursts (GRBs) and flaring active galactic nuclei (AGN) have been detected at redshifts of approximately $z \sim 0.5 - 1$ [e.g. 14–16], potentially allowing for an expansion of the redshift range for IGMF measurements.

Possibility to detect the secondary emission from such transients, which is necessary for IGMF measurements, depends significantly on the intrinsic time delay of the cascade emission, caused by the angular spreads of electron-positron pair production and subsequent inverse Compton (IC) emission. Though the recently developed Monte Carlo codes ELMAG, CRPropa and CRBeam [17–19] can account for it when estimating the time delay, achieving the required accuracy of $\epsilon \simeq c\Delta t/d \sim 10^{-17}$ may be challenging with them (e.g. given the $\epsilon = 2^{-53} \approx 10^{-16}$ accuracy of the commonly used double-precision floating-point format). At the same time, semi-analytical estimates neglecting the exact angular dependencies of these processes suggest that intrinsic time delay at GeV energies may reach $\Delta t \sim 10^2 - 10^4$ s [e.g. 6], potentially exceeding the duration of transients like GRBs or short AGN flares.

An opportunity to search for cascade emission at redshifts $z > 0.1$ has arisen with the simultaneous observation of a bright GRB190114C at redshift $z \approx 0.42$ with the Fermi/LAT and MAGIC telescopes [16, 20]. In this study, the measured VHE light curve of GRB190114C is used to predict the cascade emission at lower energies, which is then compared to the GeV band data. For this a detailed description of the cascade time-delayed light curve is developed here, considering the precise energy and angular characteristics of pair production and IC emission.

2. Calculation of the GRB190114C pair echo

In this analysis it is assumed that the cascade begins with the absorption of the initial VHE gamma ray through interactions with the extragalactic background light (EBL) photon field, modeled following [21]. Secondary photons are emitted through inverse Compton (IC) scattering of the cosmic microwave background (CMB) by electrons and positrons produced in the process. In the absence of intergalactic magnetic field, the angular distribution of the electron-positron pairs, which causes internal cascade scatter, is determined by the pair production cross section and the angular profile of the initial VHE emission (the back-reaction from inverse Compton emission [e.g. 22] is

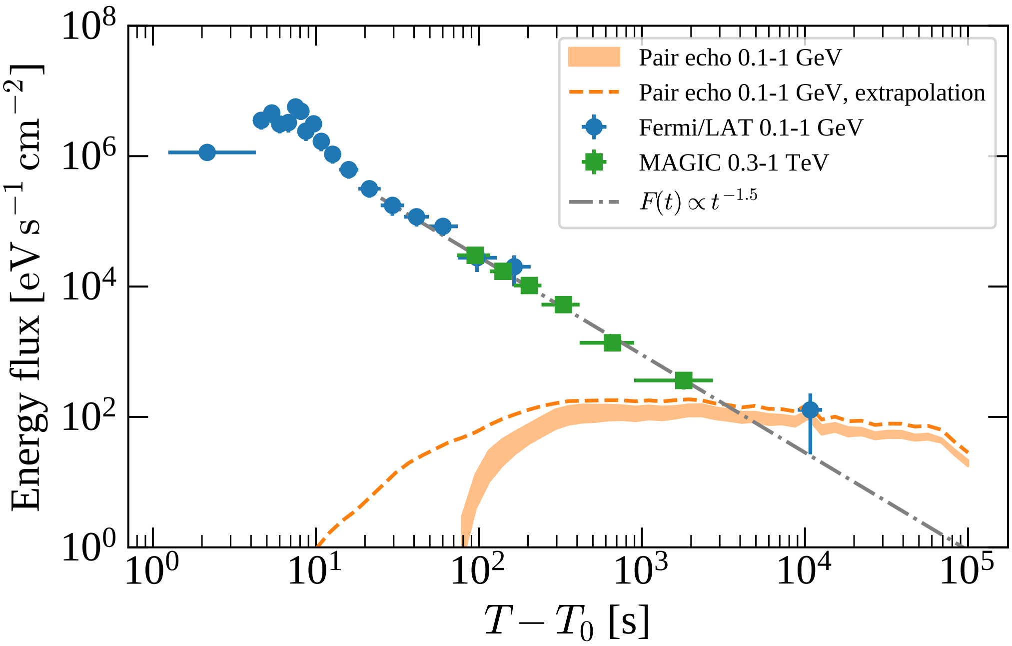

Figure 1: Predicted GRB190114C pair echo compared to the actual measurements in TeV and GeV bands [20]. "Echo" signal is estimated from the initial source emission in the $T - T_0 = [68; 2400]$ s time window, where the VHE measurements of this burst emission are available. Gray dash-dotted line depicts extrapolation of the initial source flux following the $F(t) \propto t^{-1.5}$ scaling [20]. Pair echo signal resulting from this extrapolation down to $T - T_0 = 5$ s is shown with the dashed orange line.

considered negligible for TeV-energy electron-positron pairs). The calculation of the secondary emission follows a hybrid semi-analytical/Monte Carlo approach in the following steps: (a) determine the radial (redshift) distribution of the injected electron-positron pairs following the absorption of the initial VHE photons, (b) calculate their angular and energy distributions, (c) randomly sample the pairs based on these distributions, (d) calculate the secondary gamma-ray emission through IC scattering, accounting for e^+/e^- energy loss, and (e) determine the time delay for each point along the electron/positron trajectories.

Time-delayed cascade emission from GRB190114C was calculated from the VHE spectra in the time intervals of the MAGIC measurements [20], with the uncertainties propagated via a toy MC. The obtained total time-delayed cascade flux is presented in Fig. 1 together with the corresponding measurements from [20]. The flux estimate shown there is conservative as it does not include any potential "echo" signal from before the start of MAGIC observations at $T - T_0 = 68$ s. However, the contribution of this early-time emission is not decisive – assuming the observed $F(t) \propto t^{-\alpha}$ source flux evolution and extrapolating the earliest measured VHE spectrum [16, 20] down to $T - T_0 = 5$ s leads to $\simeq 80\%$ larger cascade flux, which still falls within the uncertainties of the Fermi/LAT measurements.

3. Discussion

The cascade flux predicted from GRB190114C, as shown in Fig. 1, is consistent with the Fermi/LAT measurement at $T - T_0 \approx 10^4$ s, suggesting that the observed flux could potentially be entirely attributed to the "echo" emission. However, it is important to note that the temporal behavior of the pair echo flux differs significantly from that of the intrinsic GRB emission. This provides an opportunity to distinguish the echo emission if the HE gamma-ray light curve of GRB190114C would have been measured continuously for at least 10^4 s or if theoretical justifications for extrapolating the intrinsic GRB flux from $T \approx T_0 + 10^2$ s to later times would be found. Extrapolation of the GRB190114C GeV band flux after the prompt phase using the power law scaling $F(t) \propto t^{-\alpha}$ falls below the late-time Fermi/LAT measurement, suggesting a detection of the pair "echo" emission at $T - T_0 \approx 10^4$ s.

Such a detection is only possible if IGMF-induced deflections of the electron-positron pairs do not exceed their intrinsic scatter [6], implying a weak IGMF with $B \lesssim 10^{-21}$ G at the gamma-ray burst redshift of $z \approx 0.42$. As constraints at $z \sim 0.1$ suggest $B \gtrsim 10^{-17}$ G [e.g. 7–12], such a detection would indicate a rapid evolution of IGMF with redshift, strongly disfavoring the cosmological origin of IGMF. It could also pose challenges for galactic-origin models of IGMF predicting the field to reach its present value at $z \sim 1$ [13]. The latter tension could be alleviated considering the inhomogeneous structure of IGMF, expected for both its the primordial [e.g. 23] and galactic [24] origins.

It should be noted that the afterglow emission of GRBs itself may include time-delayed components, e.g. originating from their structured jets [e.g. 25, 26]. The collected data on GRB190114C are insufficient to distinguish them from the "echo" signal. If afterglow intrinsic emission constitutes more than 80% of the measured flux at $T - T_0 \approx 10^4$ s, the predicted "echo" signal would be excluded, imposing a $B \gtrsim 10^{-21}$ G limit on IGMF at $z \approx 0.4$.

Since GRB190114C detection, several other gamma-ray bursts have been announced in VHE band at redshifts $z \approx 0.1 - 1.1$ [27–30]. Though their measured VHE fluxes were mostly much lower than in the case of GRB190114C, these detections demonstrate that a substantial number of gamma-ray bursts may present hard VHE spectra and emission longer than few hundred seconds – key ingredients for a detectable pair echo signal in the absence of IGMF. The emerging population of such sources could play a vital role in measuring the intergalactic magnetic field at redshift $z \gtrsim 1$.

Acknowledgments

Author gratefully acknowledges the support of the Institute for Cosmic Ray Research (ICRR), the University of Tokyo in realization of this study and that of the CTA-North computing center at La Palma, Spain, for providing the necessary computational resources.

This contribution is based on the original publication [31], but was re-written and shortened for these proceedings.

References

[1] R. J. Gould and G. Schréder. Opacity of the Universe to High-Energy Photons. Phys. Rev. Lett., **16** (1966), 6, 252–254. doi:10.1103/PhysRevLett.16.252

[2] J. V. Jelley. High-Energy γ-Ray Absorption in Space by a 3.5°K Microwave Field. Phys. Rev. Lett., **16** (1966), 11, 479–481. doi:10.1103/PhysRevLett.16.479

[3] F. W. Stecker, O. C. de Jager, and M. H. Salamon. TeV Gamma Rays from 3C 279: A Possible Probe of Origin and Intergalactic Infrared Radiation Fields. ApJL, **390** (1992), L49. doi:10.1086/186369

[4] F. A. Aharonian, P. S. Coppi, and H. J. Voelk. Very High Energy Gamma Rays from Active Galactic Nuclei: Cascading on the Cosmic Background Radiation Fields and the Formation of Pair Halos. ApJL, **423** (1994), L5. doi:10.1086/187222

[5] R. Plaga. Detecting intergalactic magnetic fields using time delays in pulses of γ-rays. Nature, **374** (1995), 430–432. doi:10.1038/374430a0

[6] A. Neronov and D. V. Semikoz. Sensitivity of γ-ray telescopes for detection of magnetic fields in the intergalactic medium. Phys. Rev. D, **80** (2009), 12, 123012. doi:10.1103/PhysRevD.80.123012

[7] A. Neronov and I. Vovk. Evidence for Strong Extragalactic Magnetic Fields from Fermi Observations of TeV Blazars. Science, **328** (2010), 73. doi:10.1126/science.1184192

[8] M. Ackermann, M. Ajello, L. Baldini, J. Ballet, G. Barbiellini, et al. The Search for Spatial Extension in High-latitude Sources Detected by the Fermi Large Area Telescope. ApJS, **237** (2018), 2, 32. doi:10.3847/1538-4365/aacdf7

[9] J. Aleksić, L. A. Antonelli, P. Antoranz, M. Backes, C. Baixeras, et al. Search for an extended VHE γ-ray emission from Mrk 421 and Mrk 501 with the MAGIC Telescope. Astronomy & Astrophysics, **524** (2010), A77. doi:10.1051/0004-6361/201014747

[10] H. E. S. S. Collaboration, A. Abramowski, F. Aharonian, F. Ait Benkhali, A. G. Akhperjanian, et al. Search for extended γ-ray emission around AGN with H.E.S.S. and Fermi-LAT. Astronomy & Astrophysics, **562** (2014), A145. doi:10.1051/0004-6361/201322510

[11] S. Archambault, A. Archer, W. Benbow, M. Buchovecky, V. Bugaev, et al. Search for Magnetically Broadened Cascade Emission from Blazars with VERITAS. ApJ, **835** (2017), 288. doi:10.3847/1538-4357/835/2/288

[12] V. A. Acciari, I. Agudo, T. Aniello, S. Ansoldi, L. A. Antonelli, et al. A lower bound on intergalactic magnetic fields from time variability of 1ES 0229+200 from MAGIC and Fermi/LAT observations. Astronomy & Astrophysics, **670** (2023), A145. doi:10.1051/0004-6361/202244126

[13] E. Garaldi, R. Pakmor, and V. Springel. Magnetogenesis around the first galaxies: the impact of different field seeding processes on galaxy formation. MNRAS, **502** (2021), 4, 5726–5744. doi:10.1093/mnras/stab086

[14] M. L. Ahnen, S. Ansoldi, L. A. Antonelli, P. Antoranz, A. Babic, et al. Very High Energy γ-Rays from the Universe's Middle Age: Detection of the z = 0.940 Blazar PKS 1441+25 with MAGIC. ApJL, **815** (2015), 2, L23. doi:10.1088/2041-8205/815/2/L23

PoS(ICRC2023)712

[15] M. L. Ahnen, S. Ansoldi, L. A. Antonelli, P. Antoranz, C. Arcaro, et al. Detection of very high energy gamma-ray emission from the gravitationally lensed blazar QSO B0218+357 with the MAGIC telescopes. Astronomy & Astrophysics, **595** (2016), A98. doi:10.1051/0004-6361/201629461

[16] MAGIC Collaboration, V. A. Acciari, S. Ansoldi, L. A. Antonelli, A. Arbet Engels, et al. Teraelectronvolt emission from the γ-ray burst GRB 190114C. Nature, **575** (2019), 7783, 455–458. doi:10.1038/s41586-019-1750-x

[17] M. Blytt, M. Kachelrieß, and S. Ostapchenko. ELMAG 3.01: A three-dimensional Monte Carlo simulation of electromagnetic cascades on the extragalactic background light and in magnetic fields. Computer Physics Communications, **252** (2020), 107163. doi:10.1016/j.cpc.2020.107163

[18] R. Alves Batista, A. Dundovic, M. Erdmann, K.-H. Kampert, D. Kuempel, G. Müller, G. Sigl, A. van Vliet, D. Walz, and T. Winchen. CRPropa 3—a public astrophysical simulation framework for propagating extraterrestrial ultra-high energy particles. Journal of Cosmology and Astroparticle Physics, **2016** (2016), 5, 038. doi:10.1088/1475-7516/2016/05/038

[19] O. Kalashev, A. Korochkin, A. Neronov, and D. Semikoz. Modelling of propagation of very-high-energy gamma rays with CRbeam code. Comparison with CRPropa and ELMAG codes. arXiv e-prints, (2022), arXiv:2201.03996

[20] MAGIC Collaboration, V. A. Acciari, S. Ansoldi, L. A. Antonelli, A. A. Engels, et al. Observation of inverse Compton emission from a long γ-ray burst. Nature, **575** (2019), 7783, 459–463. doi:10.1038/s41586-019-1754-6

[21] A. Franceschini, G. Rodighiero, and M. Vaccari. Extragalactic optical-infrared background radiation, its time evolution and the cosmic photon-photon opacity. Astronomy & Astrophysics, **487** (2008), 3, 837–852. doi:10.1051/0004-6361:200809691

[22] K. Ichiki, S. Inoue, and K. Takahashi. Probing the Nature of the Weakest Intergalactic Magnetic Fields with the High-Energy Emission of Gamma-Ray Bursts. ApJ, **682** (2008), 127-134. doi:10.1086/588275

[23] P. Blasi, S. Burles, and A. V. Olinto. Cosmological Magnetic Field Limits in an Inhomogeneous Universe. ApJL, **514** (1999), 2, L79–L82. doi:10.1086/311958

[24] A. Arámburo-García, K. Bondarenko, A. Boyarsky, D. Nelson, A. Pillepich, and A. Sokolenko. Magnetization of the intergalactic medium in the IllustrisTNG simulations: the importance of extended, outflow-driven bubbles. MNRAS, **505** (2021), 4, 5038–5057. doi:10.1093/mnras/stab1632

[25] G. Oganesyan, S. Ascenzi, M. Branchesi, O. S. Salafia, S. Dall'Osso, and G. Ghirlanda. Structured Jets and X-Ray Plateaus in Gamma-Ray Burst Phenomena. ApJ, **893** (2020), 2, 88. doi:10.3847/1538-4357/ab8221

PoS(ICRC2023)712

[26] O. Sharan Salafia and G. Ghirlanda. The Structure of Gamma Ray Burst Jets. arXiv e-prints, (2022), arXiv:2206.11088

[27] H. Abdalla, R. Adam, F. Aharonian, F. Ait Benkhali, E. O. Angüner, et al. A very-high-energy component deep in the γ-ray burst afterglow. Nature, **575** (2019), 7783, 464–467. doi:10.1038/s41586-019-1743-9

[28] H. E. S. S. Collaboration, H. Abdalla, F. Aharonian, F. Ait Benkhali, E. O. Angüner, et al. Revealing x-ray and gamma ray temporal and spectral similarities in the GRB 190829A afterglow. Science, **372** (2021), 6546, 1081–1085. doi:10.1126/science.abe8560

[29] O. Blanch, F. Longo, A. Berti, S. Fukami, Y. Suda, et al. GRB 201216C: MAGIC detection in very high energy gamma rays. GRB Coordinates Network, **29075** (2020), 1

[30] LHAASO Collaboration. A tera-electronvolt afterglow from a narrow jet in an extremely bright gamma-ray burst 221009A. arXiv e-prints, (2023), arXiv:2306.06372. doi:10.48550/arXiv.2306.06372

[31] I. Vovk. Search of the pair echo signatures in the high-energy light curve of GRB190114C. Phys. Rev. D, **107** (2023), 4, 043020. doi:10.1103/PhysRevD.107.043020