Standard physics is still capable to interpret 18 TeV photons from GRB 221009A

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Abstract

The Large High Altitude Air Shower Observatory (LHAASO) has reported the detection of thousands of very-high-energy photons up to 18 TeV from GRB 221009A. We investigate the survival rate of these photons by accounting for their absorption by the extragalactic background light (EBL). Through a suite of 10^6 Monte Carlo simulations, we explore the parameter space permitted by current observations and find that the probability of LHAASO detecting at least one 18 TeV photon from GRB 221009A within 2000 seconds is 4–5%. Hence, standard physics remains capable of interpreting LHAASO's observations in the several-TeV energy range. Our methodology can be straightforwardly generalized to analyze additional LHAASO datasets and other future experiments.

Full Text

18 TeV Photons from GRB 221009A

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Abstract

The Large High Altitude Air Shower Observatory (LHAASO) has reported the detection of thousands of very-high-energy photons up to 18 TeV from GRB

221009A. We investigate the survival rate of these photons by accounting for their absorption by the extragalactic background light (EBL). Through a suite of 10^6 Monte Carlo simulations, we explore the parameter space permitted by current observations and find that the probability of LHAASO detecting at least one 18 TeV photon from GRB 221009A within 2000 seconds is 4–5%. Hence, standard physics remains capable of interpreting LHAASO's observations in the several-TeV energy range. Our methodology can be straightforwardly generalized to analyze additional LHAASO datasets and other future experiments.

1. Introduction

LHAASO observed more than 5000 photons above 0.5 TeV emitted from GRB 221009A at redshift $z = 0.1505$ within 2000 seconds after the initial detection by Swift, Fermi-GBM, Fermi-LAT, and other instruments [?, ?]. The highest-energy photons were reported to reach 18 TeV, representing the first detection of photons above 10 TeV from gamma-ray bursts (GRBs). Such remarkable observations have prompted investigations into photon mixing with axion-like particles [?], Lorentz symmetry violation [?], and both phenomena simultaneously [?]. In this work, we examine the survival probability of multi-TeV photons from GRB 221009A by considering their significant absorption by the extragalactic background light intervening between the GRB and Earth, and we assess whether standard physics can still accommodate the current observations.

Very-high-energy photons can dissipate their energy via annihilation with photons in the cosmic microwave background (CMB) and extragalactic background light (EBL), producing electron-positron pairs. The threshold energy for this process is $E_{\text{th}} = m_e^2/E_b$, where m_e is the electron mass and E_b is the average energy of background photons. For CMB photons, this threshold reaches hundreds of TeV, allowing us to safely neglect their effect. However, EBL photons have energies several orders of magnitude higher than CMB photons, which lowers the threshold by a corresponding factor. For instance, the threshold reduces to the TeV range when considering $E_b \sim 0.1$ eV. Therefore, we must account for the suppressive effect of EBL photons on the detected flux.

2. Flux of TeV Photons and EBL Attenuation

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The EBL-suppressed flux F_o depends on the intrinsic flux F_i and the optical depth $e^{-\tau}$ due to EBL absorption, giving

$$F_o(E) = F_i(E)e^{-\tau(E,z)},$$

where E is the observed photon energy and z is the redshift of GRB 221009A. We utilize the tabulated EBL and optical depth data from [?]. The intrinsic photon flux is approximated by a power-law [?]:

$$F_i(E) = A_i \left(\frac{E}{0.5\,\mathrm{TeV}}\right)^{\alpha_i},$$

where A_i and α_i represent the intrinsic flux and spectral index, respectively, at the pivot energy of 0.5 TeV.

Based on Fermi-LAT reports, we have two measured values of α_i [?, ?], obtained in the 0.1–1 GeV range but during different temporal intervals. We allow A_i to be determined by LHAASO observations. Accounting for LHAASO's performance [?], we predict the number of events above 0.5 TeV as

$$N_{>0.5\,\mathrm{TeV}} = T \int_{0.5\,\mathrm{TeV}} F_o(E) S_{\mathrm{eff}}(E,\theta)\,dE,$$

where S_{eff} is the effective area of LHAASO-WCDA (provided in Fig. 6 of Chapter 3 in [?]), $\theta = 28^\circ$ is the zenith angle of GRB 221009A, and $T = 2000$ seconds is the LHAASO observation duration.

To explore the parameter space, we perform Bayesian analysis incorporating the reported detection of more than 5000 photons above 0.5 TeV by LHAASO [?]. We assume the event count follows a Poisson distribution with probability distribution function $p(k) = \lambda^k e^{-\lambda}/k!$, where $\lambda = 5000$ is the expectation value and $k = N_{>0.5\,\mathrm{TeV}}$. Our results remain robust when choosing other λ values within [5000, 6000). We implement Bayesian inference using the affine-invariant Markov chain Monte Carlo (MCMC) ensemble sampler `emcee` [?]. We assume a uniform prior for A_i in the range $[1\times10^{-4}, 7\times10^{-4}]$ $\mathrm{TeV^{-1}m^{-2}s^{-1}}$ and Gaussian priors for α_i based on the aforementioned Fermi-LAT measurements. The optical depth is sampled using the tabulated median values and uncertainties of τ [?] from [?].

Our Bayesian analysis yields two sets of posteriors for (A_i, α_i) at 68% confidence level: $A_i = (2.51^{+0.43}_{-0.46}) \times 10^{-4}$ $\mathrm{TeV^{-1}m^{-2}s^{-1}}$ with $\alpha_i = -1.87 \pm 0.04$, and $A_i = (2.14^{+0.43}_{-0.46}) \times 10^{-4}$ $\mathrm{TeV^{-1}m^{-2}s^{-1}}$ with $\alpha_i = -2.12 \pm 0.11$. Figure 1 shows the one-dimensional posterior PDFs of A_i for both spectral index priors. For subsequent simulations, we sample A_i and α_i according to their posterior PDFs and sample τ from the tabulated data described above.

3. Probability of Detecting TeV Photons

Based on these results, we estimate the probability of LHAASO detecting at least one photon at energy E from GRB 221009A. During an observation period $T = 2000$ seconds, the event count in the energy range from $(1-\Delta E/2)E$ to $(1+\Delta E/2)E$ is

$$N(E) = T\,F_o(E)\,S_{\mathrm{eff}}(E,\theta)\,\frac{\Delta E(E)}{E},$$

where $\Delta E(E)$ is the energy resolution of LHAASO-WCDA (provided in Fig. 26 of Chapter 1 in [?]). We consider the energy range from 0.5 TeV to 30 TeV, with particular emphasis on 18 TeV. For each energy E, we perform 10^6 Monte Carlo simulations, counting the number of models that predict $N(E) \geq 1$ and computing the corresponding probability.

The Monte Carlo results are shown in Figure 2. We find that the probabilities of LHAASO detecting at least one 18 TeV photon from GRB 221009A are approximately 5.2% and 4.1% for the spectral index priors $\alpha_i = -1.87 \pm 0.04$ and $\alpha_i = -2.12 \pm 0.11$, respectively. The former index was obtained during 200–800 seconds after the trigger, while the latter during 500–3500 seconds. For comparison, the LHAASO data were accumulated within 2000 seconds after the trigger. Based on [?], we note that the TeV-band photon flux decreases significantly with time. If the events observed by LHAASO follow this temporal behavior—though this should be verified with LHAASO data when possible—we expect that the majority of events arrived within the first 1000 seconds. In either case, standard physics remains capable of interpreting 18 TeV photons from GRB 221009A.

4. Summary

In this work, we have investigated the survival rate of very-high-energy gamma rays in the LHAASO energy range by incorporating EBL attenuation effects. Within the framework of standard physics, we simulated the probability of detecting the 18 TeV signal from GRB 221009A to be a few percent. Hints of new physics may emerge at the 2.58σ level if LHAASO observes photons above 26 TeV from GRB 221009A. These conclusions could be modified if other EBL and optical depth measurements are considered, which lies beyond the scope of this paper. We defer such detailed studies to future work. Our research methodology can be straightforwardly generalized to analyze additional LHAASO datasets and other future experiments.

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Note: Figure translations are in progress. See original paper for figures.