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Cosmic-ray origin of $\gtrsim 10$ TeV gamma-rays in GRB 221009A

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On October 9, 2022, the Swift-BAT and Fermi-GBM telescopes detected the brightest long gamma-ray burst (GRB) observed so far. This provides us an opportunity to understand the high-energy processes in extreme transient phenomena. High-energy photons upto $\gtrsim$ 10 TeV, and as high as 18 TeV were detected by the LHAASO detector. Conventional leptonic models such as synchrotron and synchrotron self-Compton are insufficient to explain the emission of such high-energy photons in the afterglow phase. In this work, we use a leptonic model for the flux of γ-rays observed by the Fermi-LAT detector in the energy range of 0.1-1 GeV. This flux is severely attenuated due to $\gamma\gamma$ pair production interaction with the extragalactic background photons. We invoke an alternate process for the explanation of the high-energy photons originating in ultrahigh-energy cosmic rays. These cosmic rays, accelerated in the GRB blastwave can escape the source and initiate an electromagnetic cascade in the extragalactic medium. The resulting γ-ray flux along our line of sight can explain the observation of $\gtrsim$ 10 TeV photons, detected by LHAASO, requiring a fraction of the GRB blastwave energy in ultrahigh-energy cosmic rays. This can be the first indirect signature of ultrahigh-energy cosmic-ray acceleration in GRBs.

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1. Introduction

The sources of ultrahigh-energy cosmic rays are still unidentified. Gamma-ray bursts (GRBs) emit luminous radiation in γ-rays and are thought to be potential candidates for ultrahigh-energy cosmic ray acceleration [1, 2]. However, it is difficult to directly detect cosmic rays in coincidence with γ rays from GRBs, owing to their significant deflection and time delay in propagation through the extragalactic magnetic field. Also, there has been no confirmed neutrino signal from a GRB, thus constraining the cosmic-ray acceleration during prompt emission [see, e.g., 3–6].

Recently, the Swift Burst Alert Telescope (BAT) [7] and Fermi Gamma-ray Burst Monitor (GBM) has detected the brightest long GRB so far. The Fermi Large Area Telescope (LAT) has also detected $> 100 MeV$ photons during the time interval 200 - 800 seconds after the GBM trigger (T_0), with the highest energy photon of energy 99.3 GeV arriving at T_0 + 240 s [8, 9]. It is the most energetic photon detected by Fermi-LAT from a GRB. The Large High Altitude Air Shower Observatory (LHAASO) detected more than 5000 photons from this GRB within $T_0 + 2000$ s in the 0.5–18 TeV range [10]. Thus GRB 221009A is the first GRB detected above 10 TeV. The redshift of the event is estimated to be $z = 0.15$ [11] and hence is an interesting phenomenon because emission from the source region at such high energies is expected to be attenuated due to $e^{\pm}$ pair production in the optical/IR/UV photons of the extragalactic background light (EBL) [12–14].

The power-law nature of the Fermi-LAT photon flux $(6.2 \pm 0.4) \times 10^{-3}\,\mathrm{ph\,cm^{-2}\,s^{-1}}$ with a photon index of -1.87 ± 0.04 in the 200–800 s time window and that the LAT emission extended for about 25 ks post-GBM trigger [9], indicates that γ rays detected by LAT also originated from the afterglow. While synchrotron and synchrotron-self-Compton (SSC) processes can usually explain radio to very-high-energy (VHE, $\gtrsim$ 100 GeV) γ-ray observations [15], a large flux of TeV γ rays detected by LHAASO must originate from a different mechanism. Hadronic emission mechanisms, such as proton-synchrotron radiation [16–19] or photohadronic interactions [20, 21] can produce VHE emission from the GRB, but their flux on Earth would be severely attenuated in the EBL as well. In this work, we invoke that VHE γ-rays detected by LHAASO with energy more than a few TeV are produced by UHECRs accelerated in the GRB blastwave [22, 23]. They propagate along our line of sight and interact with the EBL and cosmic microwave background (CMB) photons to produce VHE γ rays in addition to the synchrotron-SSC emission. A similar method is also sometimes adopted to explain the unattenuated hard TeV spectrum of blazars [24]. The cosmogenic flux, however, is less severely attenuated than the other components coming directly from the GRB.

2. Gamma-ray emission

2.1 Synchro-Compton emission

The total isotropic γ-ray energy of GRB 221009A is found to be $(2 - 6) \times 10^{54}$ erg [11, 25]. Therefore, for the afterglow emission from GRB 221009A, we use an adiabatic blastwave with kinetic energy $E_k = 10^{55} E_{55}$ erg evolving in a constant density interstellar environment [26]. We calculate the synchrotron and SSC spectra using formulas in [15], which are based on the models in Refs. [27, 28]. For the time-dependent synchrotron spectrum, relevant break energies are that from the electrons of minimum Lorentz factor (E_m), cooling Lorentz factor (E_c), and saturation Lorentz factors (E_s). For modeling the 0.1–1 GeV γ-ray flux from Fermi-LAT, these energies are given by

$$\begin{aligned} E_m &= 28.6\, \epsilon_{e,-1.5}^{2} \epsilon_{B,-1.8}^{1/2} E_{55}^{1/2} t_{2.7}^{-3/2} \text{ eV} \\ E_c &= 3.9\, \epsilon_{B,-1.8}^{-3/2} E_{55}^{-1/2} n_{-3.7}^{-1} t_{2.7}^{-1/2} \text{ keV} \\ E_s &= 4.6\, \phi^{-1} E_{55}^{1/8} n_{-3.7}^{-1/8} t_{2.7}^{-3/8} \text{ GeV}\,, \end{aligned} \tag{1}$$

at $t = 10^{2.7} t_{2.7}$ s post-trigger, when the blastwave is in a decelerating phase [26]. Here we have assumed the fraction of the shock energy in non-thermal electrons as $\epsilon_e = 10^{-1.5} \epsilon_{e,-1.5}$ and in a turbulent magnetic field as $\epsilon_B = 10^{-1.8} \epsilon_{B,-1.8}$. The Compton parameter $Y \approx \sqrt{\epsilon_e/\epsilon_B} = 1.4$ in our modeling for a slow-cooling ($E_m < E_c$) synchrotron spectrum. The electrons follow a power-law distribution of Lorentz factor γ^{-p}, where we have assumed $p = 1.74$. We have also assumed the interstellar medium has a rather low particle density $n = 10^{-3.7} n_{-3.7}$ cm^{-3}. We included SSC cooling while calculating E_c and an efficiency factor $\phi^{-1} \lesssim 1$ for electron acceleration to the maximum energy E_s. For details see Ref. [29].

The model parameters are degenerate, and other values may also produce similar fits. Our chosen set of parameters, which are within the typical range for GRB afterglows, produces the estimated Fermi-LAT flux,

$$\begin{aligned} E^2 \left(\frac{dN}{dE}\right) = 1.2 \times 10^{-6} \left(\frac{E}{\text{GeV}}\right)^{0.13} \text{ erg cm}^{-2}\text{ s}^{-1}; \\ E_c \le E < E_s\,, \end{aligned} \tag{2}$$

in the 0.1–1 GeV range in the 200–800 s interval, post-trigger. The break energies in the SSC spectrum $E_{m,\text{SSC}}$ and $E_{c,\text{SSC}}$ can also be calculated with simplified assumptions as in [15]

$$\begin{aligned} E_{m,\text{SSC}} &= 2.8\, \epsilon_{e,-1.5}^{4} \epsilon_{B,-1.8}^{1/2} E_{55}^{3/4} n_{-3.7}^{-1/4} t_{2.7}^{-9/4} \text{ GeV} \\ E_{c,\text{SSC}} &= 52.9\, \epsilon_{B,-1.8}^{-7/2} E_{55}^{-5/4} n_{-3.7}^{-9/4} t_{2.7}^{-1/4} \text{ TeV}\,. \end{aligned} \tag{3}$$

The Klein-Nishina effect, however, sets in at an energy

$$E_{\text{KN,SSC}} = 1.3\, \epsilon_{B,-1.8}^{3/2} E_{55}^{3/4} n_{-3.7}^{3/4} t_{2.7}^{-1/4} \text{ TeV}\,, \tag{4}$$

and simple Thomson approximations cannot be used above this energy. Therefore, an SSC component can be estimated as below

$$E^2 \left(\frac{dN}{dE}\right) = 2.0 \times 10^{-6} \text{ erg cm}^{-2}\text{ s}^{-1} \tag{5}$$

$$\times \begin{cases} \left(\frac{E}{E_{m,\text{SSC}}}\right)^{4/3} ; E \le E_{m,\text{SSC}} \\ \left(\frac{E}{E_{m,\text{SSC}}}\right)^{0.63} ; E_{m,\text{SSC}} \le E \le E_{\text{KN,SSC}}\,. \end{cases}$$

However, most recent EBL models predict a suppression of γ-ray flux above $\approx$ 100 GeV for $z = 0.15$. The SSC flux at 18 TeV, the maximum photon energy reported by LHAASO is inadequate to explain the VHE observations. We show the synchrotron and EBL attenuated SSC fluxes in Fig. 1 by dashed orange and the dashed brown lines respectively. We present the results for a higher ϵ_e

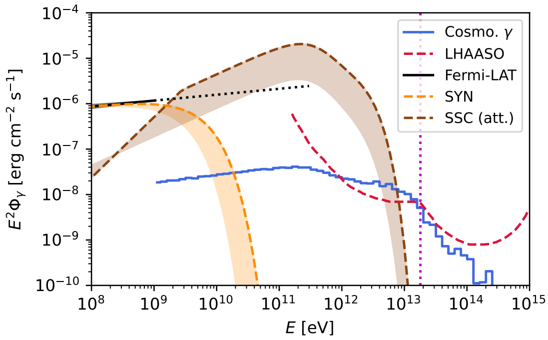

Figure 1: Line-of-sight cosmogenic γ-ray flux from UHECR interactions (blue curve). The black solid line corresponds to the Fermi-LAT preliminary flux estimate from GRB 221009A [9]. The red dashed curve indicates the LHAASO sensitivity corresponding to 2000 s of observation. The dotted vertical line corresponds to the highest energy detection by LHAASO. The synchrotron and SSC emission components are shown as orange and brown dashed curves, respectively. the figure is reused from Ref. [29].

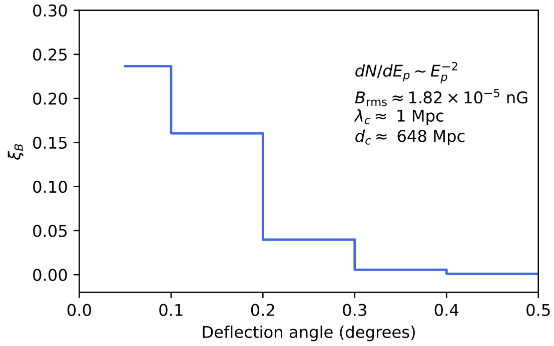

Figure 2: Distribution of UHECR fraction as a function of the deflection angle on the surface of a sphere centered at Earth and of radius 1 Mpc. The figure is reused from Ref. [29].

value to increase the SSC flux without violating the 0.1-1 GeV flux detected by Fermi-LAT, which we model as synchrotron emission. The lower bound of the shaded region in the plot corresponds to a lower $\epsilon_e = 10^{-2.5}\epsilon_{e,-2.5}$ and $\epsilon_B = 10^{-4}\epsilon_{B,-4}$, adjusted such that the Fermi-LAT flux, modeled as synchrotron emission, is not violated. To extend the SSC flux to even higher energy by reducing the ϵ_B value considered here may also increase the synchrotron flux and thus violate the Fermi-LAT flux level. Note that the detection of a 99.3 GeV photon by Fermi-LAT at $T_0 + 240$ s is broadly consistent with the SSC flux component.

2.2 Line-of-sight emission from UHECRs

We consider UHECR acceleration in the external shock of the GRB blastwave during the afterglow emission phase. The maximum proton energy for an adiabatic blastwave in a constant-density environment can be calculated as [see, e.g., 30]

$$E = 9.7 \times 10^{19}\ \phi^{-1}\epsilon_{B,-1.8}^{1/2} E_{55}^{3/8} n_{-3.7}^{1/8} t_{2.7}^{-1/8}\ \text{eV}. \quad (6)$$

By interacting with the afterglow photons, these protons can produce neutrinos in the EeV range [22, 23, 30]. Thus the IceCube flux upper limit in the 0.8–1 PeV energy range does not apply in our scenario.

We assume the UHECR protons accelerated in the GRB blastwave escape from the source and propagate through the extragalactic medium from their sources to Earth. Their interactions lead to the production of secondary electromagnetic (EM) particles ($e^{\pm}$, γ). The latter can initiate EM cascade undergoing various energy loss processes, such as pair production, including double and triple pair production, inverse-Compton scattering of background photons to higher energy, etc. The extragalactic magnetic field (EGMF) can deflect the UHECRs away from our line of sight; thus, the resultant flux at Earth can be a fraction of the emitted flux. The time delay induced by the deflection in EGMF can be expressed as [31],

$$\Delta t_{\rm IGM} \approx \frac{d_c^3}{24 r_L^2 c N_{\rm inv}^{3/2}} \approx 2000\ {\rm s} \left(\frac{d_c}{648\ {\rm Mpc}}\right)^{3/2} \times \left(\frac{\lambda_c}{1\ {\rm Mpc}}\right)^{3/2} \left(\frac{B}{1.82\times10^{-5}\ {\rm nG}}\right)^2 \left(\frac{E}{100\ {\rm EeV}}\right)^2 \tag{7}$$

where d_c is the comoving distance of the source, which in our case is $\simeq 648$ Mpc for the standard flat, ΛCDM cosmological parameters corresponding to a redshift $z \approx 0.151$. The number of inversions in the magnetic field $N_{\rm inv}$ is expressed as $max(d_c/\lambda_c, 1)$, where λ_c is the turbulent correlation length of the EGMF. The above expression yields the minimum time delay corresponding to the highest energy protons. The chosen parameter values thus give a time delay consistent with the LHAASO observation time [32].

We use CRPropa3.2 numerical framework for extragalactic propagation of UHECRs [33, 34]. For our simulation, we assume an RMS magnetic field strength of $B_{\rm rms} \approx 1.82\times10^{-5}$ nG, and a coherence length of $\lambda_c \sim 1$ Mpc, so that $\Delta t \simeq 2000$s. To calculate the line of sight component of the EM cascade, we employ a numerical method similar to that explained in Ref. [35]. We calculate the fraction of UHECRs that survives within $0^\circ.1$ of the initial emission direction on the surface of this sphere. We denote this fraction as ξ_B. Then the line of sight component of the cosmogenic γ-ray flux would be the fraction ξ_B of the entire EM cascade arising from the UHECR propagation, obtained from a 1D simulation. We include all energy loss processes of primaries and secondary EM particles in the simulations involved with a proton spectrum of the form $dN/dE_p \sim E^{-2}$ in the energy range 0.1-100 EeV and a random turbulent EGMF, given by a Kolmogorov power spectrum. The distribution of the UHECR fraction as a function of the deflection angle is shown in Fig. 2. We use the Gilmore et al. EBL model [13] and the Protheroe and Biermann model for the universal radio background [36].

We linearly scale the 1-yr flux sensitivity of LHAASO to Crab-like point sources [37], as a conservative estimate to represent the GRB 221009A detection potential in 2000 s, corresponding to the time delay Δt. In the absence of precise flux measurements at these energies, our presentation implies the lower limit to VHE flux from UHECR interactions. The corresponding UHECR luminosity in the energy range from 0.1-100 EeV can be presented as

$$L_{{\rm UHE}p} \gtrsim \frac{2\pi d_L^2(1-\cos\theta_j)}{\xi_B f_{\gamma,p}} \int_{1\ {\rm GeV}}^{100\ {\rm EeV}} \epsilon_\gamma \frac{dn}{d\epsilon_\gamma dA dt} d\epsilon_\gamma \tag{8}$$

where $2\pi d_L^2(1-\cos\theta_j)$ is the area subtended by the GRB jet at the distance of the observer. The jet opening angle is assumed to be a typical value of 6°, appropriate for GRBs [38]. $f_{\gamma,p}$ is the fraction of UHECR energy going into cosmogenic γ-rays between 1 GeV and 100 EeV. The integration is over the required flux of VHE γ-rays normalized to the LHAASO sensitivity at 18 TeV. The value of ξ_B within $0^\circ.1$ is found to be 0.24 and the value of $f_{\gamma,p}$ corresponding to $z = 0.15$ is found to be 0.04. Using these values, we get from Equation (8), $L_{\mathrm{UHE}p} \gtrsim 5.4 \times 10^{47}$ erg/s. This is the actual luminosity required in UHE protons to produce line-of-sight VHE γ-ray emission, i.e., the luminosity after the beaming correction. For $T_0 + 2000$ s LHASSO detection, it corresponds to an isotropic energy release of $\gtrsim 3.9 \times 10^{53}$ erg in UHECR protons, a small fraction of the total kinetic energy of the blastwave.

3. Summary

The recent GRB 221009A provides new opportunities for understanding high-energy processes inside them. The leptonic emission due to synchrotron and SSC emission is difficult to extend up to energies as high as $\gtrsim 10$ TeV. The SSC emission at the highest energies becomes inefficient due to the Klein-Nishina effect, and the flux is also attenuated due to $\gamma\gamma$ pair production with the EBL photons. In our analysis, the SSC spectrum falls off sharply beyond ~ 220 GeV. However, the SSC spectrum is consistent with Fermi-LAT observation of ~ 100 GeV photon. It is noteworthy that the SSC flux is well within reach of LHAASO flux sensitivity normalized for 2000 s of observation. Beyond 10 TeV, any significant flux from the source is unlikely to have originated directly from the GRB blastwave due to EBL attenuation. For this reason, we invoke the line-of-sight UHECR interactions as the origin of $\gtrsim 10$ TeV γ-rays detected by LHAASO. We adjust the RMS strength of EGMF to be $B_{\mathrm{rms}} \approx 1.82 \times 10^{-14}$ G, such that the time delay induced by UHECR propagation from the initial trigger is comparable to ~ 2000 s. Our estimate for the lower limit of proton luminosity is a fraction of the blastwave kinetic energy.

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