Ultrahigh-energy cosmic-ray signature in GRB 221009A

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ABSTRACT

The brightest long gamma-ray burst (GRB) detected so far by the Swift-BAT and Fermi-GBM telescopes, GRB 221009A, provides an unprecedented opportunity for understanding the high-energy processes in extreme transient phenomena. We find that the conventional leptonic models for the afterglow emission from this source, synchrotron and synchrotron-self-Compton, have difficulties explaining the observation of \(\gtrsim 10^{-2} \text{eV} \) (as high as \(10^{-17} \text{eV}\)) by the LHAASO detector. We modeled the \(\gamma\)-ray spectrum estimated in the energy range \(0.1 – 1 \text{GeV}\) by the Fermi-LAT detector. The flux predicted by our leptonic models is severely attenuated at \(\gtrsim 1 \text{TeV}\) due to \(\gamma\gamma\) pair production with extragalactic background light, and hence an additional component is required at \(\gtrsim 10 \text{TeV}\). Ultrahigh-energy cosmic rays can be accelerated in the GRB blast wave, and their propagation induces an electromagnetic cascade in the extragalactic medium. The line-of-sight component of this flux can explain the emission at \(\gtrsim 10^{-2} \text{eV}\) detected by LHAASO, which requires a fraction of the GRB blast-wave energy to be in ultrahigh-energy cosmic rays. This could be an indication of ultrahigh-energy cosmic-ray acceleration in GRBs.

Key words. astroparticle physics – gamma rays: general – gamma-ray burst: individual: GRB 221009A – cosmic rays

1. Introduction

The origin of ultrahigh-energy cosmic rays (UHECRs; \(E \gtrsim 10^{17} \text{eV}\)) is an outstanding problem in physics and astrophysics. Gamma-ray bursts (GRBs), the most powerful electromagnetic (EM) explosions in the Universe, are thought to be prime candidates to accelerate particles to ultrahigh energies (Waxman 1995; Vietri 1995). Direct signatures of UHECRs from GRBs, however, are absent. The non-detection of high-energy neutrinos from nearby GRBs can be used to study UHECR acceleration in the afterglow phase (see, e.g., Waxman & Bahcall 1997; Razzaque et al. 2004a; Murase & Nagataki 2006; Zhang & Kumar 2013). The neutrino signature of the UHECR acceleration in the afterglow phase of GRBs is difficult to detect with the current generation of neutrino detectors (Razzaque 2013; Tamborra & Ando 2015; Thomas et al. 2017). On the other hand, gamma-ray signatures from nearby GRBs can be used to study UHECR acceleration in these ultra-relativistic jets.

GRB 221009A is the brightest long GRB detected by the Swift Burst Alert Telescope (BAT; Dichiara et al. 2022) and the Fermi Gamma-ray Burst Monitor (GBM); it was detected on October 9, 2022, at 13:16:59.99 UT (Veres et al. 2022). Subsequently, the Fermi Large Area Telescope (LAT) detected \(\gtrsim 100 \text{MeV} \gamma\) rays in the 200–800 s time interval after the GBM trigger \(T_0\). The highest-energy photon had an energy of \(99.3 \text{GeV}\) and was detected at \(T_0 + 240 \text{s}\) (Bissaldi et al. 2022; Pillera et al. 2022). This is the most energetic photon detected by Fermi/LAT from a GRB. The Large High Altitude Air Shower Observatory (LHAASO) detected over 5000 photons from GRB 221009A within \(T_0 + 2000 \text{s}\) in the 0.5–18 TeV range, making GRB 221009A the first GRB detected above 10 TeV (Huang et al. 2022). At \(T_0 + 4536 \text{s}\), Carpet-2, a ground-based Cherenkov detector, reported the detection of a 251 TeV photon from the direction of the burst (Dzhappuev et al. 2022). The detection of such energetic photons from even a nearby GRB such as GRB 221009A at \(z = 0.15\) (de Ugarte Postigo et al. 2022) is extremely interesting given that the opacity of the Universe for \(\gamma\)-ray propagation is very large due to \(ee\) pair production with the optical, UV, and IR photons of extragalactic background light (EBL; Finke et al. 2010; Gilmore et al. 2012; Domínguez et al. 2011). This has led to the speculation that a Lorentz-invariance violation (Dzhappuev et al. 2022; Baktash et al. 2022; Li & Ma 2022; Finke & Razzaque 2023) or mixing with axion-like particles (Galanti et al. 2022; Baktash et al. 2022; Troitsky 2022) is responsible for very high-energy (VHE) \(\gamma\) rays evading \(ee\) pair production.

The afterglow of GRB 221009A has also been detected by several X-ray telescopes, such as Swift/XRT, INTEGRAL, STIX on Solar Orbiter, IXPE, NICER, and NasSTAR, by numerous optical telescopes around the world, and by radio telescopes, such as VLA, MeerKAT, and ATCA. Given the power-law nature of the Fermi-LAT photon flux \(\left(6.2 \pm 0.4\right) \times 10^{-5} \text{ph cm}^{-2} \text{s}^{-1}\) with a photon index of \(\sim 1.87 \pm 0.04\) in the 200–800 s time window and that the LAT emission extended for about 25 ks post-GBM trigger (Pillera et al. 2022), it is likely that \(\gamma\) rays detected by LAT also originated from the afterglow. While synchrotron and synchrotron-self-Compton (SSC) processes can usually explain radio to VHE \((\gtrsim 100 \text{GeV})\) \(\gamma\)-ray observations (Joshi & Razzaque 2021), a large flux of TeV
γ rays detected by LHAASO must originate from a different mechanism. Hadronic emission mechanisms, such as proton-synchrotron radiation (Razzaque et al. 2010; Wang et al. 2009; Razzaque 2010; Zhang et al. 2022) or photo-hadronic interactions (Asano & Mészáros 2014; Sahu & Fortin 2020), 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 propose that VHE γ-rays detected by LHAASO with energies up to a few TeV are produced by SSC emission, and that γ rays above this energy are produced by UHECRs and accelerated in the GRB blast wave (Waxman & Bahcall 2000; Dai & Lu 2001). They propagate along our line of sight and interact with the EBL and cosmic microwave background photons to produce VHE γ rays in addition to the synchrotron and SSC emission. A similar method is also sometimes adopted to explain the unattenuated hard TeV spectrum of blazars (Essey & Kusenko 2010). The cosmogenic flux, however, is less severely attenuated than the other components coming directly from the GRB.

2. Gamma-ray emission models

2.1. Synchro-Compton emission

The total isotropic γ-ray energy of GRB 221009A has been estimated to be (2–6) × 10^{54} erg (de Ugarte Postigo et al. 2022; Kann & Agui 2022). Therefore, after the afterglow emission from GRB 221009A, we used an adiabatic blast wave with kinetic energy \( E_k = 10^{53} E_{55} \) erg evolving in a constant-density interstellar environment (Blandford & McKee 1976). We calculated the synchrotron and SSC spectra using the formulas in Joshi & Razzaque (2021), which are based on the models in Sari et al. (1998) and Sari & Esin (2001). For the time-dependent synchrotron spectrum, relevant break energies are those from the electrons of the minimum Lorentz factor, the cooling Lorentz factor, and saturation Lorentz factors. For modeling the 0.1–1 GeV γ-ray flux from Fermi-LAT, these energies are given by

\[
E_{m,\text{SSC}} = 28.6 \frac{E_{55}}{E_{p,18}}^{3/4} \frac{B_{10}}{B_{10}^{1/2}} \text{ eV},
\]

\[
E_{c} = 3.9 \frac{E_{55}}{E_{p,18}}^{1/2} \text{ keV},
\]

\[
E_{s} = 4.0 \frac{E_{55}}{E_{p,18}}^{3/4} \text{ GeV},
\]

at \( t = 10^{2.7} t_{\odot} \) s post-trigger, when the blast wave is in a decelerating phase (Blandford & McKee 1976). Here we have assumed the fraction of the shock energy in electrons to be \( \epsilon_e = 10^{-1} \epsilon_{e,-1} \) and in a turbulent magnetic field \( \epsilon_B = 10^{-1.5} \epsilon_{B,-1.5} \). The Compton parameter \( Y = \sqrt{\epsilon_e/\epsilon_B} = 1.4 \) in our modeling for a slow-cooling \( (E_{m} < E_{c}) \) synchrotron spectrum. The electrons follow a power-law distribution of Lorentz factor \( Y^\gamma \), where we have assumed \( \gamma = 1.74 \). We have also assumed the interstellar medium has a rather low particle density, \( n = 10^{-3} \text{ cm}^{-3} \). We included SSC cooling while calculating \( E_{c} \) and an efficiency factor \( \epsilon_{Y} \leq 1 \) for electron acceleration to the maximum energy, \( E_{m} \), in Eq. (1). We note that there is significant degeneracy among the model parameters, and other sets of parameters 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,

\[
E^2 \frac{dN}{dE} = 1.2 \times 10^{-6} \left( \frac{E}{\text{GeV}} \right)^{0.13} \text{ erg cm}^{-2} \text{s}^{-1};
\]

\[
E_{c} \leq E < E_{s},
\]

in the 0.1–1 GeV range in the 200–800 s interval post-trigger.

The break energies in the SSC spectrum can be calculated with simplified assumptions as (Joshi & Razzaque 2021)

\[
E_{m,\text{SSC}} = 2.8 \epsilon_{e,-5.5}^{1/2} \epsilon_{B,-1.8}^{1/2} E_{55}^{3/4} n_{3.7}^{-1/4} \text{ GeV},
\]

\[
E_{c,\text{SSC}} = 52.9 \epsilon_{B,-1.8}^{-7/2} E_{55}^{5/4} n_{3.7}^{-9/4} \text{ TeV}.
\]

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

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

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

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

\[
\times \left( \frac{E_{\text{m,SSC}}}{E_{\text{c,SSC}}} \right)^{1/3} ; E \leq E_{\text{m,SSC}}
\]

\[
\times \left( \frac{E_{\text{m,SSC}}}{E_{\text{c,SSC}}} \right)^{1/3} ; E_{\text{m,SSC}} \leq E \leq E_{\text{KN,SSC}}.
\]

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. We present the results for a higher \( \epsilon_{e} \) value, which increases the SSC flux without violating the 0.1–1 GeV flux detected by Fermi-LAT; we modeled this 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. Reducing the \( \epsilon_{B} \) value considered here in order to extend the SSC flux to even higher energies may also increase the synchrotron flux and thus violate the Fermi-LAT flux level. We 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

Ultrahigh-energy cosmic rays accelerated in the internal shocks of GRBs are expected to produce PeV neutrinos by interacting with the prompt γ rays (Waxman & Bahcall 1997). The nondetection of these neutrinos from GRB 221009A by IceCube within three hours around the Fermi-GBM trigger allowed a time-integrated flux upper limit of \( 3.9 \times 10^{-2} \text{GeV cm}^{-2} \) in the 0.8–1 PeV energy range to be determined at the 90% confidence level (IceCube Collaboration 2022), which has implications for GRB model parameters (Liu et al. 2023; Ai & Gao 2022;
Here we consider UHECR acceleration in the external shock of the GRB blast wave during the afterglow emission phase. The maximum proton energy for an adiabatic blast wave in a constant-density environment can be calculated as (see, e.g., Razzaque 2013)

\[ E = 9.7 \times 10^{19} \phi^{-1/2} \epsilon_{B,-1.8}^{-1/2} \epsilon_{A,5}^{3/8} n_{-3.7}^{-1/8} \text{eV}. \]  

By interacting with the afterglow photons, these protons can produce neutrinos in the EeV range (Waxman & Bahcall 2000; Dai & Lu 2001; Razzaque 2013). Thus, the IceCube flux upper limit in the 0.8–1 PeV energy range does not apply in our scenario.

We assumed that the UHECR protons accelerated in the GRB blast wave escape from the source and propagate through the extragalactic medium from their sources to Earth. Their interactions lead to the production of secondary EM particles ($e^\pm, \gamma$). These particles can initiate various energy loss processes for the EM cascade, such as pair production (including double and triple pair production) and the inverse-Compton scattering of background photons to higher energies. 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 (Dermer et al. 2009)

\[ \Delta_{\text{IGM}} \approx \frac{d_\gamma^2}{24r_c^2 C_{\text{inv}}^\text{N}} \approx 2000 \left( \frac{d_\gamma}{648 \text{ Mpc}} \right)^{3/2} \left( \frac{\lambda_c}{1 \text{ Mpc}} \right)^{3/2} \left( \frac{B}{1.82 \times 10^{-5} \text{nG}} \right)^2 \left( \frac{E}{100 \text{ EeV}} \right)^2, \]  

where $d_\gamma$ is the comoving distance of the source, which in our case is ~648 Mpc for the standard flat, Λ cold dark matter cosmological parameters corresponding to a redshift $z \approx 0.151$. The number of inversions in the magnetic field, $N_{\text{inv}}$, is expressed as $\max(d_\gamma/\lambda_c, 1)$, where $\lambda_c$ is the turbulent correlation length of the EGMF. Equation (7) 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 (Huang et al. 2022).

We used the CRPropA3.2 numerical framework for the extragalactic propagation of UHECRs (Alves Batista et al. 2016, 2022). For our simulation, we assumed an rms magnetic field strength of $B_{\text{rms}} \approx 1.82 \times 10^{-5} \text{nG}$ and a coherence length of $\lambda_c \sim 1 \text{ Mpc}$ so that $\Delta r \approx 2000 \text{s}$. To calculate the line-of-sight component of the EM cascade, we employed a numerical method similar to that explained in Das et al. (2020). We considered an observing sphere around the Earth of radius 1 Mpc (i.e., the same as the coherence length) so that the deflection inside this sphere is negligible. We calculated the fraction of UHECRs that survive within $0.1$ of the initial emission direction on the surface of this sphere. We denote this fraction as $\xi_\gamma$. Then the line-of-sight component of the cosmic-ray $\gamma$-ray flux would be the fraction, $\xi_\gamma$, of the entire EM cascade arising from the UHECR propagation, obtained from a 1D simulation. We included all energy loss processes of primary and secondary EM particles in the simulations involving 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. 1. We used the Gilmore et al. (2012) EBL model and the Protheroe & Biermann (1996) model for the universal radio background.

We linearly scaled the 1-year flux sensitivity of LHAASO to Crab-like point sources (Vernetto 2016) as a conservative estimate to represent the GRB 221009A detection potential in 2000 s, corresponding to the time delay, $\Delta t$. In the absence of precise flux measurements at these energies, our analysis implies the lower limit to VHE flux from UHECR interactions. The corresponding UHECR luminosity in the energy range 0.1–100 EeV can be presented as

\[ L_{\text{UHE}, \gamma} \gtrsim \frac{2\pi d_{\text{IGM}}^2 (1 - \cos \theta)}{\xi_\gamma f_{\gamma,p} \epsilon_\gamma} \int_{1 \text{ GeV}}^{100 \text{ EeV}} dn_{\gamma} \int d\epsilon_{\gamma} dA d\Omega, \]  

where $2\pi d_{\text{IGM}}^2 (1 - \cos \theta)$ 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 $6^{\circ}$, appropriate for GRBs (Fraioli et al. 2001). Here $f_{\gamma,p}$ is the fraction of UHECR energy going into cosmogenic $\gamma$ rays between 1 GeV and 100 EeV. The integration is over the required flux of VHE $\gamma$ rays normalized to the LHAASO sensitivity at 18 TeV. The value of $\xi_\gamma$, corresponding to $\theta = 0.15$ is found to be 0.24, and the value of $f_{\gamma,p}$ corresponding to $\theta = 0.15$ is found to be 0.04. Using these values, we get from Eq. (8) $L_{\text{UHE}, \gamma} \gtrsim 5.4 \times 10^{47} \text{erg s}^{-1}$. This is the actual luminosity required in ultrahigh-energy protons to produce line-of-sight VHE $\gamma$-ray emission (i.e., the luminosity after the beaming correction). For the $T_\gamma > 2000 \text{s}$ LHAASO detection, it corresponds to an isotropic energy release of $\gtrsim 3.9 \times 10^{53} \text{erg}$ in UHECR protons, a small fraction of the total kinetic energy of the blast wave.

No track-like event with a positional coincidence with this GRB was found by the IceCube neutrino observatory in the 2 h from the initial trigger recorded by Fermi-GBM. IceCube derived a time-integrated $\nu_\gamma$ flux upper limit for this source at the 90% confidence level, assuming an $E^{-2}$ power law (IceCube Collaboration 2022). We also calculated the line-of-sight all-flavor cosmogenic neutrino flux from the GRB arriving on Earth. We used the same normalization as required for the VHE $\gamma$ rays from the EM cascade and find that the neutrino flux during the 2 h of IceCube observation is orders of magnitude lower than the IceCube upper limit.

### 3. Discussion and summary

Gamma-ray bursts have long been considered prominent candidates for UHECR acceleration. In the blast wave model, the relativistically expanding ejecta from a central engine slow down, after prompt emission, by interacting with the ambient medium. This produces a forward shock in the decelerating blast wave, whereby protons can be accelerated to ultrahigh energies. The delayed high-energy $\gamma$-ray emission observed from GRBs at $\gtrsim 1 \text{ TeV}$ energies can be explained by the interaction of UHECRs due to extragalactic propagation.

We find that in the case of the recent GRB 221009A, the leptonic emission due to synchrotron and SSC emission is difficult to extend up to energies of $\gtrsim 10 \text{ TeV}$. 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 the Fermi-LAT observation of a ~100 GeV photon. It is noteworthy that the SSC flux is well within the reach of the LHAASO flux sensitivity normalized for 2000 s of observation. Beyond 10 TeV, due to EBL attenuation, any significant flux from the source is unlikely to have originated directly from the GRB blast wave. For this reason, we invoked the line-of-sight UHECR interactions as the origin of $\gtrsim 10 \text{ TeV}$ $\gamma$ rays detected by LHAASO. We adjusted the rms strength of EGMF to be $B_{\text{rms}} \approx 1.82 \times 10^{-14} \text{G}$ so that the time delay induced by UHECR
The solid black line corresponds to the Fermi-LAT preliminary flux estimate for GRB 221009A (Pilleri et al. 2022). The dashed red curve indicates the LHAASO sensitivity corresponding to 2000 s of observation. The vertical dotted line corresponds to the highest-energy detection by LHAASO. The synchrotron and SSC emission components are shown as dashed orange and brown curves, respectively.

propagation from the initial trigger is comparable to $\sim 2000$ s. Our estimate for the lower limit of proton luminosity is a fraction of the blast wave kinetic energy.

There can be an additional time delay for UHECRs due to propagation in the host galaxy (Takami & Murase 2012), which for GRB 221009A at $z < 1$ can be a compact galaxy (Schneider et al. 2022), and the magnetic field for such galaxies is unknown. For a Milky Way-type galaxy, the time delay can be expressed as (Dermer et al. 2009) $\Delta t_{\text{gal}} = 2.25 \times 10^8 (b_{\text{had}/0.1 \text{ kpc}}^3 (B_{\text{max}}/\mu \text{G})^2 (E/100 \text{ TeV})^{-2}$ s, where $b_{\text{had}}$ is the characteristic height of the magnetic disk and $b$ is the Galactic latitude of the UHECR source. It can be seen that for a time delay on the order of $\sim 10^5$ s, the host galaxy’s magnetic field needs to be as low as 1 NG, similar to the field in protogalaxies (Beck & Wielebinski 2013). Alternatively, for our model to be valid, the GRB needs to be positioned at the outskirts of the host galaxy or away from the disk region so that the magnetic field is diminished. Similar assumptions are also made in other studies (Alves Batista 2022), which show that the cascade emission induced by heavier nuclei can extend up to energies higher than those that LHAASO has detected for this GRB.

For a Bethe-Heitler-dominated cascade, similar to the pair-echo effect (Razzaque et al. 2004b; Murase et al. 2012), the $e^+e^-$ pairs produced nearer to the source can be significantly deflected and hence induce higher time delays in the VHE $\gamma$-ray signal than what follows from Eq. (7). However, the contribution from these pairs is less significant at $\geq 10$ TeV energies because of EBL attenuation. Thus, in our model, we assumed that the production of secondaries is dominant nearer to the observer. The secondary EM particles with a higher deflection, and thus a higher time delay, are rejected by the line-of-sight survival fraction considered here. However, for protons with energies higher than the Greisen-Zatsepin–Kuzmin (GZK) cutoff energy there can be interactions near the source at $\sim 100$ Mpc, and hence the actual rms value of the EGMF needs to be lower than that estimated here.

The observation of GRB 221009A by LHAASO at $>10$ TeV provides a unique opportunity to probe particle acceleration and the emission mechanisms of GRBs. By explaining VHE $\gamma$-ray data we find, for the first time, an UHECR acceleration signature in a GRB.