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TeV Emission from Gamma-Ray Bursts: Signatures of Inverse Compton Scattering Induced by Kilonova-Jet Interactions

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The fireball model is widely used to explain the spectral energy distribution and light curves of gamma-ray bursts (GRBs) during the afterglow phase [39]. According to this model, particles are accelerated in external shocks, resulting in photon emission via synchrotron radiation and synchrotron self-Compton (SSC) processes [43, 44]. However, this framework does not fully account for all observed cases. Notably, the GeV excess detected in GRB 211211A has been attributed to external inverse-Compton (EIC) interactions, where optical kilonova photons are upscattered by electrons accelerated in the forward shock of a weaker secondary jet [30]. Observations with the High Altitude Water Cherenkov (HAWC) gamma-ray observatory revealed emission spatially coincident with a few GRBs, detected at timescales consistent with the expected kilonova emission peak. In this work, we argue that the detected VHE photons indeed originate from these GRBs, the SSC mechanism in both forward and reverse shocks fails to account for this emission. Instead, we propose that these photons result from inverse-Compton scattering of kilonova photons by electrons within the reverse shock. We searched for the TeV emission for GRB 160821B which presented a weak kilonova

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1. Introduction

Gamma-Ray Bursts (GRBs) are the most energetic events in the universe. Their emission consists of two well-defined parts: prompt and afterglow emission. The prompt emission is mostly observed in X-ray and gamma-ray energies, lasting from a few seconds to thousands of seconds [13, 24]. On the other hand, the afterglow emission is observed across the entire electromagnetic spectrum and can last from hours to months [34, 49]. The duration of the prompt emission is known as T_{90}, and based on it, two types of GRBs are distinguished: short GRBs with $T_{90} < 2$ s and long GRBs with $T_{90} > 2$ s [24, 35]. Long GRBs are associated with the collapse of massive stars (supernovae) [17, 50], while short GRBs are the result of the merger of compact binary systems (kilonovae) [15, 36]. The released material is relativistic, producing highly collimated jets [33, 39].

Prompt and afterglow emissions result from internal and external shocks of the jet, respectively [38, 40]. In these shocks, charged particles are accelerated, emitting photons through synchrotron radiation [14]. The maximum energy reached through synchrotron is around tens of GeV [2, 52], while higher energies are typically achieved via the synchrotron self-Compton (SSC) mechanism [38].

To date, only a few GRBs have been observed at TeV energies, namely: GRB 180720B [6], GRB 190114C [28], GRB 190829A [21], and GRB 201216C [7].

The limited number of observed kilonova can be attributed in part to the limited duty cycle of most sensitive instruments in the TeV energy range at the time, such as MAGIC and the now-retired H.E.S.S. [8, 11]. Moreover, as the most energetic fluxes were expected during the prompt emission, high-energy follow-ups were conducted close to the GRB trigger time [2]. However, TeV observations of GRBs have revealed that high-energy emission can also occur at later times, well beyond the prompt phase. In fact, for GRB 180720B and GRB 190829A, very high-energy (VHE) fluxes were observed at ~ 10 and $4 - 55$ hours after the trigger, respectively [1, 21]. This has proven that it is worthwhile to look for TeV emissions at unorthodox timescales.

Several mechanisms besides SSC have been invoked to explain VHE emission, such as proton synchrotron radiation [9], dark matter annihilation [20], and Lorentz invariance violation [18]. External inverse Compton (EIC) with kilonova photons has been proposed to explain GeV observations in short GRBs [27]. For example, GRB 211211A exhibited a GeV excess that could not be explained by typical emission mechanisms [41]. Notably, the GeV excess coincided with the phase during which the kilonova reached its peak brightness [41]. EIC with kilonova photons and forward-shock electrons from the GRB jet successfully reproduced the observed GeV excess [16, 26].

GeV emission through this mechanism has been theorized, but until now no theory has proposed the possibility of reaching energies of TeV. In this work, we investigate the potential for such emission resulting from up-scattered kilonova photons by electrons in the GRB jet, by searching for TeV signatures on timescales consistent with the expected peak of a possible EIC emission.

2. Kilonova Timescales and Energetics

Kilonovae are optical and infrared transients resulting from the radioactive decay of heavy r-process elements synthesized in the ejecta of binary neutron star mergers [25, 32]. The timescales and energetics of kilonovae are distinct compared to typical GRB afterglows.

The peak emission from a kilonova typically occurs on timescales of ~ 1 day to several days after the merger event [32]. The observed light curve depends strongly on the opacity of the ejecta, which in turn depends on its composition [10]. Lanthanide-rich ejecta produce longer, redder, and dimmer transients, whereas lanthanide-poor ejecta produce faster, bluer emission [10, 46].

The peak bolometric luminosities of kilonovae are in the range of 10^{40} to 10^{42} erg s^{-1}, significantly lower than those of typical GRB afterglows [31]. The typical thermal energies involved are ~ 10^{50} erg, which is about 1% of the total kinetic energy of the ejecta [31, 42]. Kilonovae peak on a timescale of about one day, much faster than for normal SNe, the progenitors of long GRBs. The characteristic timescale at which the light curve peaks is:

$$t_{\rm peak} = \left(\frac{3M\kappa}{4\pi\beta v c}\right)^{1/2} \approx 1.6\ {\rm d} \left(\frac{M}{10^{-2}M_\odot}\right)^{1/2} \left(\frac{v}{0.1c}\right)^{-1/2} \left(\frac{\kappa}{1\ {\rm cm}^2\ {\rm g}^{-1}}\right)^{1/2} \tag{1}$$

Where:
- M is the mass of the ejecta in solar masses,
- κ is the opacity, - v is the velocity of the ejecta,
- c is the speed of light,
- β is a constant related to the density profile of the ejecta.

This equation predicts characteristic durations of 1 day to 1 week [31].

3. Methods

We searched for short GRBs with observed kilonova and conducted a model-dependent search of emission in the TeV energy using data from the High Altitude Water Cherenkov (HAWC) observatory [5].

GRBs with identified kilonova include GRB 050709 [22], GRB 060614 [51], GRB 130603B [12, 47], GRB 160821B [23, 48], and GRB 170817A [45].

The HAWC observatory primary array has been fully operational since 2015; therefore, only GRB 160821B and GRB 170817A were directly evaluated. This document presents results for GRB 160821B. The HAWC observatory covers two thirds of the sky every 24 hours, observing about 15% (2 sr) of the overhead sky [5]. It is located in the northern hemisphere. ($N\,18°59'48''$, $W\,97°18'34''$) at an altitude of 4100 m on the flanks of the Sierra Negra volcano in Mexico [3, 4].

To optimize the search for TeV emission, we first estimate the instrument sensitivity at the GRB location to define the relevant energy range. To derive energy ranges, we simulate a bright point source with a power-law spectral distribution at the GRB's RA and Dec. The injected source is then reconstructed, and its significance is computed. The energy range is defined by the energies that correspond to a relative sensitivity of 75%.

Significance maps for the first transit over the HAWC field of view were produced by computing the likelihood-based test statistic for each HEALPix pixel within a 2°×2° region centered on the GBM localization, comparing the observed excess with the expected background to assess the significance of the potential gamma-ray signal.

4. Results and Discussion

The Fermi Gamma-ray Burst Monitor (GBM) triggered on GRB 160821B at 22:29:13.33 UT on 2016 August 21 (T_0), recording a short, multi-peaked light curve with $T_{90} \simeq 1$ s (50–300 keV) [29]. Spectral fitting over $T_0 - 0.13$ s to $T_0 + 0.32$ s yields a power-law index of -1.37 ± 0.22, an $E_{\rm peak} = 84 \pm 19$ keV, a fluence of $(1.68 \pm 0.19) \times 10^{-6}$ erg cm^{-2} (10–1000 keV), and a 64-ms peak photon flux of 9.16 ± 1.19 ph s^{-1} cm^{-2} [29]. Simultaneously, Fermi-LAT, at a boresight angle of 61°, searched the 0.1–300 GeV band during both prompt and afterglow phases but found no significant excess, placing deep upper limits on GeV emission [2, 37]. The MAGIC telescopes began follow-up observations of GRB 160821B just 24 s after the GBM trigger, targeting $E > 500$ GeV [8]. They recorded an excess of γ-ray–like events at $\gtrsim 0.5$ TeV during the afterglow (from T_0+24 s to T_0+4 h), reaching $\sim 3\sigma$ significance [37]. This constitutes the first hint of TeV emission from a short GRB, extending the afterglow window into the VHE domain.

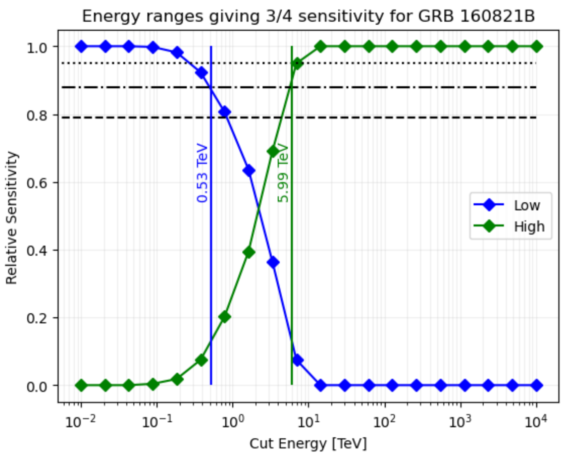

Figure 1: Normalized significance of a simulated source at coordinates and redshift of GRB 160821B. The high-cuts curve shows the reconstructed significance when applying a maximum energy limit to the injected spectrum, while the low-cuts curve represents the significance when applying a minimum energy limit. The horizontal dash-dotted line marks the 75% sensitivity threshold. The point where the low- and high-cuts curves intersect this threshold, indicated by color-matched vertical lines, defines the minimum and maximum energies in the optimal range for this GRB.

The relative significance as a function of the energy cut is shown in Figure 1. The blue line represents the variation of the low-energy cut, while the green line represents the variation of the high-energy cut. We assumed an injected spectrum given by a power law of index 2.07 using GRB 170817A [19] with a redshift of 0.160 [23]. As shown in Figure 1, the HAWC observatory has a 75% sensitivity in the declination corresponding to GRB 160821B of 0.53 to 5.99 TeV. On the basis of this simulation, we set the energy range for this GRB. Note that the energy range does not extend to hundreds of TeV, even though the HAWC observatory is sensible up to that scale. This is due to the inclusion of EBL attenuation in HAWC's sensitivity. Also, the lower limit in the energy range is constrained by the zenith at which the source is observed: the larger the zenith angle, the more atmosphere charged particles have traverse. This GRB was located at a declination of 62.39°, corresponfing to a zenith angle of 43.40 ° for the HAWC observatory location. This lies near the

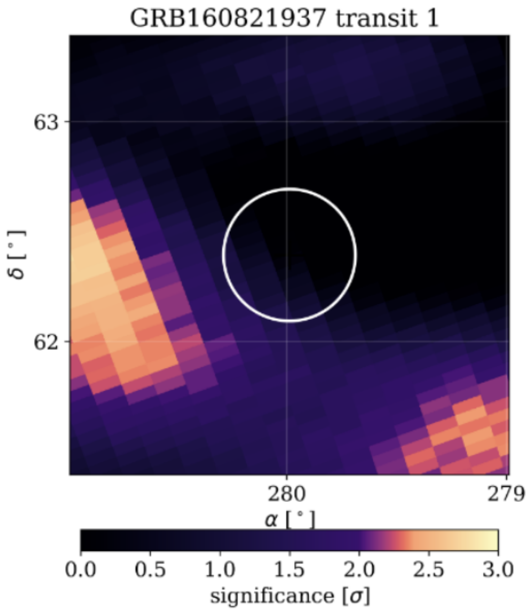

Figure 2: Significance map for the transit over HAWC FOV of GRB 160821B.

limit at which HAWC can reliably reconstruct time and directions of atmospheric showers.

Figure 2 shows the significance map of GRB 160821B using HAWC data. Within the Fermi-GBM error radius (white circle) Fig. 2), significances are lower than 5σ, therefore we proceeded to set an upper limit. The 95% upper limit on the flux is $\mathbf{3.65 \times 10^{-9}}$ $\mathrm{TeV^{-1}\,cm^{-2}\,s^{-1}}$ for a spectral index of 2.07 at a pivot energy of 1 TeV, integrated over 0.53–5.99 TeV.

In this study, we explored the possibility of TeV emission arising from external inverse Compton (EIC) scattering of kilonova photons by relativistic electrons in the GRB jet. Given that kilonova emission typically peaks around one day post-merger, we focused our analysis on the first HAWC transit after the GRB trigger, aligning with the expected peak photon density from the kilonova. Using this timing, we produced likelihood-based significance maps over a 2°×2° region centered on the GBM localization and estimated the TeV energy range via sensitivity simulations. While no significant excess was detected within this window, we derived upper limits in the 0.53-5.99 range. These limits provide the first constraints on TeV EIC emission in this context and offer guidance for future models and observational follow-ups involving kilonovae.

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