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Constraints on micro-physical parameters of GRBs using HAWC

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The physical mechanism at the origin of gamma-ray bursts (GRBs) is far from being completely understood. Describing their emission up to very high energies (GeV-TeV) is one of the most challenging and important tasks needed to unveil the physics of these peculiar events. Using data collected by the HAWC gamma-ray observatory, we search for TeV emission coming from a sample of GRBs detected by Fermi and Swift between December 2014 and May 2017. We derive upper limit over different time intervals and use them to constrain the micro-physical parameters and the bulk Lorentz factor under the assumption of Self-Synchrotron Compton within the external shock model scenario. We present the results of this analysis discussing possible interpretations.

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1. Introduction

The Large Area Telescope instrument on board the Fermi satellite (Fermi/LAT, [1]) revealed a high-energy component (> 100 MeV) from over 100 GRBs[1]. This emission lasts more and shows a different spectral evolution [2]) than the one observed at lower energies during the prompt phase. The study of the high energy emission coming from GRBs could reveal important information about emission mechanisms and physics of these peculiar phenomena. Moreover, it allows to probe the effects of the extra-galactic background light (EBL; see [3]), to derive the initial Lorentz factor of the jet and to estimate the Lorentz invariance violation (see e.g. [4]). High energy photons could be originated when the jet interacts with the external medium accelerating electrons which scatter synchrotron radiation (synchrotron self-Compton; hereafter SSC) by the shock wave up to energies from GeV to TeV. In general, the external medium can present a constant density profile (e.g. interstellar medium; ISM, see[5]), a stellar wind profile (e,g [6, 7, 8]) or a combination of these two (e.g. [9]). According to Meszaros and Rees [10], the inverse Compton scattering could be the dominant cooling mechanism of accelerated electrons in the external shock wave when it gets close to the deceleration radius. In this work we compare the theoretical predictions for the SSC emission at high energy with the flux upper limits derived for a sample of GRBs within the field of view of the High Altitude Water Cherenkov observatory (HAWC). We use the HAWC data to test the external shock model, probe the circumburst medium and constrain the micro-physical parameters involved in this scenario.

2. HAWC

HAWC is an extensive air shower array located at Sierra Negra, in the state of Puebla, Mexico. This observatory uses a water Cherenkov technique to study TeV γ-ray radiation and cosmic rays. The experiment has a field of view of ~ 2 str and it is continuously operating (24/7 monitoring) since March 2015. It covers $\sim 2/3$ of the sky every sidereal day being particularly suitable for GRB follow up at very high energies. The events or air showers detected by HAWC are classified in ten different size bins (from 0 to 9) which are based on the fraction of available PMT activated by the event as described by [11]. The lowest bin (bin 0) is excluded from this analysis.

3. Data Analysis

We search for TeV emission at the position of 108 GRBs within the field of view of HAWC from December 2014 to May 2017. Twenty-one of them are short GRBs (T_{90} [2] < 2 seconds) and eighty-seven are long ones ($T_{90} \geq 2$ seconds). Eighty out of 108 GRBs were observed by the Gamma-Ray Burst Monitor on board of Fermi (GBM). Four of them were co-detected at higher energies by Fermi/LAT. For 28 GRBs, more precise information on the position was provided by the Swift satellite. We estimate the significance of the signal in different time window durations. T_{90} is used for long GRBs and a fix duration of 2 seconds for the short ones. In order to explore

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[1] https://fermi.gsfc.nasa.gov/ssc/observations/types/grbs/lat_grbs/

[2] T_{90} is defined as the time during which the cumulative number of detected counts increases from 5% to 95% above background, thus encompassing 90% of the total GRB counts

possible late time signal we also estimate the significances in ten consecutive time windows of the same duration for each GRB. Flux upper limits in the energy range $80-800$ GeV are derived for each time window following the same procedure outlined in [12] using Monte Carlo simulations (see [11]) to obtain the HAWC effective area. We assume a power law spectrum considering two different spectral indices predicted for fast, index of -1.5, and slow cooling, index of -1.7, regimes. Then, we introduce the attenuation effects due to the EBL according to the fiducial model proposed by [13].

We focus our analysis on short GRBs since HAWC is more sensitive to this specific subclass (see [14]). The bulk of sGRB are between redshift of 0.1 and 1.3, with an average value of 0.5 (see [15]). Therefore, we assume a conservative value of 1 for the redshift when we account for the EBL effects.

3.1 Model

The dynamics of the external shock for the ejecta expanding into a surrounding medium with homogeneous density has been widely explored [9]. Using the synchrotron spectra, the evolution of synchrotron energy breaks and the maximum flux, the light curve in the fast-cooling regime is proportional to $\propto t^{-\frac{3p-2}{4}} E^{-\frac{p}{2}}$ for $E^{\rm syn}_{\gamma,\rm m} < E^{\rm syn}$ and $\propto t^{-\frac{1}{4}} E^{-\frac{1}{2}}$ for $E^{\rm syn}_{\gamma,\rm c} < E^{\rm syn} < E^{\rm syn}_{\gamma,\rm m}$, where $E^{\rm syn}_{\gamma,\rm c}$ and $E^{\rm syn}_{\gamma,\rm m}$ are the synchrotron spectral breaks for the cooling and characteristic energies, respectively [5]. Relativistic electrons accelerated in the forward shocks could scatter synchrotron photons up to energies larger than 100 GeV. The SSC spectral breaks (the characteristic ($E^{\rm ssc}_{\gamma,\rm m}$), the cooling ($E^{\rm ssc}_{\gamma,\rm c}$) and the Klein-Nishina ($E^{\rm KN}_{\gamma,\rm c}$) energies) as well as the maximum SSC flux are in the form

$$\begin{array}{lll} E^{\rm ssc}_{\gamma,\rm m} \propto \varepsilon_e^4\, \varepsilon_B^{1/2}\, n^{-1/4}\, E^{3/4}\, t^{-9/4} & \qquad & E^{\rm ssc}_{\gamma,\rm c} \propto \varepsilon_B^{-7/2}\, n^{-9/4}\, E^{-5/4}\, t^{-1/4}\,, \\ E^{\rm KN}_{\gamma,\rm c} \propto \varepsilon_B^{-1}\, n^{-3/4}\, E^{-1/4}\, t^{-1/4} & \qquad & F^{\rm ssc}_{\gamma,\rm max} \propto \varepsilon_B^{1/2}\, n^{1/4}\, D^{-2}\, E^{5/4}\, t^{1/4}\,. \end{array} \tag{3.1}$$

where n is the homogenous density, D is the luminosity distance, E is the isotropic equivalent kinetic energy, ε_e and ε_B are the micro-physical parameters defined as fraction of the energy density that goes to accelerate electrons and to amplify the magnetic field, respectively. Taking into consideration $E^{\rm ssc}_{\gamma,\rm c} \leq E_\gamma \leq E^{\rm ssc}_{\gamma,\rm m}$, the flux as a function of time in the corresponding energy regime is given by

$$F^{\rm ssc}_\nu \propto \varepsilon_B^{-5/4}\, n^{1/8}\, D^{-2}\, E^{5/8}\, t^{1/8}\, E_\gamma^{-1/2} \tag{3.2}$$

4. Results and Discussion

The distribution of the significances extracted in each time windows for all the GRBs is displayed in Fig. 1. As observed, no statistically significant detection is found. Therefore upper limits for the flux are derived.

The most constraining upper limits are the corresponding to GRB 170206A. For this case, the fluence upper limits are comparable or below the fluence measured by GBM during the prompt emission in the energy range of 10-1000 keV. GRB 170206A is the third brightest short burst detected by Fermi-GBM. Flux upper limits derived for this burst at different times for z=1 are shown in Fig. 2.

These limits can be used to constrain the normalization of equation 3.2, thus the allowed range for the micro-physical parameters ε_B and ε_e assuming different values for n (and Γ). Fig. 3 shows

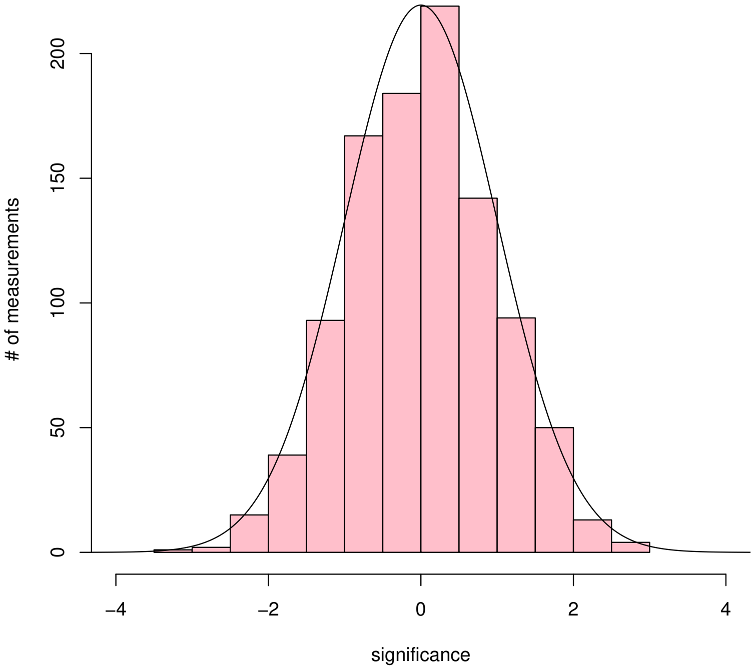

Figure 1: The plot shows the distribution of the significances derived over 10 time windows for each GRB of our sample. It is consistent with a standard normal distribution. The solid line shows a Gaussian function centered at 0 and standard deviation of 1.

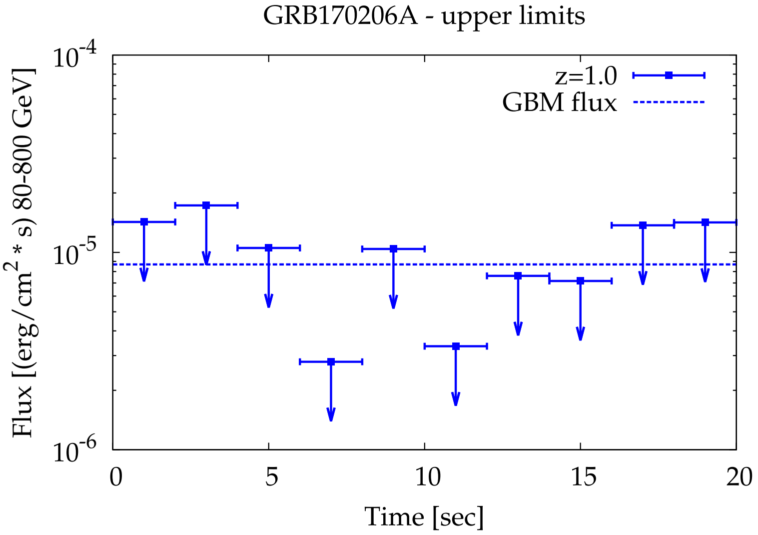

Figure 2: Flux upper limits extracted for GRB 170206A over different time windows in the energy range 80-800 GeV assuming a redshift of 1 (blue arrows). The average flux measured by Fermi-GBM in the energy range 10-1000 keV is shown for comparison (dashed blue line).

the allowed values for ε_B and ε_e derived assuming n = 0.5 cm^{-1} and considering the upper limits measured for GRB 170206A at z=1 in the fast cooling regime. We find an upper limit for ISM density of n < 1.1cm^3 in order to the model in the fast cooling regime be consistent with the limits measured by HAWC. On the other hand, assuming the slow cooling regime, we find that the density have to be lower than 12 particles per cm^3.

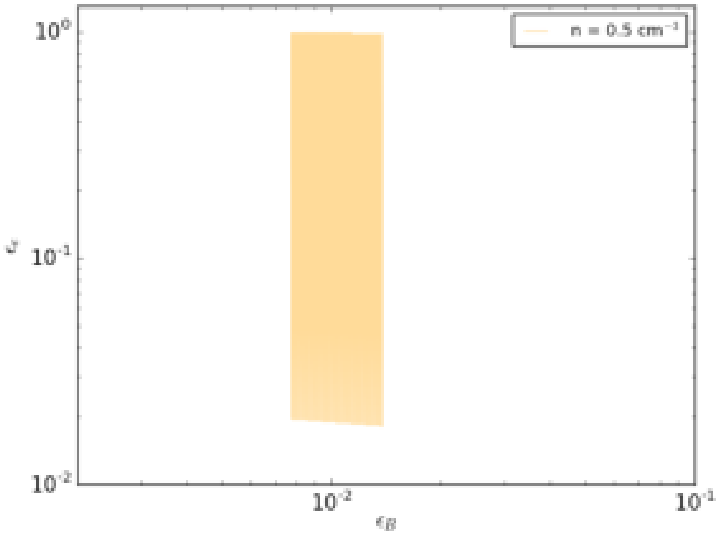

Figure 3: The allowed range for the micro-physical parameters ε_B and ε_e is derived using the GRB 170602A flux upper limits and assuming a fast cooling regime at redshift 1.0. The allowed region would be smaller assuming lower values of z (detailed results will be shown in a future work currently in progress). A density of 0.5 particles per cm^3 is considered (Γ=1150)

5. Conclusions

Using the HAWC data we search for TeV emission from 108 GRBs occurred between December 2014 and May 2017. No evidence of GRB TeV emission is found neither at early or late times. Upper limits for the flux and fluence are derived for each GRB. We use the limits derived for GRB 170206A to constrain the micro-physical parameters and to probe the prediction proposed for the VHE emission in the framework of the external shock model. Assuming a fast cooling regime, the density of the ISM is found to be n$< 1.1\,cm^{-3}$ which imply a limit on the relativistic Lorentz factor of $\Gamma = \left(\frac{3}{32\pi m_p}\right)^{1/8}(1+z)^{3/8}n^{-1/8}E^{1/8}t^{-3/8} > 1000$. For the slow cooling regime, a lower limit for the density of n$< 12\,cm^{-3}$ is found ($\Gamma > 800$). The detection of new constraining upper limits together with a multi-wavelength analysis would provide an important tool to test the physics of the GRB afterglow and to probe the nature of the VHE emission.

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