

1 Search for very-high-energy photons from 2 Gamma-ray bursts with HAWC

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Detections of very-high-energy (VHE; > 100 GeV) photons from Gamma-ray bursts (GRBs) can provide fundamental information on the involved radiative processes, physical composition of the ejecta and acceleration processes. The High Altitude Water Cherenkov (HAWC) gamma-ray observatory is the best gamma-ray instrument to study transient phenomena over a long period of time from 100 GeV to 100 TeV. Its large field of view and duty cycle ($> 95\%$) allow it to search blindly for sources of GRBs and to follow up on external alerts from satellite instruments, such as Fermi and Swift, searching for their VHE counterpart. We present results from the ongoing GRB monitoring program and VHE upper limits of the latest interesting low-redshift and/or powerful bursts in HAWC's field of view: GRB 170206A, GRB 170817A, GRB 180720B and GRB 190114C.

*36th International Cosmic Ray Conference -ICRC2019-
July 24th - August 1st, 2019
Madison, WI, U.S.A.*

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1. Introduction

Gamma-ray bursts (GRBs) are the most luminous gamma-ray transient events in the Universe. They are non-repeating flashes usually associated with the core collapse of massive stars or the merger of compact object binaries when the duration of their prompt emission is longer or less than a few seconds, respectively [1, 2]. However, independently of the progenitor associated to the prompt emission, a long-lived afterglow emission is generated by the deceleration of the outflow in the circumburst medium (e.g., see [3, 4, 5]).

The detection of very-high-energy (VHE; $\gtrsim 10$ GeV) photons from GRBs and the record of their arrival times provide an important piece of information to estimate, for example, the baryonic composition of the outflow and the particle acceleration efficiency [6, 7, 8, 9, 10, 11, 12, 13, 14]. The Large Area Telescope (LAT) on-board the Fermi satellite has detected more than 150 GRBs which exhibit photons above ≥ 100 MeV but only ~ 29 GRBs with VHE (≥ 10 GeV) photons [15]. GRB 130427A presented photons with the highest energy ever detected, 73 GeV and 95 GeV, and were observed 19 s and 244 s after the beginning of the burst, respectively [16]. Additionally, a 52-GeV photon was related to GRB 160509A [17]. It arrived 77 s after the trigger. Recently, VHE photons with energies above of 300 GeV were detected from the long GRB 190114C [18]. The MAGIC telescopes observed GRB 190114C with a significance of $\sim 20\sigma$ over the background for more than 1000 s [18]. Although VHE photons at TeV energies have been searched for by the Imaging Atmospheric Cherenkov Telescopes (IACTs), only upper limits on the TeV flux have been derived [19, 20].

The High Altitude Water Cherenkov (HAWC) observatory followed-up GRB 130427A, one of the brightest and longest burst ever detected above 100 MeV. This burst took place when only 10% of the final detector was operating and under sub-optimal observational conditions (see, [21]). Eight different time intervals during the prompt and long-lived emission were analyzed in order to searched for VHE emission, and although no statistically significant excess of counts was recorded in the GeV - TeV energy range, upper limits on the flux were placed [21].

In this work, we present the results from the on-going GRB monitoring program in HAWC and also the VHE upper limits of the latest interesting low-redshift and/or powerful bursts in the HAWC's field of view: GRB 170206A, GRB 170817A, GRB 180720B and GRB 190114C. In Section 2, we give a brief summary of the HAWC observatory and the on-going GRB monitoring program. In section 3, we present the relevant information on GRB 170206A, GRB 170817A, GRB 180720B and GRB 190114C. In section 4, we show the results and a brief summary.

2. GRB monitoring program

The HAWC observatory, located at an altitude of 4,100 m a.s.l. in the volcano Sierra Negra in the state of Puebla, Mexico, is the best TeV gamma-ray observatory for studying transient phenomena at very-high energies, such as GRBs. Thanks to its wide field of view of ~ 2 sr and its continuous operation ($> 95\%$ of duty cycle), HAWC constantly searches for TeV photons from GRBs detected by other instruments within its field of view. Since HAWC does not need to be re-pointed to the burst position, VHE data before, during, and after the burst trigger time are available, making it possible to test distinct model assumptions [22]. It is worth noting that full temporal

43 coverage only applies for bursts within the instantaneous field of view.

44 The on-going GRB monitoring program currently consists of two analyses: i) a rapid response
45 follow-up of bursts notified by orbiting instruments and ii) a self-triggered all-sky search. Both the
46 triggered and self-triggered methods are applied to archival data in order to benefit from the latest
47 reconstruction techniques.

48 The self-triggered all-sky searches permanently for VHE photons from bursts within three time
49 windows: 0.2, 1 and 10 s. The analysis of rapid response follow-ups of notified bursts fixes the
50 search window in accordance with the trigger time provided by the orbiting instrument. Details
51 concerning the on-going GRB monitoring program can be found in [23].

52 3. HAWC Upper Limits of interesting GRBs

53 HAWC has not significantly detected emission from any GRB candidate to date. Therefore,
54 upper limits in the GeV - TeV energy range for GRB 170206A, GRB 170817A, GRB 180720B
55 and GRB 190114C have been set. Below we present the flux upper limits of the nearest/brightest
56 bursts in the field of view of HAWC. The effect of extragalactic background light (EBL) attenuation
57 shown in [24] is used.

58 3.1 GRB 170206A

59 The Fermi GBM detected GRB 170206A at 10:51:57.70 UT on 2017 February 6th. The GBM
60 light curve exhibited a short and bright burst with a duration of $T_{90} = 1.2$ s in the energy range of 50
61 - 300 keV [25]. This burst was also detected at energies of MeV by Fermi LAT. The highest-energy
62 photon reported was of 811 MeV and was observed 5.17 s after the trigger time [26]. This burst
63 was also detected in gamma-rays by Konus-Wind. The Konus-Wind light curve displayed a multi-
64 peaked structure with a high-energy emission seen up to 15 MeV [27]. There is not measurement
65 of redshift for this burst.

66 The HAWC upper limit of $2.82 \times 10^{-6} \text{ erg cm}^{-2} \text{ s}^{-1}$ at 6 s after the trigger time was calculated
67 for $E_{\text{iso}} = 5.5 \times 10^{52}$ erg and an assumed $z=0.3$ [28], a likely value for a short burst. This burst
68 was within the set of burst analyzed when searching for TeV emission coincident with the prompt
69 emission. Therefore time windows of duration T_{90} , $3 \times T_{90}$ and $10 \times T_{90}$ were selected. The most
70 restrictive upper limit is found and presented here for the time window of T_{90} [29]. The isotropic
71 energy was computed taking into account the Band function parameters reported in the [30].

72 3.2 GRB 170817A

73 The gravitational-wave transient GW170817, associated with a binary neutron star system
74 with a merger time of 12:41:04 UTC, 2017 August 17, was detected by LIGO and Virgo experi-
75 ments [31, 32]. Immediately, GRB 170817A triggered on the GBM instrument at 12:41:06.47 UT
76 on 2017 August 17 [33]. The Fermi GBM located a weak gamma-ray flux at R.A.= 176.8 and
77 DEC= -39.8 (J2000) with an uncertainty of 11.6° . The gamma-ray light curve in the 50-300 keV
78 energy range displayed a weak short pulse with a duration of $T_{90} = 2$ s [33, 34]. A large multi-
79 wavelength campaign followed up this burst. In the X-ray bands, this burst was detected by the
80 Chandra and XMM-Newton satellites [35, 36]. In optical bands, GRB 170817A was detected by
81 the Hubble Space Telescope [37, 36]. In the radio wavelengths, GRB 170817A was detected by

82 Very Large Array [32]. The host galaxy associated with this burst was located with a redshift of
 83 $z \simeq 0.01$ [38, 39]. A miscellaneous set of models based on external shocks were developed to ex-
 84 plain this burst [40, 41, 42, 43, 44, 45].

85

86 Unfortunately, this burst entered the HAWC's field of view ~ 8 hours after the GW trigger
 87 [46]. Thus, the flux upper limit was set for the first transit of the burst location after the trigger
 88 time [46, 47]. Taking into account that the atypical multi-wavelength fluxes peaked at ~ 120
 89 days after the trigger time, a search for a TeV counterpart for much longer time periods than T_{90}
 90 was performed, for details see [48]. The most constraining flux upper limit found was $3.37 \times$
 91 $10^{-12} \text{ erg cm}^{-2} \text{ s}^{-1}$ for an energy range of 7 - 170 TeV and the time period of 10 - 110 days after
 92 the merger time.

93 Von Kienlin et. al. [49] identified 13 GRBs with similar features to GRB 170817A. Then,
 94 the search for TeV emission within days was extended to the 2 other bursts (out of the 13) in the
 95 HAWC's field of view, see [48].

96 3.3 GRB 180720B

97 GRB 180720B triggered on the Swift BAT at 14:21:44 UT on 2018 July 20 [50]. This burst
 98 was located at R.A.= $00^{\text{h}}02^{\text{m}}07^{\text{s}}$ and DEC= $-02^{\text{d}}56'0''$ with an uncertainty of 3 arcmin [51]. The
 99 BAT light curve exhibited a multi-peaked structure with a duration of $T_{90} = 150 \text{ s}$ [50]. Promptly,
 100 GRB 180720B was followed up by X-ray Telescope (XRT) and the Ultra-Violet/Optical Telescope
 101 (UVOT), by Fermi GMB and LAT [52, 53], by Konus-Wind [54], by CALET Gamma-ray Monitor
 102 [55] and several orbiting and ground instruments in optical and radio bands [56]. The host galaxy
 103 of GRB 180720B was located to have a redshift of $z = 0.654$ [57].

104 The VHE upper limit of $1.81 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$ is reported for an energy range of 2 - 60
 105 TeV. The observations of HAWC experiment began 18 hours after the trigger time. Thus, the flux
 106 upper limit is given for the first transit in the HAWC's field of view (lasted 4 hours).

107 3.4 GRB 190114C

108 The Swift BAT instrument triggered on GRB 190114C on January 14, 2019 at 20:57:03
 109 UTC (trigger 883832) [58]. This burst was located at R.A.= $03^{\text{h}}38^{\text{m}}02^{\text{s}}$ and DEC= $-26^{\text{d}}56'18''$
 110 (J2000) with an uncertainty of 3 arcmin. The BAT light curve displayed a very bright multi-peaked
 111 structure with a duration of $T_{90} = 25 \text{ s}$ [58]. GRB 190114C was also detected by Fermi GBM [59],
 112 by Fermi LAT [59, 60], by Swift XRT [58, 61], by Swift UVOT [58, 62], by INTEGRAL [63],
 113 by AGILE satellite [64], by Konus-Wind [65] and by a massive campaign of optical instruments
 114 and telescopes [66]. For the first time an excess of gamma-ray events with a significance of 20σ
 115 was detected during the first 20 minutes and photons with energies above 300 GeV were reported
 116 by MAGIC collaboration from GRB 190114C [67]. The host galaxy of this burst was located at a
 117 redshift of $z = 0.42$ [68, 69].

118 The VHE upper limit of $4.46 \times 10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$ for an energy range of 7 - 170 TeV is re-
 119 ported. The observations of HAWC observatory lasted 2 hours and began 5 hours after the trigger
 120 time. Similarly to GRB 170206A and GRB 180720B, the flux upper limit is given for the first
 121 transit in the HAWC's field of view.

122 The summary of the VHE upper limits are reported in Table 1.

Table 1: VHE Upper limits calculated for some GRBs. The spectral power-law index of 2.5 was used in all cases. The integration times are given in column 3.

| Bursts | Energy Range | Observation | Upper Limit [$10^{-8} \text{ erg cm}^{-2} \text{ s}^{-1}$] |
|-------------|----------------|---------------|---|
| GRB 170206A | (80 - 800) GeV | 6 - 8 s | 2.82×10^2 |
| GRB 170817A | (7 - 170) TeV | 10 - 110 days | 3.37×10^{-4} |
| GRB 180720B | (2 - 60) TeV | 18 - 22 hours | 1.81 |
| GRB 190114C | (7 - 170) TeV | 5 - 7 hours | 4.46 |

123 4. Summary

124 We analyzed data taken by the HAWC gamma ray observatory to search for VHE photons
 125 from GRB 170206A, GRB 170817A, GRB 180720B and GRB 190114C, all of which were inside
 126 HAWC's field of view and were reported by the orbiting instruments and ground telescopes. These
 127 bursts occurred from February 2017 to January 2019. Although no statistically significant excess
 128 of counts was detected by HAWC, VHE upper limits in the GeV - TeV energy were derived around
 129 the positions of GRB 170206A, GRB 170817A, GRB 180721A and GRB 190114C.

130 HAWC continues to monitor the whole sky in search of signals from potential burst candidates.

131 5. Acknowledgements

132 We acknowledge the support from: the US National Science Foundation (NSF) the US De-
 133 partment of Energy Office of High-Energy Physics; the Laboratory Directed Research and Devel-
 134 opment (LDRD) program of Los Alamos National Laboratory; Consejo Nacional de Ciencia y Tec-
 135 nología (CONACyT), México (grants 271051, 232656, 260378, 179588, 239762, 254964, 271737,
 136 258865, 243290, 132197, 281653)(Cátedras 873, 1563, 341), Laboratorio Nacional HAWC de
 137 rayos gamma; L'OREAL Fellowship for Women in Science 2014; Red HAWC, México; DGAPA-
 138 UNAM (grants AG100317, IN111315, IN111716-3, IA102715, IN111419, IA102019, IN112218);
 139 VIEP-BUAP; PIFI 2012, 2013, PROFOCIE 2014, 2015; the University of Wisconsin Alumni Re-
 140 search Foundation; the Institute of Geophysics, Planetary Physics, and Signatures at Los Alamos
 141 National Laboratory; Polish Science Centre grant DEC-2014/13/B/ST9/945, DEC-2017/27/B/ST9/02272;
 142 Coordinación de la Investigación Científica de la Universidad Michoacana; Royal Society - New-
 143 ton Advanced Fellowship 180385. Thanks to Scott Delay, Luciano Díaz and Eduardo Murrieta for
 144 technical support.

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