PROCEEDINGS OF SCIENCE

Search for TeV Gamma Ray Emission from Fast Radio Burst Locations with the HAWC Obsevatory

Elijah Willox[a,*] **for the HAWC collaboration**

[a] *University of Maryland, College Park, Dept. of Physics, College Park, MD 20742 U.S.A.*

E-mail: etabachn@umd.edu

The number of observed Fast Radio Burst (FRB) events has grown rapidly over the last few years, but their origin remains unknown. Multiwavelength follow-ups have been encouraged by radio astronomers but the transient nature of the events makes targeted follow-ups difficult unless a source is known to repeat. A wide field-of-view instrument, such as HAWC can overcome this limitation using archival data. In this study we search for very high energy (VHE) gamma rays from FRB source locations over the largest population studied at this energy. Using data from the HAWC Observatory we look at over 200 FRB events from 141 unique locations and search for persistent emission and transient activity in 600 s surrounding the burst time. The results are then placed in context of available models and maximum gamma-ray emission levels from FRBs.

PoS(ICRC2023)596

38th International Cosmic Ray Conference (ICRC2023)
26 July - 3 August, 2023
Nagoya, Japan

*Speaker

https://pos.sissa.it/

1. Introduction

Fast Radio Bursts (FRBs) are millisecond duration bursts of radio waves with high luminosity in the range of $10^{38} - 10^{43}\mathbf{erg \cdot s^{-1}}$ [1]. There are numerous theories attempting to explain the events, as well as numerous calls for multiwavelength investigations in order to constrain the possible progenitors of FRBs. The HAWC observatory, with live-time fraction over 95% and wide instantaneous field of view of 2sr, is well situated to provide limits on the highest energy emission from FRB source locations. This work presents a search for transient activity and persistent emission in TeV Gamma Rays from the burst locations.

The phenomenon of FRBs has been heavily studied since 2007 with the publication of the Lormier Burst, found in an archival search of data from the Parkes Radio Telescope, now known as FRB010724 [2]. Since then, over 700 bursts have been reported by numerous radio observatories, with all events and their burst properties publicly available on the Transient Name Server [3]. Several of these sources have been observed to repeat; however, the majority do not repeat, with a ratio of repeater to non-repeater of 18:474 in the first CHIME/FRB Catalog [4]. Understanding the progenitors of these sources has proven elusive as of yet, in addition to the distinction of repeating and solitary bursts as separate classes of events. Due to high dispersion measure of the radio signal, FRBs have been attributed to extragalactic sources, with the notable exception of FRB-like activity from the galactic source SGR1935+2154 and possible other magnetar flares [5]. The extragalactic origin of these sources has been confirmed for several sources with identified optical counterparts. Multiwavelength campaigns to understand the behavior have been encouraged by radio observatories so that we can better understand these transients. The goal of this study is to assist the development of theories to explain the origin of these events. Detection of, or limits placed on the highest energy gamma-ray emission will serve to deepen our understanding of FRBs.[6]

There are 777 distinct FRB events catalogued on https://www.wis-tns.org, of which 203 transit within the HAWC field of view with an implied redshift of less than 0.5 and occur between the dates January 1, 2015 and December 31, 2020 [3]. Of those 203, 135 are from unique locations in the sky. Of the 203 events that pass the temporal and declination cut, 156 were in the instantaneous field of view of the HAWC observatory, defined as being less than 40° from HAWC zenith at the reported time of the burst. For each source we conducted a steady-state analysis over 2090 days of HAWC data to set upper limits on the persistent gamma-ray flux from each source. In addition, for each burst occurring within the HAWC field of view we ran a sliding time-window transient search for burst durations of 1.0 and 5.0 seconds for a period of 100s before, and 500s after the reported burst time.

In this work we discuss the transient and persistent search methods used, and report the results of those searches. Section 2 will cover the HAWC observatory and its related transient work. Section 3 will briefly discuss the persistent emission search method, and give greater detail on how we can use HAWC for transient analyses. In section 4 we will present the limits determined by our analysis. We conclude the paper with a discussion of the implications of our limits on possible theories, and how future work can improve our understanding of FRBs.

2. HAWC

The HAWC Observatory is a very-high-energy (VHE) ground based water Cherenkov detector located on the Sierra Negra Volcano Mexico at an altitude of 4100m asl. HAWC has an instantaneous field of view of 2 steradians, capable of detecting air showers of primary photons in the 300GeV to over 100TeV energy range. The detector consists of 300 central area tanks outfitted with 4 PMTs each, covering an area of 22,000 m^2, and an additional outrigger array of 345 smaller tanks with a single PMT each. This analysis considers only data from the main array. For more information on the HAWC Observatory reconstruction and flux measurement read our 2019 paper on the Crab nebula [7].

Previous work from the HAWC collaboration has provided limits on bursts from transients of other origins, and this previous work informs this work. This includes limits on gamma ray bursts, neutrino coincidence, gravitational wave events and primordial black hole evaporation. Studying these potential gamma ray transients at very high energies provides a necessary constraint on the theories pertaining to the most energetic astrophysical phenomena.

3. Methods

The HAWC observatory's consistent live-time and wide field of view enable the analysis of many FRB sources for persistent emission, as well as transient activity coincident with the burst when it occurs in the instantaneous field of view of the instrument. In this work we look for both these types of emission from all of the events within HAWC's field of view. Steady-state analysis is performed using the method described in the 2020 3HWC catalog, utilizing the confidence interval method prescribed by Feldman and Cousins. [8, 9] Transient analysis was performed using the Zenith Band Reconstruction Algorithm (ZEBRA) which can calculate flux and significance over short time intervals.

3.1 Steady-State Analysis

To perform the steady state analysis we analyzed nearly 6 years of HAWC data with a live time of 2090 days and performed a fit to the flux at 1 TeV. The fit to the flux normalization is undertaken using the method described in the 3HWC catalog paper [9]. If no detection is made, upper limits are calculated using the Feldman-Cousins method for a 1 σ level above the background rate, assuming emission of a power-law spectrum with an index of -2.0 [8].

$$\phi(E) = N \cdot (\frac{E}{E_0})^{-2.0}. \tag{1}$$

FRB locations are assumed to be point sources in the HAWC maps, so we search for emission at the best fit location provided by the radio instrument. We apply a model for attenuation of gamma rays off of the extragalactic background light, then the flux normalization is calculated using a maximum log-likelihood calculation.

$$TS = \max LLR(f) = LLR(F) \tag{2}$$

$$LLR(f) = 2 \log \frac{L(f)}{L(0)} = 2 \sum_{i=1}^{N} \log \frac{P(b_i + e_i, d_i)}{P(b_i, d_i)} \tag{3}$$

Here P is the Gaussian probability of measuring an excess e_i above background b_i given an expected measurement at that location of d_i. This is tested against the background only hypothesis. For more information on how HAWC calculates flux levels, see the 3^{rd} HAWC Catalog paper [9].

3.2 Transient Analysis

To perform the transient analysis we use the ZEBRA Transient Analysis framework which looks for fluctuations above background on a sliding time-scale window using a maximum likelihood analysis [10]. The maximum likelihood analysis compares the likelihood that an event comes from a given source to the likelihood of the background-only hypothesis assuming a Poissonian distribution, testing with a log-likelihood ratio (eq. 3). In order to avoid missing bursts that occur at the edge of a time window, the search advances by half of the burst duration each step. For the FRBs selected in this analysis, we then simulate an equal number of time window trials at an identical zenith angle and redshift to obtain an expected TS distribution for each source. Once we obtain a distribution in TS, calculated by the same formula as the persistent source search (eq. 2), we calculate a rate at which background only would produce a TS greater than what we measure in the data.

3.3 Extragalactic Background Light Attenuation

As mentioned above, all analyses of gamma rays coming from extragalactic distances require consideration of the attenuation due to extragalactic background light (EBL). The attenuation occurs at high photon energies as the scattering cross-section for gamma-gamma interactions to pair-produce e+/e- increases with energy in the TeV range[11]. In this study we use the model for EBL given by Gilmore et al. in 2012 [12]. For a more in-depth treatment of the EBL effect on HAWC and extra-galactic gamma-ray sources, see the dedicated analysis on the measurement of the mid-infrared background with the HAWC Observatory [13]. Many FRBs have not been localized to host galaxies, but due to the high DM we infer extragalactic distances. For our calculations we use the estimate that is typical in FRB studies given by equation 4.[14]

$$z \approx \frac{DM}{1000} \tag{4}$$

This estimate comes from a calculation of the dispersion measure contribution from the intergalactic medium (IGM). DM_{igm} depends upon cosmological parameters and the fraction of baryons which reside in the IGM, assuming a best guess value has lead radio astronomers to this estimate. As of the writing of [14] there were 14 FRBs with measured redshift, and this relationship holds reasonably well, though the estimate could change in the future. For FRBs with no known redshift, we use this implied redshift.

4. Results

The search for gamma-ray activity during FRB events and from their sky locations yielded no significant detections. However, the limits set by this study provide a level of exclusion which is useful moving forward in the determination of FRB progenitors. This is a large population of events, with the number growing more rapidly than ever before, and the bulk properties also provide insights to other astrophysical phenomena.

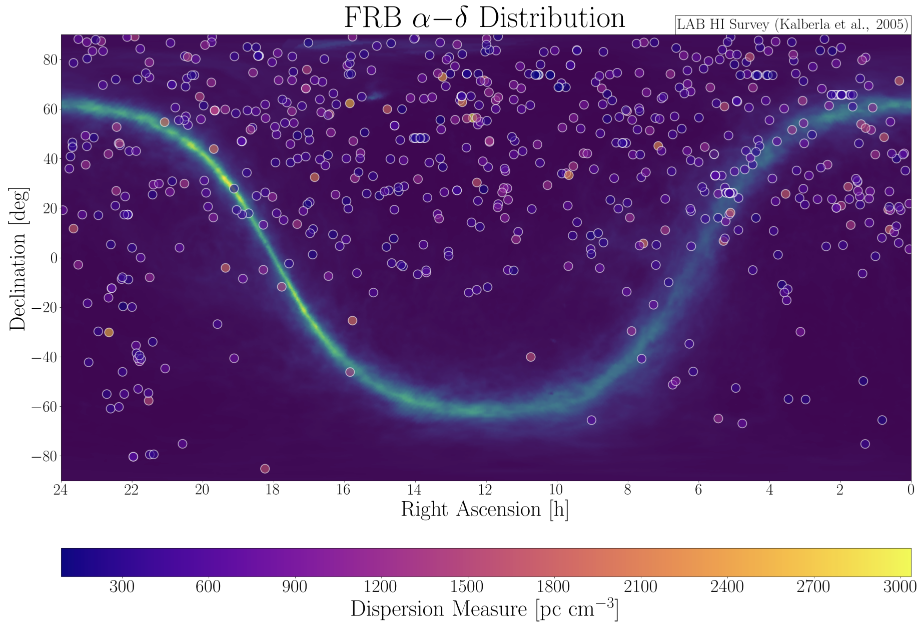

Figure 1: The locations of all FRBs from the transient name server, overlaid on the LAB Hydrogen Intensity map from the FRBStats project [17]. Most HAWC sources lie on the Galactic plane, and FRB's are known to be extragalatic.

4.1 Peristent Source Search

The search for persistent gamma-ray emission from the FRB locations in the Transient Name Sever, accounting for EBL attenuation at VHE gamma-ray energies found no new TeV gamma-ray sources. As we see in figure 1, there are several FRB's which occurred along the Galactic plane where there is a large amount of TeV gamma-ray flux. However, we know that these events happened outside of the galaxy and therefore the TeV measurements which overlap the galactic plane are not evidence of TeV emission from FRB hosts. Flux limits depend on the source declination and distance, as both are limiting factors for detection by a ground-based gamma-ray observatory. The strongest limits are for those sources which transit close to HAWC zenith, and are all less than $9x10^{-10}$, which is consistent with limits set for FRBs from MAGIC and VERITAS follow-up studies [15, 16] assuming a power law spectrum through gamma-ray energies. Our agreement with other observatories in the very high energy regime encourages further investigation, and extends the energy range over which we have limits on the behavior of FRBs.

Here we provide the largest catalog of gamma-ray constraints on FRB sources yet published. While there are challenges involved with viewing distant events with gamma-ray observatories, the fascinating nature of FRBs prompts us to learn as much as we can in order to identify the cause of the bursts. As evidenced by the galactic FRB, and it's place in the population of FRBs as a typical strength event, we can envision a burst of higher energy happening within our galaxy, or in our galactic region close enough to overcome the attenuation and be measurable in gamma-rays to help move the discussion of FRBs forward.

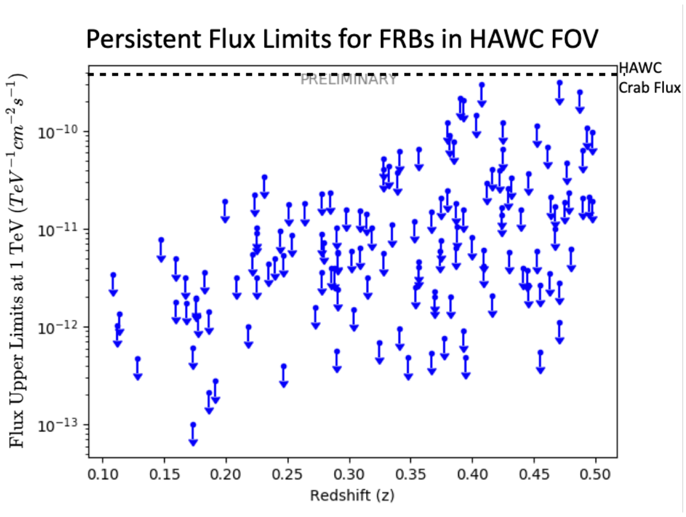

Figure 2: The population of HAWC upper limits at 1TeV versus Redshift.

4.2 Transient Search

Of the 203 burst which occurred at locations which transit the HAWC field of view, 156 happened within 40 degrees of HAWC zenith. The search for transient activity also found no significant detection. We search 600 s of HAWC data for 2 different burst durations with advancement in time of 50% of the burst duration per step, resulting in 1440 trials per burst. No individual trial exceeded the expected distribution obtained by simulation of the events.

Simulation of the standard background rate of the detector for the zenith and distance of the source yielded a distribution that agrees well with the data, and we cannot claim any emission over the background level. For each FRB searched, the TS distribution obtained for each burst duration is compared to the simulation of the background only hypothesis. An example can be seen in figure 3 for the 0.1s burst search of FRB20180915B. None of the trials rise to the level of detection, and simulation of the background at that location and redshift assumption yield statistically consistent results.

5. Conclusion

The search for activity in the regions around known FRBs, both repeating and singular yielded no significant detection in either persistent gamma-ray emission or transient activity. We have set upper limits on the steady-state emission from all FRBs in the HAWC sky and have shown no detection of transient activity coincident with these events. As an observatory suited to detection in the 300GeV-100's of TeV gamma rays, we are limited in our detection of extremely distant objects due to the infrared background light scattering described in section 3; however, after the first galactic FRB and the large all-sky rate of FRBs predicted from the radio data, we can expect more events to be reported soon. If the population of strong bursts that occur closer by increases, gamma-ray observatories such as HAWC can set more meaningful limits and stand a better chance of detection. These results show that there is no unexpected VHE emission coming from FRB sources, meaning that the mechanism is most likely not the result of a know VHE gamma-ray source such as a PWN

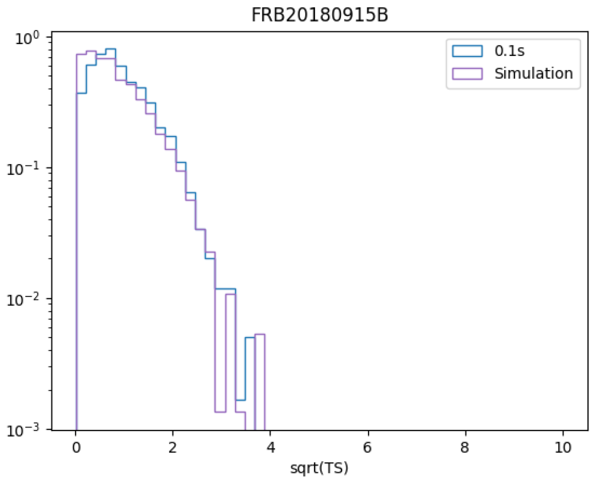

Figure 3: The distribution of the square root of the TS for the 0.1s burst search of FRB20180915B compared to a background simulation of that location for an equal number of trials.

or SNR. Future experiments such as SWGO which are proposed to have improved sensitivity at the lowest end of the HAWC energy range will further constrain these limits and tell us more about the origins of FRBs [18].

References

[1] Luciano Nicastro et al. "Multiwavelength Observations of Fast Radio Bursts". In: *Universe* 7 (3 2021). ISSN: 2218-1997. DOI: 10.3390/universe7030076. URL: https://www.mdpi.com/2218-1997/7/3/76.

[2] D R Lorimer et al. "A Bright Millisecond Radio Burst of Extragalactic Origin". In: *Science* 318 (5851 2007), pp. 777–780. DOI: 10.1126/science.1147532. URL: https://www.science.org/doi/abs/10.1126/science.1147532.

[3] *Transient Name Server*. URL: https://www.wis-tns.org/.

[4] Mandana Amiri et al. "The First CHIME/FRB Fast Radio Burst Catalog". In: *The Astrophysical Journal Supplement Series* 257 (41pp 2021), p. 59. DOI: 10.3847/1538-4365/ac33ab. URL: https://doi.org/10.3847/1538-4365/ac33ab.

[5] F Kirsten et al. "Detection of two bright radio bursts from magnetar SGR 1935 + 2154". In: (). DOI: 10.1038/s41550-020-01246-3. URL: https://doi.org/10.1038/s41550-020-01246-3.

[6] E Platts et al. "A Living Theory Catalogue for Fast Radio Bursts". In: (2019).

[7] A U Abeysekara et al. "Measurement of the Crab Nebula Spectrum Past 100 TeV with HAWC". In: (2019).

[8] Gary J Feldman and Robert D Cousins. "A Unified Approach to the Classical Statistical Analysis of Small Signals". In: (1999).

[9] A Albert et al. "3HWC: The Third HAWC Catalog of Very-High-Energy Gamma-ray Sources". In: (2021).

[10] Israel Martinez-Castellanos. "Search for very-high-energy gamma-ray counterparts of gravitational waves with HAWC". In: *PoS* ICRC2019 (2020), p. 737. DOI: 10.22323/1.358.0737. arXiv: 1908.06122 [astro-ph.HE].

[11] Robert J. Gould and Gerard P. Schreder. "Pair Production in Photon-Photon Collisions". In: *Physical Review* 155 (5 Mar. 1967), pp. 1404–1407. ISSN: 0031-899X. DOI: 10.1103/PhysRev.155.1404. URL: https://link.aps.org/doi/10.1103/PhysRev.155.1404.

[12] Rudy C. Gilmore et al. "Semi-analytic modelling of the extragalactic background light and consequences for extragalactic gamma-ray spectra". In: *Monthly Notices of the Royal Astronomical Society* 422.4 (Apr. 2012), pp. 3189–3207. DOI: 10.1111/j.1365-2966.2012.20841.x. URL: https://doi.org/10.1111%5C%2Fj.1365-2966.2012.20841.x.

[13] Mateo Fernandez Alonso. *Probing the extragalactic mid-infrared background with HAWC*. 2022. arXiv: 2204.12166 [astro-ph.HE].

[14] E Petroff et al. "Fast radio bursts at the dawn of the 2020s". In: (2022). URL: https://www.herta-experiment.org/frbstats.

[15] V A Acciari et al. "Constraining very-high-energy and optical emission from FRB 121102 with the MAGIC telescopes". In: *MNRAS* 481 (2018), pp. 2479–2486. DOI: 10.1093/mnras/sty2422. URL: https://academic.oup.com/mnras/article/481/2/2479/5090423.

[16] Matthew Lundy. "Gamma-ray and Optical Observations of Repeating Fast Radio Bursts with VERITAS". In: (). URL: https://doi.org/10.48550/arXiv.2108.09354.

[17] *HeRTA FRBSTATS*. URL: https://www.herta-experiment.org/frbstats/.

[18] P Abreu et al. *Astro2020 APC White Paper The Southern Wide-Field Gamma-Ray Observatory (SWGO): A Next-Generation Ground-Based Survey Instrument for VHE Gamma-Ray Astronomy*. 2019. URL: www.swgo.org.