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Identifying Short Gamma-Ray Bursts with potential delayed TeV Afterglows as possible counterparts to gravitational waves

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The connection between short Gamma-Ray Bursts (sGRBs) and Gravitational Waves (GWs) has long been a subject of study, motivating the search for counterparts by gamma-ray instruments. Both phenomena are thought to be produced by the same astrophysical event. However, only one event to date has been identified as a simultaneous occurrence of both, a sGRB (GRB 170817A) and a GW (GW170817). GRB 170817A was classified as an unusual burst due to its low-luminosity and prolonged non-thermal emission (afterglow) observed across radio, optical, and X-ray bands, which reached their maximum hundreds of days after the trigger time. Although TeV emissions were not immediately observed for this burst, if they exist, they are most likely generated through synchrotron-self-Compton of the delayed radio emission from each burst. We have identified 8 sGRBs within the Fermi Gamma-ray Burst Monitor catalogue that appear to share some characteristics with GRB 170817A during the time interval spanning from December 5th, 2014 until December 5th, 2022. In this work, we discuss the methodology utilized to identify sGRBs that are alike GRB 170817A and discuss the implications of our results.

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1. Introduction

Gamma-Ray Bursts (GRBs) represent some of the most intense and violent events known to occur. These phenomena are primarily distinguished by two defining parameters: their overall duration and spectral hardness. As such, GRBs are broadly categorized into long and short classes. Each class is considered unique, believed to originate from discrete astrophysical events. The progenitor event for one type of GRB would not account for the characteristics observed in the other, demonstrating a clear dichotomy in the formation mechanisms [12].

More specifically, short Gamma-Ray Bursts (sGRBs) are hypothesized to originate from the violent collision of binary compact-object systems [5, 7, 15]. This type of interaction is theorized to yield a distinctively hard spectrum, with a T_{90} duration – the time in which 90% of the burst's flux is recorded – falling under the 2 second threshold. In the period leading up to this violent encounter, the binary compact-object system begins in-spiraling due to the loss of gravitational energy in the form of Gravitational Waves (GWs) [2]. These waves can be effectively described as ripples distorting the fabric of space-time, propagating isotropically at the speed of light. Though both sGRBs and GWs are theorized to originate from the same progenitor, empirical evidence linking these two phenomena is sparse and precious. To date, there has been only one observation, designated as GW/GRB 170817A, which provides credible evidence for this connection.

On the 17th of August, 2017, the Laser Interferometer Gravitational-Wave Observatory (LIGO) and the Virgo Interferometer (VIRGO) recorded a signal indicative of a GW, denominated GW170817 [1]. Remarkably, this was subsequently followed by the detection of a sGRB - designated as GRB 170817A - by the Fermi Gamma-ray Burst Monitor (Fermi-GBM) $\sim 2\ s$ after the LIGO/VIRGO trigger [10], pinpointed to the exact same location in space as the GW. GRB 170817A is particularly intriguing due to its unique properties: notably low luminosity [19], a very small redshift of $z = 0.0098$ [11], and an unusual afterglow commencing several days post-trigger and persisting for hundreds of days [14, 17]. This intrigue is amplified by the event's role in providing empirical evidence for the theoretical relationship between sGRBs and GWs. Notably, the spatial and temporal concurrence of these phenomena, coupled with the hypothesis that both GW170817 and GRB 170817A originated from the merger of a binary neutron star system [1], significantly bolsters this scientific connection. GW/GRB 170817 is undeniably one of the most significant events ever recorded, serving as a landmark observation in multi-messenger astrophysics.

The High Altitude Water Cherenkov (HAWC) Observatory is well-equipped for the constant observation and recording of the gamma-ray sky, with an impressive duty cycle surpassing 95% and an instantaneous Field of View (FoV) of $2\ sr$. The HAWC Observatory, located at an altitude of 4,100 meters on the Sierra Negra Volcano in Puebla, Mexico, consists of 300 Water Cherenkov detectors. These detectors collectively occupy a footprint of approximately $22,000\ m^2$. Furthermore, the HAWC observatory is characterized by its wide operational energy spectrum, spanning from 300 GeV to 100 TeV. This configuration makes it particularly well suited for the monitoring of sGRBs that are similar to GRB 170817A, which can generate afterglows that could span tens to hundreds of days. In this work, we explain with detail the procedure developed to search for short GRBs that coincide with the optimal parameters of HAWC that could potentially be similar to GRB 170817A.

2. GRB selection

Our methodology starts with the creation of three distinct subsets. We filter GRBs from the Fermi-GBM Catalogue that pass through the HAWC FoV at any moment post-trigger with T_{90} values of less than 5 s, 3.5 s, and 2 s. It's crucial to highlight that while the 2 s threshold is widely accepted as the orthodox definition of a sGRB, the T_{90} distributions for long and short GRBs do show substantial overlap [18]. This overlap implies that sGRBs could last over 10 s, yet we may also encounter long GRBs falling within the sGRB category. Notably, at a T_{90} of 4.2 s, there exists a roughly 50% probability of classifying an event as either a short or a long GRB [18]. As a conservative measure to maximize our sGRB sample while minimizing potential contamination from long GRBs, we've adopted the 3.5 s definition for our sGRB categorization, keeping into consideration statistical uncertainties.

The subsequent step involves selecting bursts within HAWC's Field of View (FOV) that align with the optimal declination range. Considering a typical spectral index of -2.5, within the context of the Synchrotron Self-Compton (SSC) model, HAWC's sensitivity [3] peaks for a declination of approximately 19°, which corresponds to a zenith angle of 0° with respect to the HAWC observatory. The sensitivity declines by factors of 4.5 and 1.4 for zenith angles of 40° and 20°, respectively, deviating from the maximum [4]. Consequently, our analysis focuses on bursts with declinations ranging from $-10°$ to 50°, also considering statistical uncertainties. This range encompasses bursts with a maximum zenith angle of 20°, thereby limiting the consideration to sensitivity reductions by a factor of up to 1.4.

To begin distinguishing bursts that exhibit characteristics akin to GRB 170817A and which ultimately could be the potential electromagnetic counterparts to undetected GWs, we adopt the same methodology presented in the study by [18]. This approach allows for the characterization of specific spectral components based on distinct temporal properties. Table 1 demonstrates the fraction of bursts in each subset that meet each criterion specified in Section 2. Notably, the row indicating a T_{90} duration of less than 3.5 s, for bursts within the HAWC FoV and the declination range of $-10°$ to 50° that satisfy the temporal cuts outlined in [18], yields a sample of 102 short GRBs out of the 440 GRBs that solely comply with the $T_{90} < 3.5\,s$ condition.

Following the methodologies detailed in [16, 18], we conduct an analysis on the light curves of the resulting GRBs using a Bayesian block approach. This enables the identification of two separate emission episodes. We then carry out a manual selection, leveraging the RMFIT software[1] as per the process outlined in [16, 18]. According to [18], bursts that display tail emission aligned with thermal emission were selected, provided they present a significant improvement when modeled using a Black Body (BB) model, as compared to the alternative models. Additionally, in these previous studies, a limit was set on the Black Body (BB) temperature kT at 20 keV, which is two times the observed value for GRB 170817A. Nevertheless, in our present work, we have chosen not to apply these two specific conditions.

[1] The Gamma-ray Spectral Fitting Package (RMFIT)

Table 1: Number of bursts during the time period from December 5th, 2014 to December 5th, 2022 passing each criterion specified in Section 2. The first column details the maximum burst duration in seconds; the second column provides the range of declinations required for the burst location in degrees. The third column indicates the ratio of total bursts within the HAWC FoV meeting both the first and second column criteria to the total number of bursts complying with the first column condition. Finally, the fourth column shows the ratio of total bursts satisfying the conditions of columns one, two, three, and the temporal cuts detailed in the works of [16, 18] to the bursts that only pass the criteria of column one. The row in boldface indicates the subset used in this work, which pass the ideal characteristics specified in all of section 2.

max T_{90} (s)	DEC range (deg)	in FoV	after Temporal cuts
2	$[-20:60]$	269/373	97/373
	$[-10:50]$	232/373	84/373
	$[0:40]$	179/373	62/373
3.5	$[-20:60]$	308/440	118/440
	$\mathbf{[-10:50]}$	**265/440**	**102/440**
	$[0:40]$	203/440	77/440
5	$[-20:60]$	358/519	143/519
	$[-10:50]$	306/519	123/519
	$[0:40]$	235/519	95/519

3. Results and Discussion

Following the implementation of the criteria outlined in Section 2, our GRB sample size significantly diminishes, going from 440 to just 9 GRBs. Table 2 presents the 9 GRBs constituting our sample. Those entries annotated with an asterisk are drawn from the findings of [18]. Although GRB 170817A did not meet our optimal search criteria for HAWC observations, we have included it to enable comparative analysis with the rest of the GRBs in our sample. Among these final 9 GRBs, only two, namely GRB 170817A and GRB 150101B, exhibit positional uncertainties of zero due to the multi-mission observation efforts performed after the burst trigger, leading to well known reported positions. Although these GRBs would ostensibly make great candidates for observation with the HAWC observatory, certain conditions could potentially compromise our observational capabilities. GRB 150101B, despite having a HAWC zenith angle of 29.17°, is located at a redshift of $z = 0.135$ [6, 13] (Higher redshifts increase detection hardships at TeV due to the EBL attenuation. See [8, 9]). Conversely, GRB 170817A is characterized by an exceptionally low redshift of $z = 0.0098$, yet it's associated with a notably high HAWC zenith angle of 41.62°. Figure 1 presents a significance map with dimensions of $5° \times 5°$ centered on the reported position of GRB 150101B. The data utilized to generate this significance map encompasses the observations made by the HAWC Observatory during the initial transit of the source following the trigger event. However, the map does not reveal any substantial detections.

Our sample also includes sGRBs that exhibit ideal zenith angles. For instance, GRB 191017C has a zenith angle of 3.74° but a substantial positional uncertainty of 12.4°. GRB 200626A, while having a desirable zenith angle of 2.86°, unfortunately also reports a sizable positional uncertainty

Table 2: Spectral analysis for the GRB candidates inside HAWC's FoV. The GRBs marked with an asterisk and in boldface are those from the results of [18], while the rest are our results for this analysis.

Burst	Time [s]	Model	Epeak [keV]	Spectral index	kT [keV]	C-stat/DOF	Uncertainty [°]	Redshift	Zenith Angle [°]
GRB150101B*	-0.016:0.0002	Compt	524 ±176	-0.80 ± 0.20		638.2/885	0.0	0.135	29.17
	0.000:0.064	BB			6.0 ± 0.6	731.3/886			
GRB170111B*	-0.128:0.384	Compt	154 ±22	-0.62 ± 0.19		697.0/663	6.7	–	44.71
	0.768:0.960	BB			8.1 ± 1.0	731.3/886			
GRB170817A*	-0.512:0.512	Compt	181.7 ±85.6	-0.84 ± 0.4		256.76/253	0.0	0.0098	41.62
	0.512:2.048	BB			9.69 ± 1.16	320.74/254			
GRB180511A*	-0.032:0.032	Compt	639±220	-0.61±0.22		697.9/717	15.1	–	26.90
	0.032:0.128	BB			11.1±3.0	667.4/718			
GRB191017C	-0.064:0.768	Compt	304 ± 107	-0.81 ± 0.22		248.42/55	12.4	–	3.74
	0.768:1.92	BB			12.25 ± 3.18	316.79/256			
GRB200514B	-0.256:0.256	Compt	441.7 ± 55	-0.66 ± 0.12		2939.6/249	13.1	–	18.17
	0.256:1.408	BB			56.82 ± 1.04	10489/250			
GRB200626A	-0.768:0.768	Compt	36.83 ± 0.322	-1.14 ± 0.02		60250/249	15.2	–	2.86
	0.768:1.92	BB			20.03 ± 0.02	63729/250			
GRB210510A	-0.32:0.128	Compt	82.84±36.2	0.08336±1.76		217.14/241	21.68	–	25.75
	0.128:1.024	BB			20.37±5.01	217.57/242			
GRB210822B	-0.064:1.024	Compt	48.91±8.93	-0.4826±0.73		396.14/364	4.75	–	1.04
	1.024:2.048	BB			12.09±1.23	399.44/365			

of 15.2°. Finally, GRB 210822B distinguishes itself with the lowest zenith angle of 1.04° and the smallest non-zero positional uncertainty in the group, measured at 4.75°.

In this study, we developed a rigorous methodology to identify sGRBs that share similar characteristics to GRB 170817A and that pass over the HAWC FoV at any time post-trigger, which could be the potential electromagnetic counterparts of undetected gravitational waves emitting at TeV energies. Filtering through the Fermi-GBM Catalogue, we refined an initial selection of 440 GRBs to a final sample of nine. Although some GRBs exhibit ideal observational characteristics, large positional uncertainties or adverse conditions compromise their potential to be detected. This investigation not only showcases a promising approach to detecting and categorizing short GRBs but also illuminates the complexities and uncertainties inherent in this pursuit.

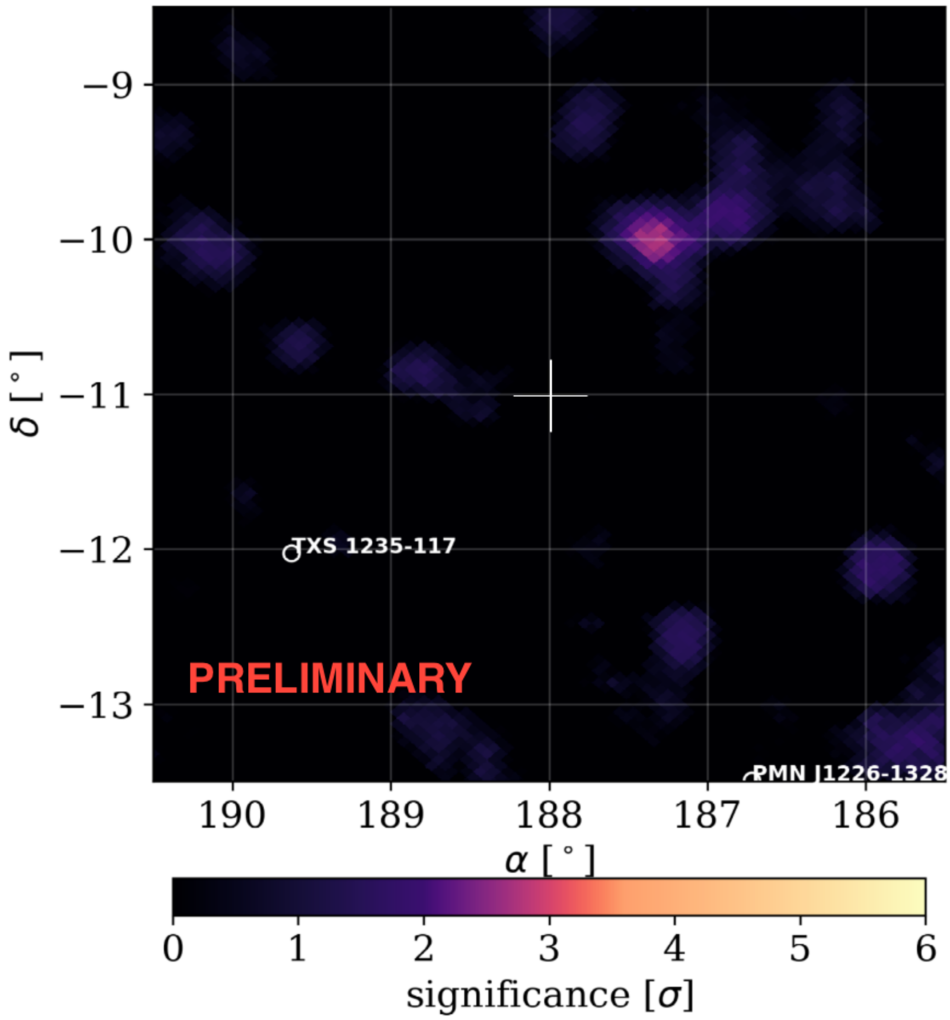

Figure 1: Significance map of GRB 150101B. The cross indicates the reported position of the burts. The circled areas with labels represent known HE and VHE sources in the Fermi Catalogue. No significant detection is observed

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