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Observations of Gamma-ray Bursts with VERITAS and Whipple

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Abstract: Many authors have predicted very-high-energy (VHE; $E > 100$ GeV) emission from gamma-ray bursts (GRBs) both during the prompt phase and during the multi-component afterglow. To date, however, there has been no definitive detection of such emission. Recently, the Swift Satellite made the exciting discovery that almost 50% of GRBs are accompanied by one or more X-ray flares, which are found to occur from several seconds to many hours after the prompt emission. The discovery of this phenomenon and the many predictions that VHE emission should accompany these flares increases the already strong motivation for making immediate follow-up VHE observations of GRBs. Observations of GRBs have high priority at VERITAS, preempting any observations that may be in progress. GRB alerts are received from the GCN via a socket connection. This is interfaced to the VERITAS Tracking Software to minimize the time between a notification arriving and the telescope being slewed to the GRB. We report here on GRB observations with VERITAS and with the Whipple Telescope from 2005 through 2007.

Introduction

Gamma-ray bursts (GRBs) have been well studied at all wavelengths since their discovery in 1969 [1]. The very-high-energy (VHE; $E > 100\,\mathrm{GeV}$) band is the only energy regime in which definitive evidence for GRB emission has yet to be detected. For the observation of photons of energies above 100 GeV, only ground-based telescopes are available at present. These fall into two broad categories, air-shower arrays and atmospheric Cherenkov telescopes (of which the majority are Imaging Atmospheric Cherenkov Telescopes). The air shower arrays, which have wide fields of view making them particularly suitable for GRB searches, are relatively insensitive. There are several reports from these instruments of possible TeV emission [2] & [3]. The Milagro Collaboration reported on the detection of an excess gamma-ray signal during the prompt phase of GRB 970417a with the Milagrito detector [4]. In all of these cases, the statistical significance of the detection is not high enough to be conclusive.

The Milagro Collaboration have performed a number of searches for VHE emission from GRBs [5], [6] & [7], but no evidence for VHE emission was found from any of these searches. Atmospheric Cherenkov telescopes, particularly those that utilize the imaging technique, are inherently more flux-sensitive than air-shower arrays and have better energy resolution but are limited by their small fields of view (3 - 5°) and low duty cycle ($\sim 7\%$). In the era of the Burst And Transient Source Explorer (BATSE), attempts at GRB monitoring were limited by slew times and uncertainty in the GRB source position [8]. Recently, upper limits on the VHE emission from the locations of seven GRBs observed with the Whipple 10m Telescope were reported [9]. With their fast-slewing telescope and low energy threshold, the MAGIC Group have placed the most stringent upper limits on VHE emission from GRBs to date [10] & [11].

The Gamma-Ray Bursts

Six different GRB locations were observed with VERITAS between March 2006 (when VERITAS was first operated as a 2-Telescope array) and June 2007. The properties of these bursts are summa-

GRB	Discovery Instrument	GCN Number	Best Location (J2000) R.A.	Dec.	T_{90}[a] (sec)	Fluence[b] ($\times10^{-6}$)	z
060501	BAT	5040	21h 53m 30s	+43° 59' 53"	26	1.2±0.1	N/A
061222a	BAT	5954	23h 53m 03s	+46° 31' 59"	72	8.3±0.2	<3
070311	IBAS	6189	05h 50m 08s	+03° 22' 30"	50	2	low-z[c]
070419a	BAT	6302	12h 10m 59s	+39° 55' 34"	116	0.6±0.1	0.97
070521	BAT	6431	16h 10m 39s	+30° 15' 22"	38	8.0±0.2	0.553[d]
070612b	BAT	6511	17h 26m 54s	-08° 45' 06"	14	1.7±0.1	N/A

Table 1: The gamma-ray bursts.

[a] T_{90} is the time during which 90% of the prompt emission was detected. The BAT T_{90} is measured between 15-350 keV while the IBAS T_{90} is measured between 20-200 keV. [b] The BAT fluence is measured between 15-150 keV while the IBAS fluence is measured between 20-200 keV. [c] [12] propose that this GRB is at low redshift (see text). [d] A galaxy at z=0.0307 was also found in the XRT error circle but it is less likely to be associated with the GRB.

rized in Table 1. For three of these GRBs, all of the data were taken at large zenith angles (elevation $< 50°$); the detailed analysis of these data will be presented at a later date. Upper limits on the VHE emission from the three bursts observed at high elevation will be presented here. Those GRBs are described in the following subsections.

Eleven GRB locations were observed with the Whipple 10m Telescope between January 2005 and May 2007. The detailed description of these bursts and their analysis will be presented in [13].

GRB 070311

This GRB was detected at 11:52:50 UT by the IBAS in the IBIS/ISGRI data [14]. It had a peak flux of 0.9 photon cm^{-2} s^{-1}. The Swift XRT light curve followed a single power law with an index of 1.9 ± 0.4 from 7 to 14 ks after the burst [15]. The robotic 20-cm REM telescope at La Silla detected optical emission from the position of the GRB with an approximate magnitude of 14.3 about 3 minutes after the burst [16]. This detection was confirmed by the 1.3m PAIRITEL project [17] and at a number of other telescopes [18], [19] & [20]. When the optical afterglow was observed with the MDM 1.3m telescope on 070313, it was found to have brightened by 0.99 mag since the previous night [12]. The authors suggested that, given the level of Galactic extinction at this GRB location, it is possible that this burst was at low redshift and that the brightening was the result of the onset of a supernova. Further monitoring of the afterglow [21] found that the re-brightening peaked on day 2 after which it declined rapidly [22]. It was proposed that the optical re-brightening of this burst was due to late central engine activity [23]. The GRB was not detected with the VLA [24].

GRB 070521

This burst was detected at 06:51:10 UT by the BAT on Swift (trigger 279935) [25]. The time-averaged spectrum from T-14.5 to T+49.7 seconds was best fit by a power law with an exponential cutoff and photon index of 1.10 ± 0.17 and peak energy of 195 ± 123 keV. The 1-sec peak photon flux measured from T+30.48 seconds in the 15 - 150 keV band was 6.7 ± 0.3 photon cm^{-2} s^{-1} [26]. The XRT light curve exhibits initial flaring behaviour superposed on the power-law decay up to ∼T + 600s [27]. [28] reported that the XRT error circle coincided with the outskirts of a nearby (z=0.0307) galaxy. Observations with the Subaru Telescope [29] revealed a faint source inside the XRT error circle at a redshift of z=0.553, and this source was also detected weakly with the Gemini North [30] and Keck Telescopes [31]. Two other sources consistent with the XRT error circle were also detected with Keck. Observations with Gemini North on 070522 detected marginal evidence for fading of the z=0.553 source [32] as well as a detection of the third source detected by the Keck. The strength of this third source was fainter than that reported by the Keck, but the authors caution that the Gemini photometry at this location is quite uncertain due to the presence of a nearby bright galaxy.

GRB 070612b

This burst was detected at 06:21:16 UT by the BAT on Swift (trigger 282073) [33]. The time-averaged spectrum from T-6.4 to T+10.3 seconds was best fit by a simple power law with a photon index of 1.55 ± 0.11. The 1-sec peak photon flux measured from T+10.84 seconds in the 15 - 150 keV band was 2.6 ± 0.4 photon cm^{-2} s^{-1} [34]. Although the XRT did detect an x-ray source, no evidence for x-ray flaring was seen [35]. Many optical telescopes performed follow-up observations of this GRB but no optical emission was detected [36].

The VHE GRB Data and Analysis

Burst notifications are received over a socket connection at both VERITAS and the Whipple 10m Telescope. GRB observations take priority over all other observations at both instruments so, whenever an observable burst is detected, the telescopes are immediately re-pointed and data are taken on the GRB location until the burst is more than three hours old. VERITAS and the Whipple Telescope can slew at 1°s^{-1} thus reaching any part of the observable sky within 6 minutes.

The VERITAS array is described in detail in [37]. The GRB data were taken in both *wobble* and *tracking* modes [38]. At all times during data-taking, the point-spread function of VERITAS was $<0.1^{\circ}$ (the field of view of one PMT is 0.15°). For the three GRBs reported upon here, the positional offset between the final GRB location and the position tracked by VERITAS were such that a conventional "point source" analysis could be performed.

The data have been analysed using independent analysis packages (see [39], [38] for details on the analyses). All of these analyses yield consistent results. The calibration techniques are described in [40]. The 99% confidence level VERITAS upper limits for these GRBs are given in Table 2.

Discussion and Conclusions

Upper limits (99% confidence level) for three of the six GRBs observed to date with the VERITAS array were presented here. The limits range from 2.0% to 6.4% of the Crab Nebula flux at a peak response energy of approximately 300 GeV. These data were taken in 2- and 3-Telescope observing mode during 2007. Analysis of the remaining three GRBs is ongoing. So far, the upper limits presented span the entire duration of the gamma-ray burst observation. Figure 1 shows the VERITAS two-dimensional significance maps for the three GRB locations. Only one of the GRBs observed here, GRB 070521, has a distance measurement, which places it at a redshift of 0.553. It is likely that GRB 070311 occurred at low redshift but no definitive distance measurement was obtained. There was no optical afterglow detected from GRB 070612b so its redshift is unknown. None of the upper limits presented here have been corrected for the effects of absorption on the extragalactic background light.

A detailed report of the Whipple 10m GRB observations and their analysis will be presented in [13]. No evidence for TeV emission was found during these Whipple observations.

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GRB	ΔT^{a} (min.)	Exp.^{b} (min.)	No. of Telescopes	99% Flux Upper Limit (Crabs)	Time span of U. L.^{c} (min.)
070311	44	110	2	3.7%	44 - 124
	5805	40	3	6.4%	96.8 - 97.4^{d}
070521	18	80	3	2.9%	18 - 98
070612b	24	80	3	2.0%	24 - 151

Table 2: The VERITAS GRB Observations.

^{a} The time in minutes between the start of the GRB and the beginning of observations. ^{b} The total VERITAS exposure time on the GRB. This is not necessarily one contiguous block. ^{c} For the analysis presented here, all data for each GRB were combined to give one upper limit. This column gives the duration after T_0 for which the upper limit pertains. ^{d} The time is quoted in hours for this observation.

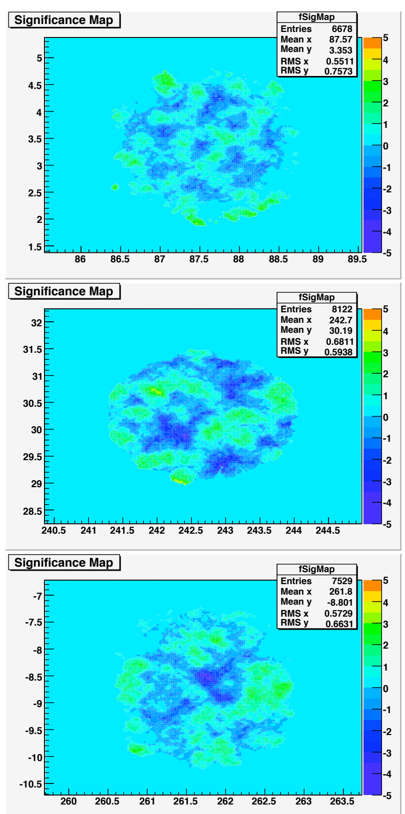

Figure 1: Two-dimensional significance maps for the three GRB locations presented here; top: GRB 070311 (on UT 070311); middle: GRB 070521; bottom: GRB 070612b.

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