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Very High Energy Observations of Gamma Ray Bursts with the Whipple/VERITAS Telescopes

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Abstract.
Gamma-ray Burst (GRB) observations at Very High Energies (VHE, E > 100 GeV) can impose tight constraints on some GRB emission models. Many GRB after-glow models predict a VHE component similar to that seen in blazars and supernova remnants, in which the GRB spectral energy distribution has a double-peaked shape extending into the VHE regime. Consistent with this after-glow scenario, EGRET detected delayed high energy emission from all five bright BATSE GRBs that occurred within its field of view. GRB observations have had high priority in the observing program at the Whipple 10m Telescope and will continue to be high priority targets when the next generation observatory VERITAS comes online. Upper limits on the VHE emission from ten GRBs observed with the Whipple Telescope are reported here.

INTRODUCTION

Since their discovery in 1969 [13], Gamma Ray Bursts (GRBs) have been well studied at many wavelengths. Although various open questions remain on their nature, there is almost universal agreement that the basic mechanism is an expanding relativistic fireball, that the radiation is beamed, that the prompt emission is due to internal shocks, that the afterglow arises from external shocks, that Lorentz factors of a few hundred are probably involved, and that the radiating particles, either electrons or protons, are accelerated to very high energies.

Some of the most significant advances in GRB research have come from correlative

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observations at longer wavelengths. In particular, the rapid, accurate localisations of the slower GRBs provided by the Italian-Dutch BeppoSAX satellite [4] made it possible to study GRBs and their afterglows in unprecedented detail at many wavelengths. Optical observations of the afterglows provided redshifts for many bursts and showed that they lie at cosmological distances. GRB980425 was detected by the gamma-ray burst monitor on BeppoSAX and was then localised with arc-minute accuracy by one of the BeppoSAX wide field cameras thus enabling optical astronomers to make rapid follow-up observations of the GRB location. With these observations came the first direct evidence that GRBs are associated with supernovae. Its position and time of occurrence were both consistent with those of supernova 1998bw [9]. Further proof of this SN-GRB association came with the observation of GRB030329 and SN2003dh by Stanek et al. [21].

For the observation of photons of energies above 100 GeV, only ground-based telescopes are available at present. However the telescopes (arrays of particle detectors) with the wide fields of view that are most suitable for GRB searches are relatively insensitive. There are several reports from these instruments of possible TeV emission (Padilla et al. [14], Amenomori et al. [1], Atkins et al. [2]). Atmospheric Cherenkov detectors are inherently more sensitive both in energy and flux but are limited by their small fields of view (3-5 degree). Early attempts at GRB monitoring were limited by slew times and uncertainty in the GRB source position [7]. Modern telescopes have fast slew capability and the next generation of gamma-ray satellites, including Swift [10], GLAST [18] and AGILE [22] will provide rapid, arcmin localizations.

GRB observations fall into two main categories, prompt observations and follow-up afterglow studies. It is important to establish whether there is, in general, a second higher energy component of emission present during either of these phases of a GRB. Understanding the nature of such emission will provide important information about the physical conditions of the emission region (Zhang & Mészáros [23], Dermer & Chiang [8], Pilla & Loeb [15]). The minimum detectable fluence with current ground-based detectors is 10^{-8} erg cm^{-2}, a factor of 30 less than GLAST, and hence predictions of high energy emission observable by GLAST suggest significant detection possibilities by ground-based detectors also. The collection area for the Whipple telescope is ≈ 3.5 x 10^4 m^2, very much larger than is possible for space-based instruments ($\approx 0.8\,\mathrm{m}^2$) thus enhancing the importance of ground-based instruments for these short duration phenomena.

Many authors have predicted VHE emission from GRBs in both the prompt and the afterglow phase. Razzaque, Mészáros & Zhang [16] investigated GeV and higher energy photon interactions in GRB fireballs and their surroundings for the prompt phase of the GRB. They predict that high energy photons escaping from the fireball will interact with infrared and microwave background photons to produce delayed secondary photons in the GeV-TeV range. They also predict a different delayed GeV component in the GRB afterglow phase from the inverse-Compton upscattering on external shock electrons. The duration of such a component is predicted to be up to a few hours, softening with time.

The GRB observational data is extraordinarily complex and there is no complete explanation for the diversity of properties observed. If the bulk of the radiation comes via synchrotron radiation as is usually supposed, then by analogy with many other systems with similar properties (supernova remnants, AGN jets), it is natural to suppose that there must also be an inverse Compton component by which photons are boosted into the GeV-TeV energy range. This process is described by Pilla & Loeb [15] who discuss the relationship between the location of the high energy cutoff, the bulk Lorentz factor and the size of the emission region. A high energy emission component due to inverse Compton emission has also been considered in detail for GRB afterglows by Sari & Esin [19]; the predicted flux at GeV-TeV energies is comparable to that near the peak of the radiation in the afterglow synchrotron spectrum. Only direct observations can confirm whether this is so. Zhang & Mészáros [23] investigated the different radiation mechanisms in GRB afterglows and identified parameter-space regimes in which different spectral components dominate. They found that the inverse-Compton GeV photon component is likely to be significantly more important than a possible proton synchrotron or electron synchrotron component at these high energies and predicted the detection possibilities with GLAST. Guetta & Granot [11] predict that in order for delayed high energy emission from the GRB due to the interaction of the $\approx$ 300 GeV photons from the prompt GRB phase with IR background photons to be detectable, extremely small intergalactic magnetic fields are required.

The main obstacle for the observation of VHE gamma rays from GRBs is the distance scale. The propagation of very high energy gamma rays though space can be affected significantly by the intergalactic infrared (IR) background radiation. Pair production interactions of gamma rays with these IR photons attenuate the gamma-ray signal thus limiting the distance to which gamma rays can be detected using VHE gamma-ray telescopes [20]. Since GRBs lie at cosmological distances, their detection in the VHE regime is expected only for rare nearby events.

OBSERVATIONS AND ANALYSIS

The observations presented here were made with the 10m Gamma-ray Telescope at the Fred Lawrence Whipple Observatory. Located on Mount Hopkins approximately 40 km south of Tucson in Southern Arizona at an altitude of 2300m, the telescope consists of 250 mirrors mounted on a 10m dish with a multi-pixel camera at its focus.

The imaging camera consists of 379 photo-multiplier tubes (PMTs) arranged in a hexagonal pattern. A plate of light-collecting cones is mounted in front of the PMTs to increase their light-collection efficiency. The pattern sensitive trigger fires whenever three adjacent PMTs register a signal above a preset level [5]. The PMT signals for each triggering event are read out and digitized using fast electronics. In this way, a digital image of the amount of charge in each PMT is recorded for each event and stored for offline analysis.

The data were analyzed using the standard imaging technique and analysis procedures pioneered and developed by the Whipple Collaboration [17]. In this method, each image is first cleaned to remove pixels with signals that most likely result from noise. The cleaned images are then characterised by calculating the first, second and third moments of the light distribution in each image. These parameters are used to calculate the image *length*, *width*, *size*, *distance* and *alpha* (defined elsewhere [17]), which form the basis for the selection of gamma-ray-like events.

TABLE 1. Summary of the Gamma-ray Bursts observed. Those redshifts marked with an star (*) were determined using the redshift estimator described in Atteia et al. [3]. The other redshifts were obtained from Caldwell et al. [6] and Stanek et al. [21].

GRB	Discovery Satellite	Trigger Number	Redshift	T_{OBS}-T_{GRB} (hrs)	Exposure (mins)	Position Offset (deg.)
021112	HETE-2	2448	0.8	3.69	193.46	0.013
021204	HETE-2	2486	—	16.91	55.34	0.009
021211	HETE-2	2493	—	20.69	82.79	0.058
030324	HETE-2	2641	3.93*	2.98	19.88	0.112
030328	HETE-2	2650	1.52	20.27	27.76	0.001
030329	HETE-2	2652	0.17	64.55	334.17	0.06*
030429	HETE-2	2695	2.65	16.99	83.42	0.084
030501	INTEGRAL	596	—	4.75	221.81	0.001
031026	HETE-2	2882	14.0*	3.33†	178.79	0.007
040422	INTEGRAL	1758	—	1.69	249.06	0.062

* On subsequent nights of observation, the position offset was 0.022 deg.

† GRB observations started at Whipple $\sim$ 3 mins after receiving the GRB notification. The main delay between the GRB start and the start of the observations was due to the delay in the position being sent out to the Global Coordinates Network.

The locations of ten GRBs were observed between 2002 and 2004 with the Whipple 10m telescope. Out of these GRBs, eight were detected by the HETE-2 satellite and two by the INTEGRAL satellite. Some of the properties of the GRBs observed are summarised in Table 1.

All of the observations reported here were made at times significantly later than that of the prompt GRB emission. The earliest observation occurred 2.9 hours after the GRB (GRB 040422). This is due for the most part to the fact that most GRB notifications arrive when observing is not underway. In the case of GRB031026, Whipple observations commenced within 3 minutes of the GRB notification arriving. Unfortunately though, the notification was sent $\sim$ 3 hours after the GRB occurred. The observations are summarised in Table 1.

DISCUSSION AND CONCLUSION

The results of the GRB observations are summarised in Table 2. No statistically significant excesses or deficits above or below the background were recorded for any of the GRBs observed over any of the timescales investigated. Many of the GRBs were observed over the course of several nights. The flux upper limits are typically about 40% of the Crab flux.

Most of the observations described here were taken a number of hours after the prompt GRB emission. However, although many models predict delayed high energy emission from GRBs, most predict it to occur within the first hour or so after the prompt GRB emission. When the next generation of space-based and ground-based telescopes come online, many improvements will be made in our capabilities to carry out these time-sensitive observations. Swift should provide rapid, accurate GRB locations to the astronomical community.

A significant role in the propagation of high energy gamma rays through space is played by the intergalactic infrared background radiation. Pair production interactions of gamma rays with these IR photons attenuate the gamma-ray signal thus limiting the distance to which VHE gamma-ray telescopes can detect sources. The most distant source of TeV gamma rays detected to date lies at a redshift of 0.129 [12]. Six of the GRBs observed here have redshift estimates (some from spectroscopic observations, others using redshift estimators) and the closest, GRB030329, lies at $z = 0.17$. The TeV upper limits presented here have not yet been corrected to account for the absorption of gamma rays by the IR background radiation. Many of the GRBs were possibly located at redshifts beyond the range over which a detection is possible in this energy range from the ground.

The Swift satellite is scheduled for launch in November 2004. Each GRB that it observes should be very well characterized due to the presence of the three dedicated GRB instruments on board, the BAT (Burst Alert Telescope), the UVOT (Ultra Violet Optical Telescope) and the XRT (X-ray Telescope). Redshifts should be available for a large fraction of the bursts detected making it easier to interpret any upper limits derived from TeV observations. Instruments such as VERITAS, with their increased sensitivity and greater background rejection capabilities will expand the energy range over which ground-based gamma-ray telescopes can operate thus extending the redshift range that can be explored. Both the Whipple 10m telescope and the first of the VERITAS telescopes should be operational by the time Swift is launched, providing increased capabilities for GRB observations. Prompt observations of at least ten Swift or GLAST GRBs should be possible each year with VERITAS.

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TABLE 2. The GRB observations.

GRB	T_{UL}-T_{GRB}* (hrs)	Exposure (mins)	Flux (C.U.)†	Flux (F.U.)**
021112	4.8	138.18	$<$0.253	$<$2.513
	29.0	55.28	$<$0.418	$<$4.142
021204	17.3	55.34	$<$0.452	$<$4.488
021211	21.6	82.79	$<$0.443	$<$4.391
030324	3.1	19.88	$<$0.654	$<$6.486
030328	20.4	27.76	$<$0.655	$<$6.492
030329	66.2	65.21	$<$0.473	$<$4.688
	91.4	64.96	$<$0.482	$<$4.778
	113.8	83.17	$<$0.370	$<$3.669
	137.0	37.55	$<$0.440	$<$4.361
	162.2	27.74	$<$0.659	$<$6.533
	186.2	27.73	$<$0.552	$<$5.470
	261.1	27.81	$<$0.710	$<$7.037
030429	17.5	55.62	$<$0.581	$<$5.764
	40.8	27.80	$<$0.763	$<$7.567
030501	6.2	194.03	$<$0.270	$<$2.676
	29.8	27.78	$<$0.778	$<$7.718
031026	4.8	178.79	$<$0.496	$<$4.917
040422	2.9	165.97	$<$0.412	$<$4.090
	25.9	83.09	$<$0.666	$<$6.610

* The length of time after the GRB for which the upper limits (ULs) are quoted.

† This is the flux upper limit in units of equivalent Crab flux.

** The 99.9% flux upper limits are quoted above the peak response energy ($\sim$ 400 GeV) in units of 10^{-11} cm^{-2} s^{-1}.

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