*Proceedings of the 30th International Cosmic Ray Conference*
Rogelio Caballero, Juan Carlos D'Olivo, Gustavo Medina-Tanco,
Lukas Nellen, Federico A. Sánchez, José F. Valdés-Galicia (eds.)
Universidad Nacional Autónoma de México,
Mexico City, Mexico, 2008
Vol. 3 (OG part 2), pages 1111–1114



30TH INTERNATIONAL COSMIC RAY CONFERENCE

# Gamma-Ray Burst Follow-up Observations with STACEE During 2003-2007

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**Abstract:** The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is an atmospheric Cherenkov telescope (ACT) that uses a large mirror array to achieve a relatively low energy threshold. For sources with Crab-like spectra, at high elevations, the detector response peaks near 100 GeV. Gamma-ray burst (GRB) observations have been a high priority for the STACEE collaboration since the inception of the experiment. We present the results of 20 GRB follow-up observations at times ranging from 3 minutes to 15 hours after the burst triggers. Where redshift measurements are available, we place constraints on the intrinsic high-energy spectra of the bursts.

## Introduction

The Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) is a showerfront-sampling Cherenkov telescope sensitive to gamma rays above 100 GeV. It is located at the National Solar Thermal Test Facility (NSTTF) at Sandia National Laboratories outside Albuquerque, New Mexico, USA. The NSTTF is located at 34.96°N, 106.51°W and is 1700 m above sea level. The facility has 220 heliostat mirrors designed to track the sun across the sky, each with 37 $m^2$ area. STACEE uses 64 of these heliostats to collect Cherenkov light produced by air showers. STACEE employs five secondary mirrors on the solar tower to focus the Cherenkov light onto photomultiplier tube (PMT) cameras, as shown in Figure 1. The light from each heliostat is detected by a separate PMT and the waveform of the PMT signal is recorded by a flash ADC. A programmable digital delay and trigger system[1] selects showers for acquisition while eliminating most random coincidences of night sky background photons. Under good observing conditions, STACEE operates with a threshold around 5 photoelectrons per channel. A detailed description of the instrument can be found in D.M. Gingrich et al.[2].

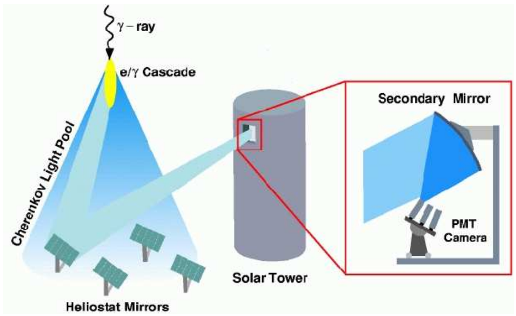


Figure 1: Conceptual drawing of STACEE.

The large mirror area of the STACEE detector leads to an energy threshold lower than those attainable by most single-dish imaging telescopes or water-Cherenkov telescopes. The energy threshold - defined as the energy at which the trigger rate peaks - is determined by the spectrum of the source and the effective area of the detector at the target position. For targets above 60° in elevation with power-law spectral indices between 2 and 3, the energy threshold is typically between 150 and 200 GeV. For targets near zenith, STACEE has significant effective area at energies as low as 50 GeV.

A low energy threshold opens up the possibility of detecting more distant sources[3]. Collisions of gamma rays with extragalactic background light (EBL) photons produce electron-positron pairs, attenuating the gamma-ray flux from distant sources. The extinction becomes more severe with increasing energy, producing an energy-dependent horizon for gamma-ray observations. Thus, a low energy threshold is advantageous when attempting to characterize the high-energy emission of GRBs, for which the mean measured redshift (for Swift bursts) is 2.7[4].

STACEE observations are typically taken in pairs of on-source and off-source runs. The off-source runs serve as measurements of the background event rate produced by cosmic-ray showers. Under normal conditions, the cosmic-ray trigger rate is $\sim$5 Hz. Background rejection techniques have been explored and the most effective technique is described elsewhere[5, 6, 7]. After background rejection cuts, STACEE typically obtains a $5\sigma$ detection of the Crab with approximately 10 hours of on-source observations. Under good observing conditions, STACEE would obtain a $5\sigma$ detection in 30 minutes for a source with a spectrum equal to 4.5 times that of the Crab.

## GRB Observing Strategy

Observing gamma-ray bursts is a high priority for STACEE. Burst alerts from the GRB Coordinates Network (GCN)[8] are monitored with a computer program that alerts STACEE operators when a burst is observable by updating a web page and initiating an audio alert. Email alerts are also sent to a cellular phone and pager that are carried by the telescope operators. Upon receiving a burst alert, operators immediately abort any observations in progress and retarget the detector. In addition to doing immediate GRB follow-up observations, we search for afterglow emission from bursts discovered within the previous 12 hours. EGRET detected GeV emission from GRB940217, including an 18 GeV photon, for more than 90 minutes after the start of the burst[9].

The Swift GRB Explorer[10] launched in November of 2004, is able to pinpoint burst directions on the unprecedented timescale of about 20 seconds. In the summer of 2004, the 64 heliostats used by STACEE were outfitted with new motors to increase their slewing speed. The new motors have performed very well, allowing the detector to be retargeted from any of the sources typically observed to most observable GRB positions within 1 minute. In the fall of 2005, a socket connection was established between the STACEE burst alert system and the GCN, effectively eliminating the delays associated with sending and receiving emails. In principle, STACEE should be able to begin observations of some bursts within 100 seconds of their Swift triggers.

## STACEE GRB Observations

Since the summer of 2003, follow-up observations have been made for 20 bursts with STACEE. For two of those bursts, GRB 031220 and GRB 061222, the observing conditions were very poor and the data could not be analyzed with a standard on-off comparison. Analysis of the event rates during the on-source runs for these bursts did not reveal any significant spikes. The remaining burst observations are described in Table 1. Two of the most interesting observations are discussed briefly in this section.

GRB 050509B was the first short burst for which a host galaxy was determined. The host is a large elliptical galaxy at a redshift of 0.225 [11]. Because of the low redshift of this burst, EBL attenuation would not be expected to totally obscure this burst in STACEE's energy band. The optical depth would be below 1 for photons below about 400 GeV in energy.

STACEE observations of GRB 050509B began 23 minutes after the initial burst detection and consisted of two 28-minute on/off pairs. After data quality cuts, approximately 35 minutes of livetime remained, split almost equally between the two on-source runs (which were separated by 32 minutes). The burst was at a very nearly optimal position, reaching its transit, about 6 degrees south of zenith, halfway through the first on-source run. Simulations were used to determine the effective area, as a function of energy, for STACEE under the conditions of these observations. Assuming a photon spectrum of dN/dE $\sim$ E$^{-2.5}$, the event rate limit determined from observations was then converted into a flux limit. After accounting for EBL attenuation, the STACEE flux limit translates to a limit on the average isotropic equivalent luminosity during the period of observations of $L_{95} < 9.1 \times 10^{46}$ ergs/s in STACEE's energy range.

Our observation of GRB 050607 also stands out. When observations began, only 3 minutes and 13 seconds after the Swift burst trigger, the burst was at a relatively high elevation of almost 62 degrees. Approximately 5 minutes after the burst trigger a large flare in the X-ray flux was detected by Swift's X-Ray Telescope (XRT). Many believe that such flares are evidence of late activity in the central engine of the burst[12] and it has been predicted that they may be accompanied by flares of high-energy gamma rays[13]. If that is the case the flares may provide additional hints about the prompt emission. No high-energy flaring was seen in STACEE observations during the X-ray flare or in the subsequent twenty minutes (Figure 2). Unfortunately, the absence of a redshift measurement for this burst prevents us from making any stronger statements about the nature of these flares.

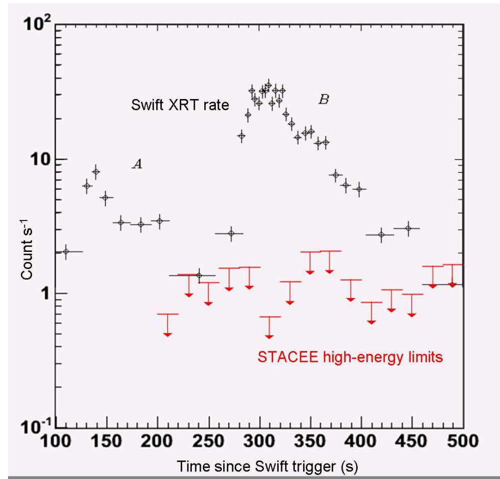


Figure 2: The Swift XRT light curve and STACEE high-energy rate limits for the early afterglow GRB 050607.

## GRB Followups in the Swift Era

The Swift GRB Explorer has enabled ground-based observatories to perform GRB followup observations with unprecedented response times. STACEE has been able to begin observations of four bursts within 4 minutes of their initial Swift triggers. Swift also discovered that the early X-ray afterglows of GRBs often contain large flares that are thought to be evidence of late activity in the central engines of some bursts. Because of its high sensitivity, Swift is able to detect more distant bursts than previous experiments. The mean redshift of bursts detected by Swift is 2.7 whereas the pre-Swift mean redshift was 1.5[4]. Because of their high redshifts, most bursts will be obscured at high-energies due to EBL attenuation. In addition, redshift measurements have only been possible for a small fraction of Swift bursts, making it difficult to translate flux limits into limits on the intrinsic spectra of the bursts. These factors magnify the importance of obtaining fast, low-threshold followups for as many GRBs as possible, as we have attempted to do with STACEE. These factors also heighten excitement about future experiments, such as GLAST, that will bridge the energy gap between earlier satellite and ground based telescopes.

| Burst ID | Redshift | Ref. | Time to Target (min) | Livetime (min) | Significance | Energy Threshold (GeV) | 95% CL Upper Flux Limit (ergs cm$^{-2}$ s$^{-1}$) |
|---|---|---|---|---|---|---|---|
| 040422 | | | 95.3 | 28 | -0.77 | 480 | $3.5 \times 10^{-10}$ |
| 040916 | | | 309.7 | 28 | 0.98 | 320 | $9.0 \times 10^{-10}$ |
| 041016 | | | 142.0 | 4.4 | -1.3 | 310 | $2.4 \times 10^{-9}$ |
| 050209 | | | 217.5 | 24 | 0.34 | 260 | $6.1 \times 10^{-10}$ |
| 050402 | | | 4.0 | 18 | 0.05 | 470 | $8.3 \times 10^{-10}$ |
| 050408 | 1.236 | [14] | 642.5 | 17 | 0.28 | 530 | $1.3 \times 10^{-9}$ |
| 050412 | | | 7.2 | 6.9 | 2.1 | 250 | $1.5 \times 10^{-9}$ |
| 050509B | 0.225 | [11] | 23.2 | 35 | 0.69 | 150 | $3.5 \times 10^{-10}$ |
| 050509A | | | 476.4 | 16 | 0.26 | 520 | $9.0 \times 10^{-10}$ |
| 050607 | $< 5$ | [15] | 3.2 | 22 | -1.4 | 160 | $2.1 \times 10^{-10}$ |
| 060121 | | | 384.7 | 30 | -0.96 | 650 | $5.0 \times 10^{-10}$ |
| 060206 | 4.045 | [16] | 269.8 | 52 | 0.79 | 180 | $3.5 \times 10^{-10}$ |
| 060323 | | | 880.5 | 18 | -0.26 | 240 | $4.0 \times 10^{-10}$ |
| 060526 | 3.21 | [17] | 685.6 | 40 | 1.38 | 250 | $5.0 \times 10^{-10}$ |
| 061028 | | | 339.2 | 57 | -0.04 | pending | pending |
| 070223 | | | 357.9 | 42 | 0.85 | pending | pending |
| 070418 | | | 360.1 | 25 | -0.81 | pending | pending |
| 070419A | | | 3.3 | 27 | -0.71 | pending | pending |

Table 1: Summary of STACEE GRB observations since the summer of 2003. The targeting times and livetimes take into account time removed by data quality cuts. The energy thresholds and flux limits assume a source photon spectrum dN/dE $\sim$ E$^{-2.5}$ that is integrated between 100 GeV and 10 TeV for the flux limits.

## Acknowledgments

This work was supported in part by the U.S. National Science Foundation, the Natural Sciences and Engineering Research Council of Canada, Fonds Quebecois de la Recherche sur la Nature et les Technologies, the Research Corporation and the University of California at Los Angeles.

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