Prospects for GRB detection and other measurements with the HAWC observatory

Dmitry Zaborov (Pennsylvania State University) for the HAWC collaboration

- Brief introduction to HAWC
- Sensitivity to steady sources
- Sensitivity to gamma ray bursts
Physics objectives

- Diffuse emission from galactic plane, extended sources (Cygnus, Fermi bubbles?)
- Galactic point sources (SNR, PWN)
- AGN and AGN flares
- GRB
Observable sky

Wide field of view provides several advantages:

- Survey of a large fraction of the sky (look for the unknown)
- Measure the highest energy emission from astronomical objects
- Observe larger objects (nearby supernova remnants & pulsar wind nebulae, Galactic disk)
- Observe transient events (gamma ray bursts, flares from active galactic nuclei)

Wide field of view limited by atmospheric depth
45° from zenith (Milagro standard analysis)
50 mCrab survey in 1 yr
HAWC - High Altitude Water Cherenkov Observatory

- Direct detection of gamma-induced atmospheric showers
- Successor of Milagro
- Under construction in Mexico
- Collaboration of ~100 scientists from US & Mexico

Pico de Orizaba, altitude 4100 m, latitude 18° 59' N
Two hours drive from Puebla, four from México City
Also site of Large Millimeter Telescope
300 water Cherenkov detectors, 7.3 m diameter x 4.5 m tall, 200,000 liters of water, 3 upward looking 8” PMTs per tank, ~20,000 m² area, >60% active Cherenkov volume
Energy threshold and effective area

- Geometric area \( \sim 10^5 \text{ m}^2 \) (6 x Milagro pond area)
- Energy threshold \( \sim 30 \text{ GeV} \), fully efficient at \( E > 3 \text{ TeV} \)
- Still \( \sim 100 \text{ m}^2 \) at \( E = 100 \text{ GeV} \)

Alternative triggers which would substantially increase effective area at low energies are under investigation.

Nhit > 70
Angular error < 1°
No hadron rejection cut applied

Fermi LAT (0.8 m²)
Angular resolution

- Angular resolution up to 0.1 degree at TeV energies
- Determined by information in the particles that reach the ground
Energy resolution

- Uncertainty from two sources:
  - Measurement of energy deposited at ground level
  - Fluctuations in shower development in atmosphere (naturally log-normal)
- Higher elevation means HAWC has a big advantage over Milagro
Gamma hadron separation

Gamma-hadron separation is based on shower lateral size, clumpiness, and high amplitude pulses produced by muons.

Currently use parameter $C = \frac{n\text{Hit}}{\text{CxPE}}$

$\text{CxPE} = \text{largest hit (in PEs)} > 30\text{ m from shower core}$

Already gives ~10x better rejection than Milagro for fixed energy
Sensitivity to Crab-like point sources

- Long integration times lead to excellent sensitivity at highest energies (> few TeV)
- $5\sigma$ sensitivity to:
  - 10 Crab in 3 minutes
  - 1 Crab in 5 hr (1 transit)
  - 0.1 Crab in $\frac{1}{3}$ year
- 10-15x Milagro sensitivity
  - Lower energy threshold
  - Better angular resolution
  - Better rejection of cosmic rays

50 hr observation time assumed for IACTs, HAWC source transit 15° off zenith
Guided search for GRB: two approaches

- Objective: extend GRB observations to high energy (E > 30 GeV)
- Both analyses, main DAQ and scalers, can be done offline

HAWC main DAQ
- reconstructed showers (event time, position on the sky)

HAWC scaler DAQ
- variations of counting rates

Satellite & ground based measurements
- time, duration, position on the sky

Guided search with main DAQ data
Guided search with scaler data
Sensitivity vs. zenith angle (main DAQ)

Simulated GRB:
duration = 20 seconds
spectral index = 2
redshift = 0.5 (EBL absorption following Gilmore et al.)

Number of events in the time window (20 s) is examined

Shown is the flux detectable at 5 sigma significance with 50% probability

EBL absorption removes high energy gammas from GRB spectra
--> Have to work with low energies
Relatively background-free analysis due to narrow time window (duration of GRB)
--> Angular resolution and gamma-hadron separation performance not critical
--> Easier to go to low energy
--> Low trigger threshold very useful
Sensitivity as function of spectral index and cutoff

Brightest GRBs detected by Fermi should be observable with 5 sigma significance if cutoff is above ~100 GeV, even without improvements in the trigger and reconstruction algorithms.

Simulated GRB:
- $T = 1$ s
- zenith = 20 deg

Power law spectrum with Heaviside cutoff

The cutoff is intended to mimic either an intrinsic or an EBL absorption cutoff

Nhit > 70 (5 kHz trigger)
Same for reduced trigger threshold

Nhit > 30 (16 kHz trigger)

Accessible cutoff range extends from ~100 GeV to ~60 GeV

Final choice of trigger threshold depends on many factors (hardware design, background rejection at low energies, etc)
Scalor DAQ “Effective area”

- GRB produces simultaneous increase of PMT counting rates
- Sudden increase in PMT counting rates may reveal a GRB
- Only counting rates are analyzed (no shower reconstruction)

* It is the sum of effective areas of 900 PMTs, not the usual detector effective area

Non-negligible sensitivity down to a few GeV (much lower than for the main DAQ analysis)
Scaler DAQ sensitivity

Scaler analysis complements the main DAQ analysis, covering short GRBs with soft spectra and cutoffs <100 GeV
Above 10 GeV HAWC’s sensitivity will be comparable to Fermi LAT’s (for short GRBs)

Redshift is modeled according to Gilmore et al.

No intrinsic spectral cutoff

Fermi LAT curve: 1 photon above 10 GeV

Fermi LAT is essentially “background free” (sensitivity $\sim 1 / T$)

HAWC scalers are background dominated (sensitivity $\sim 1 / \sqrt{T}$)
A possible way to measure spectral cutoff

Assumption 1: GRB is detected by both scalers and main DAQ
Assumption 2: spectral index at some reference energy (e.g. 10 GeV) is known from other observations (e.g. Fermi LAT)

Simulated GRB: spectral index = 1.62
Sharp cutoff at 150 GeV

Green band: region compatible within 1 sigma with observation of 18 events with the main DAQ
Blue curve: line of constant significance for the scalers
Systematic errors not included

A ±30 GeV accuracy in the measurement of the effective cutoff energy might be feasible
Various approaches to combined analyses

- Use external data in offline analyses (when/where available)
  - e.g. set search time window based on Fermi LAT data, use coordinates and redshift measured by optical/infrared telescopes
- Receive GCN alerts
  - temporarily lower trigger threshold to improve efficiency
- Generate GCN alerts based on HAWC data
  - HAWC will be efficient enough to produce meaningful alerts
When?

- **VAMOS** (ready June 2011)
  - 7 tank test array
- **HAWC-30** (6 months)
  - Implementation of all subsystems
  - Considerable sensitivity to GRBs
- **HAWC-100** (18 month)
  - Science operations with 2 times Milagro’s sensitivity
- **HAWC-300**
  - Full detector

GRB searches with HAWC greatly profit from external guidance
--> Important to run at the same time as Fermi
Summary

• HAWC is a new generation wide field of view gamma-ray telescope currently under construction in Mexico

• HAWC will be sensitive to gamma rays with energies down to 30 GeV

• HAWC will have effective area ~10000 m² and angular resolution ~0.1 degree at TeV energies

• The wide field of view and high duty cycle of HAWC offer exciting prospects for the first detection of a gamma ray burst by a ground-based experiment

• HAWC measurements could constrain high energy cutoff in GRB spectra, providing information on intrinsic spectral cutoff and/or EBL absorption
Thank you for your attention!

(backup slides follow)
Milagro gamma ray observatory

2650 m altitude, near Los Alamos, New Mexico

2650 m above sea level
898 photomultipliers
450 in top layer of pond
273 in bottom layer of pond
175 outrigger tanks (8’ dia. x 3’ deep)
3600 m$^2$ pond, operational Jan. 2001
34,000 m$^2$ outrigger array, fully operational June 2004

Optimal energy $\sim 20$ TeV
Effective area $\sim 10^4$ m$^2$ (pond), $10^5$ m$^2$ (outtrigger)
Background rejection $\sim 95$
Angular resolution $\sim 0.7^\circ$
Energy resolution $\sim 50$
95% duty cycle / $\sim 1.8$ sr aperture
Milagro galactic survey

- Observations with Milagro wide-field TeV telescope, 2000–06
- 4 detected sources, additional 3-4 candidates (<5σ post-trials)
- 5/7 have EGRET GeV counterparts (13 sources in the region, p=3x10^-6)
- Significant diffuse emission in the Cygnus region

Other Milagro results: CR anisotropy, Geminga, TeV diffuse emission from Galactic plane

Mialgrito’s GRB

One of 54 GRBs observed by Milagrito
18 events on background of 3.3
Chance probability (post-trials) of $1.7 \times 10^{-3}$ (2.9σ)
TeV fluence $>$ 10x keV fluence

Milagro: Atkins et al., 2000
From Milagro to HAWC

- Redeploy Milagro at Volcán Sierra Negra, México
- Increase altitude from 2650 m to 4100 m
- Increase area from 3,600 m² (pond) to 22,000 m²
- Segment the Cherenkov medium: separate tanks instead of a single pond
- Better angular resolution and background rejection, lower energy threshold
- Achieve 10-15 x sensitivity of Milagro
- Detect Crab at 5σ in 6 hours instead of 3 months
Effective area: HAWC vs. Milagro

- EAS detectors are tail-catching calorimeters
- Higher altitude means more particles survive to reach the detector
- HAWC fully efficient above ~2 TeV
- Still ~100 m² area at 100 GeV
- ~100x Milagro after background rejection

HAWC: Nhít > 30
Gamma-hadron separation in HAWC

- Cosmic ray showers are clumpier than gamma rays
- Algorithm looks for high-amplitude hits more than 40 m from the reconstructed core location
Old layout version (used in simulation)

- 300 tanks in a square layout
Counting rates and Fano factor

- Entries: 163
- Mean: 1.891e+04
- RMS: 560.3

Low Energy Cutoff (GeV):
- 2
- 3
- 4
- 5
- 6
- 7
- 8
- 9
- 10

Fano Factor:
- 17.0
- 17.5
- 18.0
- 18.5

Uncorrelated noise = 7.5kHz
Afterpulse after 2μs
Electronics time window = 20ns

Slope = 0.091 / GeV
Sensitivity for $E^{-2}$ spectrum
EBL absorption

\[ e^+ \rightarrow \gamma \sim eV \]

\[ e^- \rightarrow \gamma \sim TeV \]

P. Gorham