Gamma-Ray Astronomy with Milagro and HAWC

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## Comparison of Gamma-Ray Detectors

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Milagro Gamma Ray Observatory
2350m altitude near Los Alamos, NM

How Does Milagro Work?

- Detect Particles in Extensive Air Showers from Cherenkov light created in 60m x 80 m x 8m pond containing filtered water.
- Reconstruct shower direction to ~0.5° from the time different PMTs are hit.
- 1700 Hz trigger rate mostly due to Extensive Air Showers created by cosmic rays.
- Field of view is ~2 sr and the average duty factor is >90%.

energy response

12 TeV
Development of a 2TeV Gamma Ray Shower from first interaction to the Milagro Detector

Viewed from below the shower front -
Color coded by Particle Type

This movie views a CORSIKA simulation of a gamma ray initiated shower. The purple grid is 20m per square and is moving at the speed of light in vacuum. The height of the shower above sea level is shown at the bottom of the screen.

Blue – electrons and gamma
Yellow - muons
Green - pions and kaons
Purple - protons and neutrons
Red - other, mostly nuclear fragments

Blue – Electrons   Muons – Yellow   Pions – Green   Nucleons – Purple
Gamma Shower 2 TeV (movies by Miguel Morales)

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Proton Shower 2 TeV (movies by Miguel Morales)

Development of a 2TeV Proton Shower from first interaction to the Milagro Detector

Viewed from below the shower front -
Color coded by Particle Type

This movie views a CORSIKA simulation of a proton initiated shower. The purple grid is 20m per square and is moving at the speed of light in vacuum. The height of the shower above sea level is shown at the bottom of the screen.

Blue - electrons and gamma
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Milagro

• Milagro was a first generation wide-field gamma-ray telescope that viewed the entire Northern sky everyday

– Discovered:
  • more than a dozen TeV sources
  • diffuse TeV emission from the Galactic plane
  • a surprising directional excess of cosmic rays

– Showed that most bright galactic GeV sources extend to the TeV
Inside the Milagro Detector
Array of 175 Outriggers

8’ dia. x 3’ deep
Milagro Operations

2000-2004
Pond Only

2004-2008
Full Detector

Operations Ended in May 2008
Use bottom layer of Milagro to detect penetrating particles (primarily muons) which are more prevalent in cosmic-ray (hadronic) showers than gamma-ray (electromagnetic) showers.
Background Rejection

**A₄ Distribution**

- Data
- Proton MC
- Gamma MC

Logarithmic scale on the y-axis from $10^{-4}$ to $10^{-1}$.

The graph shows the distribution of $A₄$ for different types of data and simulations.
In 2007, Milagro reported our Galactic plane survey based on data collected up to June 2006.

Detected 4 sources at $>5\sigma$ post-trials.

Detected 4 candidate sources at $>4.5\sigma$ pre-trials.

~100,000 trials in Galactic plane, 500,000 in the sky.
What has changed since the last in the last three years?

• Improved detector simulation.
• Improved stability.
• Improved γ/hadron separation.
• Data binned in 9 energy bins.
• Spectrum analysis complete.
• Additional year of data added.
• ~25% increase in sensitivity.
• Analysis “tunable” for various spectral hypotheses.

Fermi
16 TeV associations out of 34 likely galactic sources in our field of view
GeV Pulsars are Coincident with TeV sources

GeV Emission is pulsed & due to rotation axis misaligned with Magnetic Dipole of $\sim 10^{12}$ G

TeV Emission is produced by particles further accelerated in the shock interacting with the ambient medium.
• Associated with MGRO J1908+06, discovered by Milagro and confirmed by HESS and VERITAS (left)

• J1900.0+0356 has no known association (right)

• Milagro detects an excess of $7.4\sigma$ and $3.6\sigma$ respectively at the location of the Fermi sources.


Previously not reported in TeV
Coincident with SNR G65.1+0.6 (left) and LAT pulsar PSR 1957+2831 (right).

Milagro detects excess of significance 4.3σ and 4.0σ respectively.

Previously not reported in TeV.
• BSL source associated with previously reported MGRO J2019+37
• Most significant source in the Milagro data set apart from the crab.
• Young pulsar (17.2 kyr) discovered by AGILE
• Milagro detects a 12.4σ excess at the position of the Fermi source

New Fermi reports PSR J2030+3641: P = 200 ms, $F_{\text{gamma}} \sim 1\%$ Geminga’s, hard spectrum
- J2021.5+4026 LAT discovered pulsar associated with gamma-Cygni SNR.
- J2032.2+4122 is a LAT discovered pulsar associated with HEGRA, Milagro and MAGIC TeV detections.
- Milagro observers excesses of 4.2σ and 7.6σ respectively at the positions of the Fermi sources.

With low energy cut we see two clear sources
• “Boomerang” PWN
• Associated with radio pulsar J2229+6114
• Milagro detects a 6.6σ excess at the location of the Fermi source.
• Noted excess was very extended (4 deg)
• Fermi pulsar (Science July 09) located in the southern ‘tail’ with 4.7σ in Milagro data.

Previously not reported in TeV
• Most Significant source in BSL
• Old (300 kyr) and nearby (169 pc)
• $3.5\sigma$ at the location of Geminga
• $6.3\sigma$ when assuming $1^\circ$ extended source
• Fitted FWHM $2.6^\circ$ extent, consistent with IACT observations of more distant PWN
Spectrum of the Crab
RA: 83.65 DEC: 22.05

Fit Results: (no cutoff)
Io = 6.6 [5.0, 8.0] x 10^{-7} /s/m^2/TeV
α = 2.95 [2.85, 3.03]
χ^2 = 28.3 (25 dof)

Softer than IACT spectra (α_{IACT} ~ 2.6)

Fit Results: (3-parameter)
Io = 5.2 [2.0, 8.0] x 10^{-7} /s/m^2/TeV
α = 2.75 [2.22, 3.03]
Γ = 71 [22, ∞]
χ^2 = 27.1 (24 DOF)

Energy reach from ~3 TeV to >100 TeV
Peak sensitivity for E^{-2} source at ~100 TeV
Fit Results: (3-parameter)
Io = 5.2 [1.9, 14.0] x 10^{-7} /s/m^2/TeV
\alpha = 1.90 [1.50, 3.5]
Ec = 2.5 [1.4, 20]
\chi^2 = 33.5 (24 DOF)

Fit Results: Fix spectral index at 2.1 (2-parameter)
Io = 5.4 [3.0, 10.1] x 10^{-7} /s/m^2/TeV
Ec = 2.8 [1.8, 4.0] TeV
\chi^2 = 28.3 (25 dof)
Fit Results: (no cutoff)
Io = 6.6 [3.4,12.1] x 10^{-7} /s/m^2/TeV
\alpha = 3.00 [2.8,3.2]
\chi^2 = 29.3 (25 DOF)

Fit Results: (3-parameter)
Io = 0.62 [0.29,4.9] x 10^{-7} /s/m^2/TeV
\alpha = 1.50 [1.50,2.65]
Ec = 14 [10,50] TeV
\chi^2 = 22.1 (24 DOF)

Fit Results: (hold \alpha=2.1)
Io = 2.1 [1.1,3.1] x 10^{-7} /s/m^2/TeV
Ec = 14 [10,40] TeV
\chi^2 = 23.3 (25 DOF)
Summary of Spectral Results

• All of the brightest Milagro sources are spatially coincident with Fermi Pulsars (PWN).

• Fits to the Crab/Mrk 421/MGRO J1908+06 have spectra compatible with IACT observations.

• Insufficient significance/resolution to distinguish a soft spectra from hard spectra that cut off.

• A cutoff is favored in all sources if the TeV scale if the spectrum is assumed to be hard (2.1).
Cosmic Ray Anisotropy

- Is the arrival directions of Cosmic Rays uniform
  - Should it be?
  - Compton-Getting
Two Approaches to CR Anisotropy

1) Forward backward asymmetry method to study “large scale anisotropy”.
   Derive shape of large scale features.

2) “Direct Integration” background subtraction to study “intermediate scale anisotropy”.
   Background derived from vicinity of source. High pass filter.
Sky Map of CR large scale anisotropy

Similar results to Tibet and Super-K (and now IceCube)
84th string installed yesterday.
Cosmic Ray Anisotropy

Tibet-III
(5° smoothing)

Preliminary

IceCube-40
(3° smoothing)

5 TeV

20 TeV

statistical significance

Li-Ma Significance

courtesy Kazuki Muñakata

-12 -10 -8 -6 -4 -2 0 2 4 6 8 10
Galactic Magnetic Fields

- Eduardo Battaner, Joaquín Castellano, and Manuel Masip ’09
  - They combine effects of the regular and the turbulent (fluctuating) magnetic fields in our vicinity.
  - They use a galactic $B_{\text{galactic}} \sim 3-5$ μG and a fluctuating field of $B_{\text{random}} \sim 3-5$ μG
  - They show that they can match the Milagro results in both in shape and strength
  - The preferred anisotropy direction is orthogonal to the local regular magnetic field
Galactic Magnetic Fields?

Eduardo Battaner, Joaquín Castellano, and Manuel Masip ‘09
Large Scale Anisotropy

- All experiments see the large scale anisotropy
- All see the same phase
- The amplitude appears to vary slightly perhaps decreasing with energy
- Amplitude and Phase are inconsistent with Compton-Getting
- May be due to local galactic mag. fields
Suppression of large scale features to look for smaller scale features

2hr background interval
Cosmic Ray Observations

- No weighting or cutting.
- Map dominated by *charged* cosmic rays.
- $10^{\circ}$ smoothing, looking for intermediate sized features.
- Two regions of excess $15.0\sigma$ and $12.7\sigma$. Fractional excess of $6\times10^{-4}$ ($4\times10^{-4}$) for region A(B).

PRL 101, 221101 (2008)
Milagro Observation using Background Calculation over 2 hour (30° in RA) intervals

Abdo, A. et al astro-ph/0801.3827

Tibet AS Observation after subtracting model of large scale anisotropy

K. Munakata, M. Amenomori, et al AIP Conf Vol 932, 283
No Background Subtraction

RA strip for Dec range 10°-20 background estimate is shown in black.

Large scale structure due to exposure variation + LSA
• **Milagro** can separate gamma-ray and hadron induced events through the presence of large depositions in the bottom layer.

• **Region A:**
  \[ \chi^2(\text{hadron}) = 10.3/16 \text{ dof} \]
  \[ \chi^2(\text{gamma}) = 124.0/16 \text{ dof} \]

• **Region B:**
  \[ \chi^2(\text{hadron}) = 19.0/16 \text{ dof} \]
  \[ \chi^2(\text{gamma}) = 84.8/16 \text{ dof} \]

\[ A_4 = \frac{(f_{\text{Top}} + f_{\text{Out}}) \times n_{\text{Fit}}}{m_{\text{PE}}} \]

- **mxPE:** maximum # PEs in bottom layer PMT
- **fTop:** fraction of hit PMTs in Top layer
- **fOut:** fraction of hit PMTs in Outriggers
- **nFit:** # PMTs used in the angle reconstruction
Spectral fit to excess

Region A

(a)

Fractional Excess \( \times 10^{-3} \)

Region A
Average
Region B
Average

\( \log_{10}(\text{Fraction of Outriggers Hit}) \)

Region B

(b)

Proton Energy (TeV)

\( \log_{10}(\text{Fraction of Outriggers Hit}) \)

HAWC Co
PAMELA

Payload for Antimatter Matter Exploration and Light Nuclei Astrophysics

“Either a significant modification in the acceleration and propagation models for cosmic-rays is needed, or a primary component is present”

Candidates for a primary component...

(1) annihilation of dark matter particles in the vicinity of our galaxy.

(2) a contribution from near-by astrophysical sources, such as pulsars.
Advanced Thin Ionization Calorimeter (ATIC) observed an anomalous electron excess.
Fermi and ATIC

![Graph showing particle flux against energy with various data points and a model line.](image)
Yuksel, Kistler and Stanev (09)

- They explain the Pamela excess and Milagro data with Geminga as the source.
How do you make Milagro better?
From Milagro to HAWC

- Move it to higher altitude
- Improve optical isolation
- Cover more area with water
- Reuse PMTs and most electronics
- Total Cost (HW + construction) <$12M

Milagro
- 2350m asl
- One big pond
- Pond area 4,000 m²

HAWC
- 4150m asl
- Individual tanks
- Tank area ~20,000 m²
The HAWC (High Altitude Water Cherenkov) Observatory
The HAWC Collaboration

University of Maryland: Jordan Goodman, Andrew Smith, Greg Sullivan
Los Alamos National Laboratory: Gus Sinnis, Brenda Dingus, John Pretz
University of Wisconsin: Teresa Montaruli, Stefan Westerhoff
University of Utah: Dave Kieda
Univ. of California, Irvine: Gaurang Yodh
Michigan State University: Jim Linnemann, Kirsten Tollefson
George Mason University: Robert Ellsworth
University of New Hampshire: James Ryan
Pennsylvania State University: Tyce DeYoung, Patrick Toale, Kathy Sparks
University of New Mexico: John Matthews, William Miller
Michigan Technical University: Petra Hüntemeyer
NASA/Goddard Space Flight Center: Julie McEnery
Georgia Institute of Technology: Ignacio Taboada
Harvey Mudd College: Richard Haskill, Ann Esin, Pat Little and Greg Lyzenga

Instituto Nacional de Astrofísica Óptica y Electrónica (INAOE): Alberto Carramiñana, Eduardo Mendoza, Luis Carrasco, William Wall, Daniel Rosa, Guillermo Tenorio Tagle, Sergey Silich
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Universidad Autónoma de Chiapas: Cesar Álvarez, Eli Santos Rodriguez, Omar Pedraza
Universidad de Guadalajara: Eduardo de la Fuente
Universidad Michoacana de San Nicolás de Hidalgo: Luis Villaseñor, Umberto Cotti, Ibrahim Torres, Juan Carlos Arteaga Velazquez
Centro de Investigacion y de Estudios Avanzados: Arnulfo Zepeda
Universidad de Guanajuato: David Delepine, Gerardo Moreno, Edgar Casimiro Linares, Marco Reyes, Luis Ureña, Mauro Napsuciale, Victor Migenes
HAWC
300 - 7.2m x 4.3m Steel Tanks with 3 PMTs at 4100m asl in Mexico
HAWC Tank
HAWC Science Objectives

• Discover the **origin of cosmic rays** by measuring gamma-ray spectra to 100 TeV
  – Hadronic sources have unbroken spectra beyond 30-100 TeV
  – Galactic diffuse gamma rays probe the distant cosmic ray flux

• Understand **particle acceleration** in astrophysical jets with **wide field of view, high duty factor** observations.
  – Trigger Multi-Messenger/Multi-Wavelength Observations of Flaring Active Galactic Nuclei (including TeV orphan flares)
  – Detect Short and Long Gamma-Ray Bursts

• Explore **new physics** via HAWC’s **unbiased survey** of ½ the sky.
  – Increase understanding of TeV sources to search for new physics.
  – Study the local TeV cosmic rays and their anisotropy.
Fermi Bubbles

Two bubble structures extending to $b \pm 50^\circ$ appear above and below the GC

Spectrum of these lobes is significantly harder than the galactic diffuse emission - An example of something for HAWC to study
Gamma/Hadron Separation

Rejection factor $\sim e^{-\langle \mu \rangle}$

Energy Distribution at ground level
HAWC Gamma Hadron Separation
Milagro/Fermi/HAWC Comparison

• Taking into account the Fermi exposure and signal vs Milagro we find that for galactic sources Fermi is ~15x more sensitive than Milagro.

• HAWC at TeV will have approximately the same sensitivity as Fermi has at GeV for galactic sources.
Transients

![Graph showing transient events in terms of energy flux and time. The graph compares Fermi keV-MeV and HAWC TeV AGN flares over time scales ranging from seconds to years. The graph includes lines for different redshift values: $z=0$, $z=0.1$, $z=0.3$, and $z=0.5$. The Fermi and HAWC regions are marked with green and red shading, respectively.](image)
Fluence-fluence diagram for EGRET GRBs.

Short GRBs appear to have systematically larger high-energy LAT/GBM fluence ratios

Gamma-Ray Bursts

- Fermi observations indicate that:
  - No internal absorption of $\gamma$-rays < 70 GeV
  - Both long and short GRBs emit GeV $\gamma$-rays
  - GeV lightcurves show a few sec delayed onsets and >10 times longer durations than MeV lightcurves

- HAWC’s effective area at 100 GeV is 100 times Fermi’s

Fermi Observation of $z=4.35$ GRB with no high energy attenuation

Highest energy gamma-ray detected from GRB080916 was emitted at $(13 \text{ GeV})(z+1)=70$ GeV
Fermi observation of GRB090510 at z=0.9

- Bursts have energies up to at least ~100 GeV
- The brightest 4 bursts were emitted (i.e. corrected for the observed redshift) at energies of 70, 60, 94, and 61 GeV, GRBs 080916C, 090510, and 090902B, 090926.
GRB090510 with HAWC

- HAWC should see these signals even if they cut off at 100 GeV.
Pico de Orizaba and Sierra Negra
Existing Infrastructure - Mexico
Commercial Water Storage Solution
TeV Gamma-ray astronomy has opened another new window on the Universe and, as before, it’s full of exciting surprises!