Results from the First Year of the HAWC Gamma Ray Observatory

KICP Colloquium
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Talk Overview

- Intro
  - Gamma Ray Astronomy
  - Cosmic Rays
  - Ground based arrays and air showers
- HAWC
  - Design, Construction, Performance
- New Results
  - HAWC Survey and New Extended Sources
  - Transients - AGN, IceCube Event
  - Dark Matter Limits
  - Anisotropy
Complementarity of Gamma-Ray Detectors

- Space-based detectors - continuous full-sky coverage in GeV
- Ground-based detectors have TeV sensitivity
  - IACTs (pointed) excellent energy and angle resolution
  - HAWC has 24-hour >1/2 sky coverage
Imaging Atmospheric Cherenkov Telescopes

VERITAS (KICP) Arizona

HESS - Nambia

MAGIC - La Palma

CTA - Future
176 known TeV gamma-ray sources (as of May 2016)

galactic:
Supernova Remnants
Binary systems

extragalactic:
AGNs
GRBs (GeV)
What can you do with a wide-field instrument?

• Gamma Ray Astrophysics
  – Galactic Gamma-Ray Sources - Survey
    • Discovery of Pulsars, PWNs, Binaries - especially extended sources
    • Study of high energy behavior - source of galactic cosmic rays
    • Morphology of sources
    • Galactic Diffuse and Fermi Bubbles
  – Transients
    • Gamma Ray Bursts - high energy behavior
    • AGN - Continuous monitoring
    • IceCube, LIGO multimessenger observations

• Particle Physics
  – Dark Matter - can look for places with no visible signal
  – Primordial Black Holes
  – Violations of Lorentz Invariance
  – Look for sources of positron excess

• Cosmic Ray Anisotropy
High Energy View of our Galaxy

Fermi LAT 0.05 — 2 TeV, >6 years

HESS >1 TeV, 10 years

HAWC 1—100 TeV, 1 year

Credits: NASA/DOE/Fermi LAT Collaboration

Pulsar Wind Nebulae

Supernova Remnants

TeV Binaries

Mirabel, Science, 312, 1759
Cosmic Ray Discovery

- Physikalische Zeitschrift: “The results of these observations seem best explained by a radiation of great penetrating power entering our atmosphere from above.”

<table>
<thead>
<tr>
<th>Elevation</th>
<th>Rate</th>
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<tr>
<td>Ground</td>
<td>12</td>
</tr>
<tr>
<td>1 km</td>
<td>10</td>
</tr>
<tr>
<td>2 km</td>
<td>12</td>
</tr>
<tr>
<td>3.5 km</td>
<td>15</td>
</tr>
<tr>
<td>5 km</td>
<td>27</td>
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The flux of charged cosmic rays follows nearly a single power law over:

- 10 decades in energy
- 30 decades in flux

Single particles have been observed with energies above $10^{20}$ eV!

There are several “kinks” in the spectrum where the exponent changes, steepening at the “knee” and flattening at the “ankle”.

The source of the high-energy cosmic rays remains elusive.
More than 100 Years Later

- We know a lot about Cosmic Rays
  - We have found sources of high energy photons (gamma rays)
  - We have a number of ideas of how particles can be accelerated to high energies
- But we still don’t know the origin of the high energy Cosmic Rays!
  - Gamma-rays (and neutrinos) can point to the sources!
Candidate accelerators

Hillas Plot

\[ B = 2T \quad r = 1.5 \times 10^{11} \text{m} \]
\[ p = 10^{11} \text{ GeV/c} = 10^{20} \text{ eV/c} \]

Large radius

Large magnetic field

Kotera, K; Olinto AV. 2011

p = 0.3 \text{ Br}

p in Gev/c
B in Tesla
r in meters
Active Galactic Nuclei (AGN)
Hubble AGN M87

1.5 kpc (5 kly)
GRBs are now seen to produce gamma rays up to nearly 100 GeV
High-Energy Astrophysics Needs
Sensitivity > 10 TeV. PeVatrons.
Sensitivity to Extended Sources
Continuous Observation - Catch Flares > 100 GeV
Extensive Air Shower Development
Gamma Shower 2 TeV (movies by Miguel Morales)

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 gammas
Yellow - muons
Green - pions and kaons
Purple - protons and neutrons
Red - other, mostly nuclear fragments

Blue – Electrons   Muons – Yellow   Pions – Green   Nucleons – Purple
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

Blue - Electrons
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Pions – Green
Nucleons – Purple

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Milagro

- In the mountains above Los Alamos at 2650m
- In an existing pond
  - 60m x 80m x 8m
  - 175 outriggers
  - 20,000 m²
- Operated from 2000-2008
- 1st wide-field TeV Observatory
Milagro
Milagro
Milagro
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.
Milagro TeV Sources
• Measuring the spectrum from 30-100 TeV will tell if this a hadron accelerator
• High energy emission comes from a different spot than the lower energy

From E. Aliu - VERITAS

Cosmic Ray Anisotropy

Milagro + IceCube TeV Cosmic Ray Data (10° Smoothing)

Milagro 5 TeV

IceCube 20 TeV

significance [$\sigma$]

High Altitude Water Cherenkov
Gamma/Hadron Separation

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

Energy Distribution at ground level

Gammas

Protons

Size of HAWC

Size of Milagro deep layer
The HAWC Site

Latitude: 18°59.7′N  
Longitude: 97°18.6′W
5 years of HAWC operations will give similar sensitivity at 10 TeV as 1 TeV for ACTs
Fermi Observation of GRB 090510

![Diagram of Fermi Observatory and GRB 090510 Detection]

- GBM Nails (8-260 keV)
- GBM BGOs (0.2-10 MeV)
- LAT (All events)
- LAT (> 100 MeV)
- LAT (> 1 GeV)
Fermi Observation of GRB 090510 with

- Assume spectrum extends to 125 GeV and attenuation with EBL model of Gilmore
- HAWC: 200 events from GRB 090510 if near zenith
  - ~few background events
- Major Improvements!
  - Low-threshold DAQ
  - 10-inch PMTs
  → HAWC would observe 100s of events for spectrum to only 31 GeV
Milagro/Fermi/HAWC Comparison

• HAWC is \( \sim 15 \times \) more sensitive \((\text{sig/\sqrt{bg}})\) than Milagro
  • HAWC sees the Crab at \( \sim 6\sigma \) in a day - Milagro took 6 months to see 6\( \sigma \)
  • Taking into account the Fermi exposure and signal vs Milagro we find that for galactic sources Fermi is \( \sim 15 \times \) more sensitive than Milagro.
  • HAWC at TeV has approximately the same sensitivity as Fermi has at GeV for galactic sources.
HAWC Tanks

air shower

Che ligh

5 m
Tank Construction
Safe PMT Deployment and Recovery
Angle Reconstruction

Photons convert to $e^+e^-$ in the water.
HAWC-30: Engineering Test of full detector
HAWC-111: Operations Begins: August 2013 (283 days)
HAWC-250: November, 2014 (~150Days)
HAWC-300: March 2015 – Present : >95% uptime

HAWC Inauguration, HAWC-300: March, 2015
300th WCD tank constructed
~3,900 tanker truck trips
Construction Video
Gamma Hadron Separation (MC)

Monte Carlo Simulation

Gammas

Protons

Energy deposited away from core
HAWC-250 Data

Hadron Shower (off source)  

Likely Gamma Shower (Crab event)
Photon - Hadron Separation

- Hadronic event
  - Lateral distribution
- Gamma/hadron parameter
  - >75% of PMTs Hit
    - Surrounding Region
    - Crab Bin
- Gamma ray-like event
  - Lateral distribution

J Goodman — Particle Astrophysics — Univ. of Maryland
Spring 2016 50
Photon rich sample from the Crab

With Strong Photon Cut

1 in $10^4$ Events Kept
25% Efficiency for Photons
Shower Curvature

- shower front
- shower plane
- T₀
- 2Tₛ
- Tₖ
- detector plane
- hit
- core
- shower axis
Curvature Correction

On-Detector Events want a different curvature.
Gamma-Pure Sample: Before Curvature Correction Fix

$\sigma \sim 0.22$ deg

Gamma-Pure Sample: After Curvature Correction Fix

$\sigma \sim 0.13$ deg
Significant Improvement

$44\sigma$ (211d)

$80\sigma$ (211d)
Significant Improvement

3σ/√(day)

5.5σ √(day)
Angular Resolution

Bin 6-9 - 49-100% of PMTs Hit

$N$ Events/sr

$\Delta \theta^2$ [deg$^2$]

$10^5$

7

6

5

4

3

2

1

0

0.0

0.2

0.4

0.6

0.8

1.0

$<0.2^\circ$ PSF$_{68\%}$ at highest energy

68% Containment Angular Resolution

Angular Resolution [Deg]

$1.2$

$1.0$

$0.8$

$0.6$

$0.4$

$0.2$

$0.0$

1

2

3

4

5

6

7

8

9

Event Size - fHit Bin

J Goodman — Particle Astrophysics – Univ. of Maryland

Spring 2016
HAWC 341-Day TeV Sky Survey

- Skymap from 341 days of data taken with the finished HAWC array.
- Point source analysis assuming power-law index of 2.7.
HAWC 341-Day TeV Sky Survey

- Skymap from 341 days of data taken with the finished HAWC array.
- Point source analysis assuming power-law index of 2.7.
Milagro is located near Los Alamos, New Mexico different declination along Galactic plane. HAWC is ~15x more sensitivity with lower energy threshold, and more sensitive towards Galactic center.
Point Sources

Figure 3: Markarian 421, Markarian 501, Crab.
HAWC view of the Galactic Plane

- ~40 sources seen in first year
- 25% are new

Association unclear
Supernova remnant with very energetic pulsar
Pulsar ~8kpc (26,000 ly) away
New TeV Sources!

New TeV emission region
2HWC J1927+187*
- ~7σ pre-trials
- current blind search algorithm identify this region associated with 2HWC J1930+188, ongoing analysis on spatial morphology

2HWC J1930+188
- coincident w/ VER J1930+188 (SNR G54.1+00.3 - PSR J1930+1852)
- TeV emission was reported to be point-like and likely from PWN
- nearby molecular CO cloud

New TeV source
2HWC J1928+178
- ~8σ pre-trials
- coincident with PSR J1928+1746
- tail towards unidentified source 3FGL J1925.4+1727
- VERITAS point source upper limit ~1.4% of Crab

Cygnus Region

2HWC J2019+368 is coincident with MGRO J2019+37 and VER J2019+368
• extended emission including PSR J2021+3651 and HII region Sh 2-104

New TeV source 2HWCJ2006+340:
• >6σ pre-trials
• 0.6° from unidentified source 3FGL J2004.4+3338

0.6-1 TeV
>1 TeV

24.0m 22.0m 20h20.0m 18.0m 16.0m 14.0m
+37.5° +37.0° +36.5° +36.0°
Cygnus Region

MGRO J2031+41 is resolved into two distinct TeV sources:

- 2HWC J2031+415 — TeV J2032+4130, a PWN
- 2HWC J2020+403 — VER J2019+407, UID encompassing SNR G78.2+2.1 and PSR J2021+4026
- extended emission region 2HWC J2025+410* and 2HWC J2027+403* at Fermi cocoon
Crab Nebula at highest energies

- photons up to 80 TeV reported by IACTs
- insight into magnetic field environment and efficiency of particle acceleration

Aleksic et al. JHEA (2015)

- Direction consistent with Crab Nebula.
- Signal to noise in this bin is 7.
Pulsar Wind Nebulae - Geminga

- Closest known middle aged pulsar
- Possible nearby cosmic ray acceleration site — explanation for positron excess (Yuksel et al. 2009)
- Not seen by IACTs, extent maybe larger than IACT FOV.
- Ongoing morphological and spectral studies
Figure 4: Region around Geminga. Left: TS map for a point source hypothesis with a spectral index of -2.7. Right: TS map for an extended source hypothesis represented by a disk of radius 2.0 degrees with a spectral index of -2.0.
Propagation of Positrons out of their Sources

• Knowing details of the pulsar not the same as knowing input to the interstellar medium (ISM)

• Does the nebula...
  – …pass all positrons to ISM?
  – …modify the spectrum?
  – …absorb all positrons?

• Need to model propagation through nebula to determine input to ISM
Geminga

- Old pulsars with high velocity may escape their remnant.
- If remnants absorb positrons, perhaps pulsars like Geminga are the only PWNe supplying positrons to ISM.
Transient Search - The Crab Nebula

- Crab flares, continue up to TeV?
- No activity in radio, IR, and X-rays.
- HAWC Pass 4 data from Nov 26 2014 to Dec 9 2015.
- >80σ in 315 transits.
- Lightcurve binned in sidereal day.
- Consistent with constant flux.

![Lightcurve plot](image)

Credit: NASA/DOE/Fermi LAT/R. Buehler
Transient Search - Mrk 421 / Mrk 501

\[ \frac{dF}{dE} = F_0 \left( \frac{E}{E_0} \right)^{-\gamma} e^{-E/E_0}, \gamma = 2.40, E_0 = 6.0 \text{ TeV} \]

PRELIMINARY
Pass 4

Mrk 421
- constant flux best fit
- 7-transit running average
- 1-transit

Mrk 501
- constant flux best fit
- 7-transit running average
- 1-transit

Integrated flux \( \geq 1.0 \text{ TeV} \) [Crab Units]
Astronomer’s Telegram to immediately alert community of activity.

Monitoring all gamma-ray sources visible to HAWC every day.
Multi-wavelength / Multi-messenger

- We have follow-up agreements with:
  - Swift
  - Fermi-LAT
  - IACTs
    - FACT
    - HESS
    - MAGIC
    - VERITAS
  - AMON
  - IceCube
  - ANTARES
  - LIGO/VIRGO

HAWC-triggered:
- New source candidates lists.
- Follow-up observations by IACTs such as VERITAS and MAGIC from Pass 1 release.
- Flares from known gamma-ray sources.

Externally triggered:
- IceCube alert on high confidence neutrino event (highest energy pointed astrophysical track-like).
- Fermi alerts on flaring activities.
- LIGO/VIRGO gravitation wave event follow-up
IceCube >2.6 PeV Muon Neutrino

- HAWC-111 live. Several hours out of HAWC’s FOV.
- Searches:
  - Integrated dataset (Steady, Aug 2013-May 2015 dataset)
  - Next Day / Prior Day
  - ±2 and ±5 days around the event.
- All searches consistent with cosmic-ray background.
Title: GCN Circular Number: 19423
Subject: GRB 160509A: non-observation of VHE emission with HAWC
Date: 16/05/11 17:27:37 GMT
HAWC: Dark Matter

- HAWC has sensitivity to indirect detection of TeV WIMPs in:
  - Satellite galaxies, the Galactic Center, and galaxy clusters
- Cosmological simulations predict more satellite galaxies than observed
  - Higher M/L galaxies have been found by Sloan Deep Survey
  - HAWC will observe all M/L galaxies in half the sky, even if $L=0$
AMS Results

Figure 2. Measured proton flux as a function of rigidity.
From AMS

- The AMS results on the positron fraction, the electron spectrum, the positron spectrum, and the combined electron plus positron spectrum are consistent with dark matter collisions and cannot be explained by existing models of the collision of ordinary cosmic rays.

- There are many new models showing that the results may be explained by new astrophysical sources (such as pulsars) or new acceleration and propagation mechanisms (such as supernova remnants).
HAWC Data - no gamma ray cut
Anisotropy

Fit dipole+quadrupole+octupole to map for 24-hr background estimation
Subtracted fit relative intensity from 24-hr map

Regions A, B and C are the only statistically significant excesses (>5σ post-trials)
IceCube/HAWC
Small-scale Anisotropy

PRELIMINARY

Relative intensity \(10^{-4}\)

HAWC250: bins 3-5
IC86: bins 0-2

HAWC250: Direct Int \(\Delta t = 4\) hr
IC86: \(\Delta t = 24\), \(\mu l \leq 3\) subtracted
Outriggers

- HAWC Sparse Outrigger Array: Enhanced Sensitivity above 10 TeV
  - Accurately determine core position for showers off the main tank array.
- Increase effective area above 10 TeV by 3-4x
- Funded by LANL/Mexico.
- 2500 liter tanks: 1/80th size of HAWC tanks.
Storm on the 13-14 January
Outlook

• The HAWC observatory began full-scale operation in March 2015.
• It is now providing a nearly continuous view of the transient TeV sky.
• Catalog of first year full operation is in prep (2HWC), with new TeV sources!
• Diverse science results, stay tuned!
• Upgrade to expand the array to enhance effective area >10 TeV by 3-4x is currently under installation.
Summary

HAWC is now operational
It is giving a new wide-field view of the TeV sky
It is synergistic with other instruments:
  MOUs with VERITAS, IceCube, MAGIC, HESS, Fermi
It is now providing a nearly continuous view of the transient TeV sky
Large-scale structures e.g. Fermi Bubbles

- Large scale, non-uniform structures extending above and below the Galactic center.
- Edges line up with X-ray features.
- Correlate with microwave excess (WMAP haze)
- Both hadronic and leptonic model fit Fermi LAT data.
  Leptonic model can explain both gamma ray and microwave excess.
- First limits in TeV, hard spectrum is highly unlikely.
Diffuse Emission

Fermi Bubbles

No Cut-off

150 GeV Cut-off
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H. Ayala (E13: DM, Indirect, Gamma-rays, Apr 16)