The HAWC (High Altitude Water Cherenkov) Gamma-Ray Observatory

Wayne Springer
University of Utah

- The HAWC Gamma Ray Observatory
- Detector Description
- Science Goals
- Status and Schedule

- Overview of Gamma-Ray Astronomy
- Properties of Gamma Rays
- Astrophysical Sources of $\gamma$-Rays
- Gamma Ray Observatories
They are Photons....
Energy > ~124 keV.

\[ \lambda < \frac{hc}{E} = \frac{1240 eV \cdot nm}{124,000 eV} = 0.01 \text{nm} = 10 \text{pm} = 10^{-11} \text{m} \]

\[ \nu > \frac{c}{\lambda} = \frac{3 \times 10^8 \text{ m} / \text{s}}{10^{-11} \text{ m}} = 3 \times 10^{19} \text{ Hz} \]

Penetrates Earth's Atmosphere?

Radiation Type
Wavelength (m)

- Radio: $10^3$
- Microwave: $10^{-2}$
- Infrared: $10^{-5}$
- Visible: $0.5 \times 10^{-6}$
- Ultraviolet: $10^{-8}$
- X-ray: $10^{-10}$
- Gamma ray: $10^{-12}$

Approximate Scale of Wavelength

- Buildings
- Humans
- Butterflies
- Needle Point Protozoans
- Molecules
- Atoms
- Atomic Nuclei

Frequency (Hz)

- $10^4$
- $10^8$
- $10^{12}$
- $10^{15}$
- $10^{16}$
- $10^{18}$
- $10^{20}$

Temperature of objects at which this radiation is the most intense wavelength emitted

- $1 \text{K} = -272 \degree \text{C}$
- $100 \text{K} = -173 \degree \text{C}$
- $10,000 \text{K} = 9,727 \degree \text{C}$
- $10,000,000 \text{K} = -10,000,000 \degree \text{C}$

http://mynasadata.larc.nasa.gov/images/EM_Spectrum3-new.jpg
Photons are the mediators of the Electromagnetic Force

“Substantial” coupling to matter

Good

Bad

Easy to Detect

Propagation range limited
Gamma Ray Production Mechanisms

- Radioactive Decay
- Electron-Positron Annihilation
- Neutral Pion Production and Decay
- Electron Brehmsstrahlung
- Synchrotron Radiation
- Inverse Compton Scattering
Radioactive Decay

$^{60}_{27}$Co

5.272 a

$^{60}_{28}$Ni

Energy Range only to a Few MeV

0.31 MeV $\beta^-$ 99.88%

1.1732 MeV $\gamma$

1.3325 MeV $\gamma$

0.12% 1.48 MeV $\beta^-$
Mass $e^-, e^+ = 0.511$ MeV

Energy of gamma rays depends upon electron positron energy
Pion Production and Decay

\[ p + p \rightarrow \pi^0 + \pi^+ + X \]

\[ \pi^0 \rightarrow \gamma + \gamma \]

>98.7% of time
Mass \( \pi^0 = 134.976 \text{ MeV} \)

Energy of gamma rays depends upon proton energy

Bubble Chamber Image
LBL photo library
Energy of gamma rays depends upon electron positron energy and medium.
Synchrotron Radiation Spectrum

Energy of gamma rays depends upon electron positron energy and magnetic field

J.D. Jackson, Classical Electrodynamics 3rd Edition

Carroll & Ostlie Introduction to Astrophysics
Inverse Compton Scattering

\[ e^- (E_{e,0}) + \gamma (E_{\gamma,0}) \rightarrow e^- (E'_{e}) + \gamma (E'_{\gamma}) \]

Energy of gamma rays depends upon electron energy
1. Photons produced by synchrotron emission
2. Inverse Compton scatter with high-energy electrons

High Energy Gamma Rays
With basic particle physics and theory of accretion disks, and plasmas and magnetohydrodynamics and shocks one should 
easily calculate the spectrum of gamma rays from any given source.
Can’t get away from this plot!!

Gamma ray spectra related

Cosmic ray flux several orders of magnitude greater than gamma ray flux for all energies…

background to gamma ray measurements
What are Gamma Rays Interaction with Matter

Interaction processes

- $\sigma_{\text{p.e.}}$: Atomic Photo effect
- $\sigma_{\text{Coherent}}$: Rayleigh Scattering
- $\sigma_{\text{Incoh}}$: Compton Scattering
- $\kappa_N$: Pair production, nuclear field
- $\kappa_e$: Pair production, electron field
- $\sigma_{\text{nuc}}$: Photonuclear absorption

Large Cross Sections!!!

Measured in units of Barns…

1 Barn = $10^{-28} m^2 = 10^{-24} cm^2$

Easily Detected!!!
Comparison to Neutrino Cross Sections

at E=1 Gev \[ \frac{\sigma_{\text{Tot}}(\gamma,^{12}\text{C})}{\sigma_{\text{Tot}}(\nu,N)} \approx 10^{14} \] Difficult to Detect Highly Penetrating
What are Gamma Rays?

Interaction with Earth’s Atmosphere

- Direct Detection of Gamma Rays require a satellite based observatory
- Gamma Rays do not penetrate through the atmosphere, but...
- Gamma rays of sufficient energy produce “Extensive Air Showers” ...
- EAS secondary particles and Cerenkov light do reach the ground
Fortuitous that atmosphere is transparent in visible and radio wavelengths
What are Gamma Rays Interaction with Matter

Figure 27.20: An EGS4 simulation of a 30 GeV electron-induced cascade in iron. The histogram shows fractional energy deposition per radiation length, and the curve is a gamma-function fit to the distribution. Circles indicate the number of electrons with total energy greater than 1.5 MeV crossing planes at \(X_\sigma/2\) intervals (scale on right) and the squares the number of photons with \(E \geq 1.5\) MeV crossing the planes (scaled down to have same area as the electron distribution).

The mean longitudinal profile of the energy deposition in an electromagnetic cascade is reasonably well described by a gamma distribution [57]:

\[
\frac{dE}{dt} = E_0 b \frac{(lt)^{\alpha-1} e^{-lt}}{\Gamma(\alpha)}
\]  

(27.34)
Cerenkov Radiation

- Radiation emitted by charged particles that exceed the speed of light c/n in a medium

- Similar to Sonic Boom

\[
\cos \theta = \frac{1}{n\beta}. 
\]
Gamma Ray “Window”

- Electromagnetic shower radiation length = 37.1 g cm$^{-2}$
- Thickness of Atmosphere is 1023 g cm$^{-2}$
- 28 radiation lengths = 1m thickness of lead
- Observation of secondary particles with ground based detectors
  - Directly using ground arrays
  - Indirectly via Cerenkov radiation

http://www.dur.ac.uk/~dph0www4/ground.php
Extensive Gamma-Ray Air Showers

Development of gamma-ray air showers

- Primary particle (gamma ray)
- First interaction with nucleus in air (pair production)
- Bremsstrahlung on nucleus in air
- Pair production
- Bremsstrahlung

http://www.mpi-hd.mpg.de/hfm/CosmicRay/Showers.html
Electromagnetic component of an Air Shower

Mean energy per particle

\[ E_0 \] \quad \gamma \quad e^+ \quad e^- \quad \lambda \quad \frac{1}{2}\lambda

\[ E_0/2 \] \quad \gamma \quad e^+ \quad e^- \quad \lambda

\[ E_0/4 \] \quad \gamma \quad e^+ \quad e^- \quad \lambda

\[ E_0/8 \] \quad e^+ \quad e^- \quad \gamma \quad e^- \quad \gamma \quad e^+ \quad e^- \quad \lambda

\[ E_0/16 \] \quad \gamma \quad e^+ \quad e^- \quad \gamma \quad e^- \quad \gamma \quad e^+ \quad e^- \quad \lambda

Electromagnetic
\[ N_{em}(x) = 2^n = 2^{x/\lambda} \]
\[ N(x_{\text{max}}) = N_{\text{max}} = E_0/E_c \]
\[ x_{\text{max}} = \lambda \cdot \ln(E_0/E_c) \]

- EM component well/easily described...
- \sim 90\% of energy in EM component
- Detector samples shower at a certain age, \( s \) and distance \( r \) from shower core.

Longitudinal EM Shower Development
\[ N_e(x) = N_{\text{max}} \left( \frac{x - x_0}{x_{\text{max}} - x_0} \right)^{(x_{\text{max}} - x_0)/\lambda} \exp \left( \frac{x_{\text{max}} - x}{\lambda} \right) \]

Lateral EM Shower Distribution
\[ \rho_e = \frac{\Gamma(4.5 - s)}{\Gamma(s) \Gamma(4.5 - s)} \left( \frac{n_e}{2\pi r_M^2} \right) \left( \frac{r}{r_M} \right)^{s-2} \left( 1 + \frac{r}{r_M} \right)^{(s-4.5)} \]

\[ s = \frac{x}{x + 2x_{\text{max}}} \]
Development of a 2TeV Gamma Ray Shower from first interaction to the Milagro Detector

Viewed from below the shower front - Color coded by Energy

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 displayed at the bottom of the screen.

Color coded by Kinetic Energy. The log base 2 of the kinetic energy is converted linearly to a color with red corresponding to 2TeV and blue 10MeV.
One person’s Signal….is another person’s background!!!

Hadronic showers are “clumpier”

http://www.mpi-hd.mpg.de/hfm/CosmicRay/Showers.html
Overview of Gamma Ray Astronomy

- **Astronomy in General**
  - Photons point back to sources
  - “Ordinary” astronomy observes thermal universe
  - Relativistic processes produce non-thermal spectra

- **Gamma Ray Detectors**
  - Gamma Rays are “easy” to detect
  - “Simple” detectors
  - Earth’s Atmosphere Opaque to Gamma Rays…except

- **Gamma Ray Sources**
  - “Compact” Sources:
    - Pulsars
    - AGN
    - GRB
  - Diffuse Background
    - Dark-Matter Annihilation?
    - Associated with Cosmic-Ray acceleration and propagation

- **Gamma Ray Propagation**
  - How far can you see in gamma rays?
  - Extra-Galactic background Light
What is Astronomy?

**Ordinary Astronomy**

Photons point back to sources

**Extraordinary Astronomy**

Artist's view of an Active Galactic Nucleus, such as PKS 2155-304

Thermal processes in the Universe

non-thermal spectra from relativistic processes in the Universe
What is Astronomy?

Optical Astronomy
Galilean/Newtonian Telescope
- Larger Aperture
- Smaller Detectors
- Small field of view
- TMT ~0.33 degree

Gamma Ray Astronomy
“Particle Physics Detectors”
- Aperture = Detector Area (IACT larger)
- Wide field of view ~2 pi
- ~120 degree
- Imaging done by timing….
What can be studied with Gamma Rays?

- The physics of compact objects and their relativistic outflows.
- The origin and propagation of Galactic cosmic rays.
- Dark matter
- Extra-Galactic background light
- Fundamental physics, such as testing the quantum structure of space-time.
Astrophysical Sources of Gamma Rays

- Active Galactic Nuclei (TeV)
- Gamma Ray Bursts (short,long) (TeV)
- Pulsar Wind Nebula (TeV)
- Starburst Galaxies (TeV)
- Supernova Remnants (TeV)
- Pulsars
- Solar Flares....
- Diffuse emission
  - Dark matter annihilation
  - Sources of UHECR acceleration
Active Galactic Nuclei

Unified AGN model: Carroll & Ostlie Introduction to Astrophysics
Gamma Ray Bursts

 Gamma-Ray Bursts (GRBs): The Long and Short of It

**Long gamma-ray burst**
- (>2 seconds' duration)
- A red-giant star collapses onto its core...
- Becoming so dense that it expels its outer layers in a supernova explosion.

**Short gamma-ray burst**
- (<2 seconds' duration)
- Stars* in a compact binary system begin to spiral inward...
- Eventually colliding.
- The resulting torus has at its center a powerful black hole.

*Possibly neutron stars.
Gamma Ray Bursts (short duration)

Crashing neutron stars can make gamma-ray burst jets

Simulation begins

7.4 milliseconds

13.8 milliseconds

15.3 milliseconds

23.2 milliseconds

26.5 milliseconds

Credit: NASA/AEI/ZIB/M. Koppitz and L. Rezzolla
Gamma Ray Bursts (short duration)
Gamma Ray Bursts (long duration)

- Peculiar supernova explosions of massive stars.
- Generated by a central engine that is likely to be a newborn black hole at the heart of the dying star.
- Supernovae are all of spectral type Ibc.
- Core-collapse supernovae.

http://cerncourier.com/cws/article/cern/41720
Pulsar Wind Nebula

Crab pulsar wind nebula
http://apod.nasa.gov/apod/ap081227.html

Model of the Crab pulsar wind nebula
http://www.nature.com/nature/journal/vaop/current/full/nature10793.html

SED for the pulsar wind nebula of PSR J1718–3825.
http://dx.doi.org/10.1051/0004-6361:20078775
The Cigar Galaxy (M82) is located 12 million light years from Earth, in the direction of the Ursa Major constellation. It has an active starburst region in its center. Image courtesy of NASA, ESA, and the Hubble Heritage Team (STScI/AURA).

VERITAS Observation of M82
http://arxiv.org/abs/0912.3807
This composite shows the Cassiopeia A supernova remnant across the spectrum: Gamma rays (magenta) from NASA's Fermi Gamma-ray Space Telescope; X-rays (blue, green) from NASA's Chandra X-ray Observatory; visible light (yellow) from the Hubble Space Telescope; infrared (red) from NASA's Spitzer Space Telescope; and radio (orange) from the Very Large Array near Socorro, N.M. Credit: NASA/DOE/Fermi LAT Collaboration, CXC/SAO/JPL-Caltech/Steward/O. Krause et al., and NRAO/AUI

Astrophysical Sources of Gamma Rays
Pulsars
Astrophysical Sources of Gamma Rays
also source of UHECR?

High energy gamma ray counterparts of astrophysical sources of ultra-high energy cosmic rays

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Abstract

If ultra-high energy cosmic rays (UHECRs) are accelerated at astrophysical point sources, the identification of such sources can be achieved if there is some kind of radiation at observable wavelengths that may be associated with the acceleration and/or propagation processes. No radiation of this type has so far been detected or at least no such connection has been claimed. The process of photopion production during the propagation of UHECRs from the sources to the Earth results in the generation of charged and neutral pions. The neutral (charged) pions in turn decay to gamma quanta and electrons that initiate an electromagnetic cascade in the universal photon background. We calculate the flux of this gamma radiation in the GeV-TeV energy range and find that for source luminosities compatible with those expected from small scale anisotropies in the directions of arrival of UHECRs, the fluxes can be detectable by future Cerenkov gamma ray telescopes, such as VERITAS and HESS, provided the intergalactic magnetic field is not larger than $\sim 10^{-10}$ Gauss and for source distances comparable with the loss length for photopion production.
Ultra-high Energy Cosmic Rays from Gamma Ray Bursts?

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"Searching for the Origins of Cosmic Rays"
Trondheim, Norway, June 15-18, 2009
Propagation of Gamma Rays
Gamma ray attenuation due to Extragalactic Background Light (EBL)

\[ \gamma_{HE} + \gamma_{EBL} \rightarrow e^- + e^+ \]
Fig. 1.— Attenuation as a function of observed gamma-ray energy for the EBL models of (Franceschini et al. 2008) and (Stecker et al. 2006). These models predict the minimum and maximum absorption of all models in the literature, and thus illustrate the range of optical depths predicted in the Fermi-LAT energy range.
Fig. 3.— Highest-energy photons from blazars and GRBs from different redshifts. Predictions of $\gamma\gamma$ optical depth $\tau_{\gamma\gamma} = 1$ (top panel) and $\tau_{\gamma\gamma} = 3$ (bottom panel) from various EBL models are indicated by lines. Photons above model predictions in this figure traverse an EBL medium with a high $\gamma$-ray opacity. The likelihood of detecting such photon considering the spectral characteristics of the source are considered in the method presented in section 3.2.1.

http://arxiv.org/abs/1005.0996v2
Gamma-Ray Observatories
A Comparison of Techniques

Satellite Based “HEP” detector

Complementary ways to observe Gamma Rays:
• Directly
• Through Extensive Air Shower
  • Via Cherenkov light produced in atmosphere
  • Via charged particles that hit surface

Imaging Atmospheric Cherenkov Technique

10 TeV Photon Air Shower
F. Schmidt, "CORSIKA Shower Images",
http://www.ast.leeds.ac.uk/~fs/showerimages.html

Surface Detector Array
Gamma-Ray Observatories
A Comparison of Techniques

Satellite Based “HEP” detector
- Small Area
- Wide Field of View
- “Background free”
- High Duty Cycle
- High Resolution
- Low Sensitivity to highest energies

- Unique Potential at <200 GeV
- Extragalactic Sources
- Dark Matter

Imaging Atmospheric Cherenkov Technique
- Large Effective Area
- Narrow Field of View
- Excellent Background rejection
- Low Duty Cycle
- High Resolution
- Sensitivity to intermediate energies

- Morphology of TeV Emission sources (SNR, PWN)
- High Resolution Energy Spectra to 20 TeV
- Studies of known sources
- Surveys of limited regions of sky

Surface Detector Array
- Moderate Area
- Wide Field of View
- “Good/Excellent” rejection
- High Duty Cycle
- Good/Excellent resolution
- Best Sensitivity at Highest Energies

- Unbiased Sky Survey
- Extended Sources and cosmic ray PeVatrons
- Energies up to about 100 TeV
EXPLORER XI EXPERIMENT ON COSMIC GAMMA RAYS*

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Received November 23, 1964

ABSTRACT

A search for cosmic gamma rays in the energy range 100 MeV and greater with the satellite Explorer XI has given an apparent average intensity of about $3 \times 10^{-4}$ cm$^{-2}$ sec$^{-1}$ sterad$^{-1}$. Internal evidence favors the identification of the particles which give rise to this intensity as cosmic gamma rays, but because a celestial anisotropy is not evident the measurement must be regarded as an upper limit on the true intensity. The apparent intensity is 10 to 20 times as large as predicted for $\pi^0$-decay gamma rays from cosmic-ray collisions with interstellar hydrogen, but can be accounted for if one assumes a modest intensity of high-energy electrons in intergalactic space.
Explorer XI Gamma Ray Detector
Fig. 3.—Detection efficiency in the forward direction
### Flux Upper Limits of Explorer XI

#### TABLE 2

**Data and Approximate Gamma-Ray Flux Upper Limits for a Number of Possible Discrete Sources**

<table>
<thead>
<tr>
<th>Source</th>
<th>Detected Events</th>
<th>Random Events</th>
<th>Flux Upper Limit</th>
</tr>
</thead>
<tbody>
<tr>
<td>Andromeda</td>
<td>0</td>
<td>17</td>
<td>$16 \times 10^{-4}\text{cm}^{-2}\text{sec}^{-1}$</td>
</tr>
<tr>
<td>Small Magellanic Cloud</td>
<td>0</td>
<td>25</td>
<td>11</td>
</tr>
<tr>
<td>Large Magellanic Cloud</td>
<td>0</td>
<td>29</td>
<td>9.4</td>
</tr>
<tr>
<td>Taurus A</td>
<td>2</td>
<td>123</td>
<td>6.6</td>
</tr>
<tr>
<td>Hydra A</td>
<td>0</td>
<td>155</td>
<td>1.7</td>
</tr>
<tr>
<td>Virgo A</td>
<td>1</td>
<td>199</td>
<td>2.7</td>
</tr>
<tr>
<td>Centaurus A</td>
<td>0</td>
<td>90</td>
<td>3</td>
</tr>
<tr>
<td>Hercules A</td>
<td>1</td>
<td>156</td>
<td>3.4</td>
</tr>
<tr>
<td>Cygnus A</td>
<td>1</td>
<td>107</td>
<td>5</td>
</tr>
<tr>
<td>Cassiopeia A</td>
<td>1</td>
<td>23</td>
<td>23</td>
</tr>
<tr>
<td>Galactic center</td>
<td>2</td>
<td>154</td>
<td>5.3</td>
</tr>
</tbody>
</table>
Space-based Gamma Ray “Observatories”
Early history

http://astronomy.nmsu.edu/tharriso/ast536/ast536week11.html
Declassified results from VELA published in 1973...

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Observations of Gamma-Ray Bursts of Cosmic Origin

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Received 1973 March 16; revised 1973 April 2

Abstract

Sixteen short bursts of photons in the energy range 0.2–1.5 MeV have been observed between 1969 July and 1972 July using widely separated spacecraft. Burst durations ranged from less than 0.1 s to ∼30 s, and time-integrated flux densities from ∼10⁻⁵ ergs cm⁻² s⁻¹ to ∼2 × 10⁻⁴ ergs cm⁻² s⁻¹ in the energy range given. Significant time structure within bursts was observed. Directional information eliminates the Earth and Sun as sources.
FIG. 1.—Count rate as a function of time for the gamma-ray burst of 1970 August 22 as recorded at three Vela spacecraft. Arrows indicate some of the common structure. Background count rates immediately preceding the burst are also shown. Vela 5A count rates have been reduced by 100 counts per second (a major fraction of the background) to emphasize structure.
Space-based Gamma Ray Observatories

GRO

Fig. 2. Schematic view of the Gamma Ray Observatory
Fig. 3. Schematic arrangement of the EGRET instrument.

<table>
<thead>
<tr>
<th>TABLE 1</th>
</tr>
</thead>
<tbody>
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<td>EGRET physical characteristics</td>
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<table>
<thead>
<tr>
<th>Item</th>
<th>Value</th>
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<tbody>
<tr>
<td>Mass:</td>
<td>1830 kg</td>
</tr>
<tr>
<td>Length/Diameter:</td>
<td>2.25 m/1.65 m</td>
</tr>
<tr>
<td>Power (incl. heater):</td>
<td>190 W</td>
</tr>
<tr>
<td>Data:</td>
<td>6859 bits s(^{-1})</td>
</tr>
</tbody>
</table>
Gamma-Ray Observatories
GLAST/Fermi
The Gamma Ray Sky as seen by Fermi
Solar Flare on March 7, 2012

March 6, 2012

March 7, 2012

Vela Pulsar

Galactic Plane

The Sun
“Fermi Bubbles” on Milky Way Galaxy…

Fermi data reveals giant gamma-ray bubbles

Credit: NASA/DOE/Fermi LAT/D. Finkbeiner
Artist Rendering of “Fermi Bubbles” on Milky Way Galaxy...
The Gamma Ray Sky as seen by Fermi
Gamma-Ray Observatories
VERITAS

VERITAS Snapshot:
- Array of four atmospheric Cherenkov telescopes
- Telescope design is based on Whipple 10m Telescope
- 350 individual mirrors on each telescope reflector
- Each telescope aperture: 12m
- 499 pixel camera on each telescope
- Field of view of 3.5 degrees
- Energy range of 50 GeV to 50 TeV

VERITAS Science Topics:
- black holes at the centres of active galaxies
- pulsars
- X-ray binaries
- gamma-ray bursts
- supernova remnants
- globular clusters
- galaxies including our own Milky Way Galaxy.
- Galaxy clusters
- Dark Matter
- Astroparticle physics
- Unidentified sources

http://veritas.sao.arizona.edu/about-veritas-mainmenu-81
Gamma-Ray Observatories
Milagro

- Water Cerenkov Detector
- Located at 2300 m altitude
- 8 meter deep pool
- 723 Photomultipliers in 2 layers
- Array of outrigger detectors

- Proved capability of gamma/hadron separation in WCD
And growing...
Sensitivity v Energy for Gamma Ray Observatories

IACT, Ground and space-based gamma-ray observatories

Complementary

Point Source Sensitivity vs Energy

- 10 event (5 $\sigma$) flux limit
- 50 hours on source for IACT
- HAWC 10-15 times more sensitive than Milagro

HAWC sensitivity for 1 year (dotted black line) and 5 year (solid black line) observations of a point source with a Crab-like spectrum. The sensitivities of current generation IACT instruments (MAGIC, HESS, VERITAS) are plotted in blue.
HAWC Science Goals

- **Particle Acceleration in Astrophysical Jets**
  - Act as a trigger for multi-wavelength observing campaigns
  - Observing GRBs (using scalers with 30 GeV threshold)

- **The Origin of Galactic Cosmic Rays**
  - Measure Gamma Ray Spectra to 100 TeV
    - Harder spectra require hadronic component because inverse Compton of electrons has expected cut-off at 10-30 TeV
  - Map the multi-TeV diffuse gamma-ray emission
    - Strong emission regions correlated with matter in the Galaxy
    - Extended SuperNova Remnants, Pulsar Wind Nebucae
  - Measure Cosmic Ray (hadronic) anisotropies at energies > 10 TeV
    - Pointing to local sources of cosmic rays?

- **New Physics and Exotic Phenomema**
  - Understanding the astrophysical background for Dark Matter searches requires understanding sources of “backgrounds”
  - Study spectra of distant AGN (lower attenuation at high energies --> Axion-like particles)
  - Search for signals consistent with Heavy Dark Matter, Highly Ionizing Slow particles,..
  - Study of energy dependent delays from GRBs --> hint of Violation of Lorentz Invariance

- **Solar Physics,....**
HAWC Science Tasks

- Perform an unbiased sky survey over $2\pi$ sr.
  Source detection threshold will be 50 mCrab in a single year.

- Search for extended sources of TeV gamma rays
  Significantly better sensitivity that the current generation of IACTs for low surface brightness extended sources.

- Measure the spectra of TeV sources
  Measure to the highest possible energies – above that accessible to FERMI or IACTs.

- Search for transient sources
  (AGN flares and GRBs) that require long observations to catch rare episodic phenomena.
One of the primary goals of HAWC is to perform a complete, unbiased TeV survey of the gamma-ray of the sky. An all-sky, high-duty cycle instrument such as HAWC, is the only instrument suited to perform such a survey.

- HAWC has wide FOV and ~100% duty cycle
- Sky survey (20 mCrab in 5 years)
- 6 $\sigma$ on the Crab in 1 transit (Milagro 120 days)
- 64% of Sky Access,
- 40% overlap with HESS galactic plane
- 90% overlap with ICE-CUBE sky
- Spatial/Temporal overlap VERITAS
- Galactic Center at 48$^0$ from zenith, about 10% of Crab

$$\Omega_{\text{sur}} = 4\pi \cos(\text{lat}) \sin(\theta) \approx 4\pi(2/3)$$

HAWC 1 year survey sensitivity vs source declination. 44% of 4$\pi$ sr will be surveyed with a 5$\sigma$ sensitivity of 50 mCrab in one year.
HAWC provides a substantial increase in flux sensitivity at energies above 3-10 TeV.

The increased sensitivity is due directly to the continuous operation of the observatory.

This gives a substantially larger number of hours of source observation per year (~1200) compared to a typical IACT observation (20-50 hours/year).
Extended TeV Sources

Gamma rays are produced when higher energy particles interact with matter or radiation fields. Because these particles can escape from the acceleration region, many sources of very-high-energy gamma rays are extended. HESS has observed that most Galactic sources are extended.

When source size larger than angular resolution sensitivity depends on source size

Longer exposures of HAWC give increased sensitivity over IACTs to diffuse sources with low-surface brightness.

Figure 2 – Comparison of $\gamma$-ray sensitivity between the IACT and HAWC 2 year sky surveys as a function of source angular diameter. The HESS detected Galactic sources are shown as well as the Milagro source in the Cygnus region.
Galactic Plane Sources

Regions in the Milagro data around FERMI/LAT sources in Galactic Plane

• Milagro Showed that most Bright GeV galactic sources extend into the TeV range

• HAWC PSF resolution will be better than Milagro

• HAWC will be 15x more sensitive than Milagro
Extended Sources: Geminga

Most Significant source in Fermi BSL
• Old (342 kyr) nearby (169 pc) pulsar
• 3.5σ at the location of Geminga (assuming point source)
• 6.3σ when assuming 1° extended source
• Fitted FWHM of the emission region ≈2.6° corresponding to ≈10 pc.
• HAWC will be able to observe pulsar winds with at least x15 sensitivity.
• Better PSF of HAWC will also help
Transient Sources

- Flaring AGN
- GRBs
- X-ray binary systems and micro-quasars
- new classes of objects

Simultaneous multi-wavelength campaign of 1959+650 involving both HEGRA and Whipple TeV observations as well as x-ray observations showed flares correlated with x-rays as well as an orphan flare. The 5 sigma HAWC sensitivity will be ~1 Crab for one day’s observation and 0.3 Crab for 10 days. The orphan flare flux of 5 times the Crab could be detected in 10 minutes.

5σ discovery flux as a function of flare duration for HAWC and flux needed by Fermi to detect 3 photons with E > 10 GeV assuming 2.4 sr FoV (from Fermi AGN BSL) downgraded by 10% to account for off-axes eff. area losses.

Fermi GRBs have been detected up to tens of GeV
Energy Spectrum Measurements

HAWC will be able to measure spectra to energies beyond 100 TeV for a source as bright as the Crab Nebula.

Peak Sensitivity for $E^{-2}$ source at $\sim$100 TeV
HAWC OBSERVATORY DESIGN
HAWC Observatory Design

• Close packed array of 300 Water Cherenkov detectors

• Located at Sierra Negra, Mexico (18° 59’ 41”N, 97° 18’ 28” W, 4100 m a.s.l.).

• Commercial water tanks 4.5m deep by 7.3m diameter

• Light-tight water bladder in steel support structure

• Three 8" Hamamatsu R5912 PMTs from Milagro in each tank

• Mix of refurbished Milagro electronics and new commercial electronics

An image of a single HAWC tank in the GEANT4 simulation. The tracks from the EM shower produced by a single 100 MeV gamma-ray are shown (50x thinning).
# Performance Parameters Compared to Milagro

<table>
<thead>
<tr>
<th></th>
<th>Milagro</th>
<th>HAWC</th>
</tr>
</thead>
<tbody>
<tr>
<td>Detector Area</td>
<td>4000 m² (surface)</td>
<td>22,500 m²</td>
</tr>
<tr>
<td></td>
<td>2500 m² (muon)</td>
<td></td>
</tr>
<tr>
<td>Time to 5σ on the Crab</td>
<td>120 days</td>
<td>1 day</td>
</tr>
<tr>
<td>Median Energy</td>
<td>4 TeV</td>
<td>1 TeV</td>
</tr>
<tr>
<td>Angular Resolution</td>
<td>0.40° – 0.75°</td>
<td>0.25° – 0.50°</td>
</tr>
<tr>
<td>Hadron Rejection eff.</td>
<td>90%</td>
<td>95%-99%*</td>
</tr>
<tr>
<td>Gamma-Ray Efficiency</td>
<td>50%</td>
<td>50%</td>
</tr>
<tr>
<td>Q for gamma/hadron rejection</td>
<td>1.6</td>
<td>2.5-5*</td>
</tr>
<tr>
<td>Time to detect 5 Crab flare at 5σ</td>
<td>5 days</td>
<td>10 minutes</td>
</tr>
<tr>
<td>Eff. Area at 100 GeV</td>
<td>5 m²</td>
<td>100 m²</td>
</tr>
<tr>
<td>Eff. Area at 1 TeV</td>
<td>$10^3$ m²</td>
<td>$20x10^3$ m²</td>
</tr>
<tr>
<td>Eff Area at 10 TeV</td>
<td>$20x10^3$ m²</td>
<td>$50x10^3$ m²</td>
</tr>
<tr>
<td>Volume of Universe where 10⁻⁶ erg/cm² GRB detectable</td>
<td>2 Gpc³</td>
<td>47 Gpc³</td>
</tr>
<tr>
<td>Flux Sensitivity to a Crab -like source (1 year) (5 σ detection)</td>
<td>625 mCrab</td>
<td>50 mCrab</td>
</tr>
</tbody>
</table>
Commercial Water Storage Solution
Light-tight Bladder
Water System

- Water quality ensured by filtration system
- ~40,000 gallons/tank
- Logistical challenge...
Electronics and PMTs

• Recycled from Milagro
  • 900 Encapsulated PMTs
  • Front-end electronics
  • $2M worth of equipment
  • Technical expertise/experience
• New off-the shelf equipment
  • VME TDCs, trigger scaler
  • HV
Electronics/DAQ Overview
Software

10-20 Khz data rate ==> $10^{12}$ events
~300 TB/year raw data storage
~10 MB/sec ==> ~Petabyte scale storage
HAWC Simulation

Need to model detector
- Aperture/Sensitivity
- Background Rejection
- Resolution
  - Energy
  - Angular

• Standard tools used
  - CORSIKA
  - GEANT4

• Cosmic Ray Measurements
  • input to determine background rates

Simulation of Gamma/Hadron Rejection parameter
Hadronic Showers are “clumpier” than Gamma Ray Showers
HAWC/MILAGRO Comparisons
Hadronic Background Rejection Efficiency

![Graph showing comparisons between HAWC and Milagro for hadronic background rejection efficiency.](image-url)
HAWC/MILAGRO Comparisons
Angular Resolution

Diagram showing the angular resolution as a function of energy for HAWC and Milagro detectors.
HAWC Calibration System
An Astrophysical “Test Beam”
Using the Crab

- Utilize available sources to calibrate detector
  - cosmic rays
    - Zenith distribution
    - Shadow of Moon
  - Crab Nebula
    - Known source of gamma-rays
    - Use to verify background rejection resolutions….
HAWC Schedule

- Started Feb 2011
- Summer 2012 - 30 Tanks (~Milagro sensitivity)
- Summer 2013 – 100 Tanks (operations begin)
- Fall 2014 – 300 Tanks (construction complete)
Based on the proven technology of Milagro
- Monitors nearly the entire sky and can serve as a “Trigger” for other observatories for multi-wavelength campaigns.
- Funding has been secured in both Mexico and USA.
- Construction has started
- Maximize Science Impact by running coincidentally with FERMI, VERITAS, Ligo, Icecube
- Well suited to make significant contributions to Astrophysics
HAWC Status March 2012
HAWC Status Fall 2014?
Astrophysical Sources of Gamma Rays
Pulsars