Surveying the TeV Sky with HAWC

Andres Sandoval
UNAM, Mexico

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TeV gamma rays

• They are of non thermal origin
• photons can not be accelerated
• therefore they have to be created by higher energy charged particle interactions or by decay or annihilation of higher mass dark matter particles
How are TeV gamma-rays produced?

- Synchrotron radiation
- Inverse Compton production
- Hadronic pions from cosmic ray interactions
- Dark matter annihilation or decay

\[ \chi + \chi \rightarrow \gamma, W^\pm, q\bar{q}, \tau^\pm \]

\[ \chi \rightarrow q\bar{q}, \tau^\pm \]
Gamma Ray Astrophysics

Pulsars Wind Nebula

Pulsars

Supernova Remnant

X-ray Binaries

Active Galactic Nuclei

Starburst Galaxies

Gamma-Ray Burst

Indirect Dark Matter
High Energy Gamma-Ray Detectors

Simulation (CORSIKA)

Satellite Detector

Wide Field of View, Continuous Operations

Extensive Air Shower (EAS) Detector

TeV Sensitivity

Imaging Atmospheric Cherenkov Telescope (IACT)
High Energy Gamma-Ray Detectors

Simulation (CORSIKA) Extensive Air Shower (EAS) Detector Imaging Atmospheric Cherenkov Telescope (IACT) Satellite Detector

Wide Field of View, Continuous Operations

TeV Sensitivity

NASA VERITAS

S

High Energy Gamma-Ray Detectors

P8R2 SOURCE V6, 10 years, TS=25, >

\[ E' \times \text{Flux} \quad \text{[ergs cm}^{-2} \cdot \text{s}^{-1}] \]

\[ 10^{10} \]

\[ 10^{11} \]

\[ 10^{12} \]

\[ 10^{13} \]

\[ 10^2 \]

\[ 10^3 \]

\[ 10^4 \]

\[ \text{Energy [MeV]} \]

\[ 10^{-1} \]

\[ 10^0 \]

\[ 10^1 \]

\[ 10^2 \]

\[ \text{Energy [TeV]} \]

\[ 10^{-10} \]

\[ 10^{-11} \]

\[ 10^{-12} \]

\[ 10^{-13} \]

\[ \text{Differential Sensitivity} \ E'^2 \ dN/dE \ TeV/cm}^2 \cdot \text{s}^{-1} \]

Fermi 10 Years

HAWC 507-day

HESS - 50 Hrs

VERITAS - 50 Hrs

MAGIC - 50 Hrs

0.1x Crab

0.01x Crab

Imaging Atmospheric Cherenkov Telescope (IACT)
Milagro “1st Generation” of water based gamma-ray detectors
- Elevation of 2650 m a.s.l. near Los Alamos, NM
- Operated from 2000-2008
- Detected new Galactic TeV sources, the small scale cosmic ray anisotropy, and established limits for the gamma-ray emission from GRBs

HAWC “2nd Generation” of water Cherenkov gamma-ray detector
- Large aperture and continuously operating covers 2/3 of the sky every day
- Elevation of 4100 m a.s.l in central Mexico
- 300 tanks of 200,000 liters covering an area of ~22,000 m²
- Construction 2011-2015
- Records 25 kHz of high energy air showers, mostly from cosmic rays
Location of the observatory

Latitude: 18° 59.7’ N
Longitude: 97° 18.6’ W
Location of the observatory

Citlaltepetl
Pico de Orizaba
5636 m a.s.l.

Tliltepetl
Sierra Negra
4582 m a.s.l.

HAWC
4100 m a.s.l.

Large Millimeter Telescope
Alfonso Serrano
HAWC’s field of view and duty cycle

Field of view down up to $\sim 45^\circ$ from zenith
Due to Earth’s rotation, HAWC is able to scan $2/3$ of the sky each day

A source is visible for HAWC up to 6 hours each day

The shower plane is reconstructed from the arrival times of the signals in each tank; the perpendicular to it gives the direction of the originating particle: cosmic- or gamma-ray
Air shower propagation through the HAWC PMTs
Gamma/hadron discrimination in HAWC

Air shower consistent with a gamma-ray produced at the Crab Nebula

Hadronic shower

Lateral distribution

effective charge [PE] vs impact parameter [m]

Run 2054, TS 584212, Ev# 226, CXPE40= 21.2, Cmptness= 28.3

Run 2118, TS 45004, Ev# 41, CXPE40= 55.7, Cmptness= 10.7
HAWC’s sky coverage

- The Crab nebula transits overhead of HAWC
- The galactic center is at the boundary of the field of view

There are 205 known gamma-ray sources (Oct 2017)

HAWC Collaboration
Astroparticle Physics 50-52 (2013)
Scientific targets of HAWC

• Monitor 2/3 of the sky continuously, searching for very high energy gamma-ray emission

• Measure the spectrum and temporal variations of gamma-ray sources (for both known and recently discovered) up to the highest energies

• Look for very high energy gamma-ray emission from Gamma-Ray Bursts (GRBs)

• Study fundamental physics topics such as: dark matter, primordial black holes, Lorentz invariance, supersymmetric particles such as Q-Balls ...

• Study in detail the cosmic-ray anisotropy discovered by Milagro

• Solar physics
Fermi-LAT count map 10 GeV — 2 TeV with >1500 objects in 84 months of data.
• HAWC TeV skymap in 17 months of data.
• 39 2HWC sources: 2 blazars, 5 UID off the Galactic plane, 19 are unassociated with any known TeV source.
Skymap from 507 days of data: Most sensitive TeV survey up to now
Point source analysis assuming power-law index of 2.7
Second Gamma-Ray Catalog

HAWC Collaboration

Skymap from 507 days of data: Most sensitive TeV survey up to now
Point source analysis assuming power-law index of 2.7
The Crab Nebula

- At approximately 6500 light years from the Earth
- Diameter of approximately 11 light years, expanding at 0.005 c

NASA

The Crab Nebula seen by HAWC

The standard candle of TeV gamma-rays sources: First high confidence TeV detection
Brightest steady source in the northern sky above 1 TeV

\( \gamma / \text{hadron discrimination} \)

Detector livetime

\( C = \frac{N_{\text{hit}}}{C \times \text{PE}_{40}} \)

Angular resolution

Energy spectrum

- Used to refine analysis and validate simulations

HAWC Collaboration
Galactic Plane (an example section of it)

39 sources detected, **19 are new** (not associated with known TeV sources)
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Galactic Plane (an example section of it)

39 sources detected, 19 are new (not associated with known TeV sources)
With HAWC’s study of the galactic plane we found point and extended sources, some of them not previously reported.

PAMELA and AMS have measured a positron excess at energies > 10 GeV.

Could this excess be due to a nearby pulsar instead of a product of dark matter annihilation?

Requirements for the pulsar hypothesis:
- Old enough so we can be receiving its wind of $e^+e^-$
- Young enough so it is still emitting this wind
- Close enough so the $e^+e^-$ can reach us

AMS Collaboration
PRL 110, 141102 (2013)
Discovery of very extended TeV halos

Geminga \( [3 \times 10^5 \text{ y old, 250 pc away}] \) and PSR B056+14 \( [1 \times 10^5 \text{ y old, 288 pc away}] \) are candidates to be the source of this positron excess. HAWC is the only instrument able to characterize these extended sources.

Before HAWC, Milagro was the only TeV instrument to detect Geminga, 2HWC J0700+143 is a new source discovered by HAWC with a pulsar similar to Geminga.
The positron excess and extended sources

The measured gamma ray emission is produced by the leptons diffusing into the ISM and IC scattering from the CMB. Using the properties measured by HAWC of these sources, we can infer the propagation of the $e^{\pm}$ to Earth.

The measured positron flux cannot be explained by the contributions from Geminga and 2HWC J0700+143.
Variability of sources: Detection of increased TeV flux from the active galaxy Markarian 501

An Astronomer’s Telegram was immediately sent to alert the community about this observation.

Studies of the variability can provide insights into the acceleration mechanisms.

HAWC monitors continuously multiple gamma-ray sources every day in an unbiased way.
Observations with Fermi-LAT reported a flare at lower gamma-ray energies (>100 MeV), approximately 1.7 times the average flux.

- Crab flares, continue up to TeV?

- A likelihood test shows that the data is consistent with a constant flux.

NASA/DOE/Fermi LAT/R. Buehler
Active galaxy Markarian 421

First extragalactic object discovered in the TeV band, is a galaxy with an active nucleus whose jet points in Earth’s direction

Variability in timescales of hours or less

A Bayesian block analysis [to find regions of constant flux] is used to identify 19 distinct flux states

The highest per-transit fluxes exceed the Crab Nebula flux by a factor of approximately 5
Active galaxy Markarian 501

- Also a BL Lacertae type blazar
- Second of such objects discovered at TeV energies
- The highest per-transit fluxes exceed the Crab Nebula flux by a factor of approximately 3
- 14 distinct flux states in this period of time
Cosmic Ray Spectrum

359 days of data

HAWC

All Species Cosmic Ray Energy Spectrum

Flux (m$^2$sr GeV$^{-1}$sec$^{-1}$)

10 TeV

1 PeV

Flux (GeV s m$^{-2}$ sr$^{-1}$)

Preliminary

Cosmic Ray Spectra of Various Experiments

LEAP - satellite
Poseidon - satellite
Takahet - ground array
Haverah Park - ground array
Kakiva - ground array
AGASA - ground array
FiTeR - fluorescence
Hires1 mono - air fluorescence
Hires2 mono - air fluorescence
Hires Slalom - air fluorescence
Auger - hybrid

(1 particle/m$^2$-year)

Knee

(1 particle/km$^2$-year)

Ankles

(1 particle/km$^2$-century)

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Search of TeV gamma-ray counterparts to IceCube neutrinos

Looked for gamma-ray sources in the direction from where the 28 highest energy neutrinos arrived.

No detections so far
• sources opaque to gamma-rays?
• sources too far away?
• too many sources?

Performing searches in real time in order to look for transients
Decay or annihilation of DM particles in the regions of enhanced DM density to SM particles eventually leads to gamma-rays. If $m_{DM}$ is 1 TeV-100 TeV HAWC could detect it indirectly.

Dark Matter targets

- Virgo Cluster
- M31
- Galactic Center
- Dwarf spheroidals
Constrains on Multi-TeV Mass DM

Annihilation

\[ \chi \chi \rightarrow b\bar{b} \]

\[ \chi \chi \rightarrow \tau^- \tau^+ \]

Decay

\[ \chi \rightarrow b\bar{b} \]

\[ \chi \rightarrow \tau^- \tau^+ \]
TeV counterparts to GRBs

HAWC effective area is of $\approx 100 \text{ m}^2$ at 100 GeV

Fermi with an effective area of $\approx 1 \text{ m}^2$ has detected $\approx 100 \text{ GeV}$ gamma-rays from GRBs

No detections so far, but HAWC has set limits from 64 GRBs detected by Swift and Fermi

GRB 170206
Third brightest short GRB detected by Fermi-GBM

HAWC Collaboration
APJ 843:88 (2017)
First observation of a binary neutron star inspiral
Associated with a gamma-ray burst detected by Fermi-GBM
First direct evidence of a link between mergers and short gamma-ray bursts
Multi-messenger observations of the merger

Follow up observations from 60 collaborations around the world, including HAWC

- The region where the event happened was not in the field of view of HAWC
- Transited through 9 hrs after at an unfavorable zenith angle for HAWC (42°)
- Upper limits from HAWC for energies > 40 TeV assuming an $E^{-2.5}$ spectrum were reported in a GCN (Gamma-ray Coordinates Network) circular.

APJ Letters 848:L12 (2017)
First upgrade: Outriggers

Air shower with a core far from the array

Run 4486, TS 13, Ev# 405, CXPE40= 446, RA= 359.2, Dec= 31.8
First upgrade: Outriggers

- HAWC Sparse Outrigger Array:
  - Increase the sensitivity for air showers with energies $> 10$ TeV
  - Precise location of the shower core, for showers that occur at the edges of the array
  - Increase of the effective area for energies $> 10$ TeV by 3-4x
- Funding from LANL/Mexico/MPI Heidelberg.
- Composed of tanks of 2500 liters: 1/80 of the volume of the current WCDs
Conclusions

• The HAWC observatory began full-scale operation in March 20, 2015

• The 2HWC catalog of gamma ray sources contains 39 sources, including 19 new sources

• HAWC produced the first TeV light curves with daily binning from the Crab Nebula, Markarian 421 and 501. HAWC can study the variability of any TeV source within its field of view and provide alerts to other observatories

• The measurements of HAWC from Geminga and 2HWC J0700+143 show that the associated pulsars are not the main contributors to the detected positron excess

• HAWC is performing follow-up observations triggered by partner observatories like IceCube and LIGO-Virgo

• Lots of interesting scientific results coming up!