Recent results from the High Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory

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High Energy Gamma-Ray Detectors

Extensive Air Shower (EAS) Detector (HAWC, ARGO, Milagro)

Imaging Atmospheric Cherenkov Telescope (VERITAS, HESS, MAGIC)

Satellite Detectors (Fermi, AGILE, EGRET)

Wide Field of View, Continuous Operations

TeV Sensitivity

Fermi LAT

HAWC

VERITAS
High Altitude Water Cherenkov (HAWC) Extensive Air Shower Detector

- 22,000 m² air shower array
- 300 Water Cherenkov detectors (WCD)
- 200,000 liters of purified water per WCD
- 4 sensors (photo-multiplier tubes) per WCD
- Completed March 2015

Citlaltepetl
Pico de Orizaba
5160m a.s.l.

Tlaltepetl
Sierra Negra
4582m a.s.l.

Large Millimeter Telescope

HAWC
4100 m a.s.l.
High Energy Gamma-Ray Sensitivity

- Fermi and HAWC have instantaneous field of view of ~2 sr
- IACT observations of 50 hours are typical after a few years of operation
- HAWC observes 8 sr (i.e. 2/3) of the sky each day
- HAWC has the best sensitivity > 10 TeV of currently operating observatories (CTA is planned for mid 2020s)
Crab with HAWC

- The Crab is $> 100 \sigma$.
- Probes the highest energy gamma-rays

\[ \gamma / \text{hadron discrimination} \]

\[ \text{hadrons} \]

\[ \text{PSF} \]

\[ \text{angular resolution vs energy bins} \]

\[ \text{60 TeV } \gamma \text{-ray from the Crab} \]

\[ \text{Energy Spectrum} \]
HAWC’s 2.5 year Sky Map

2HWC catalog ApJ 2017, arXiv:1702.02992, was 507 days and contained 39 sources of which 10 were new
Fermi, HAWC, and HESS

Fermi >50 GeV (2015)

HAWC

HESS (2016)

H.E.S.S. (2016) preliminary
HAWC >50 TeV, HAWC, and HESS
HAWC’s Galactic Plane with 2.5 years of data
VERITAS Confirms HAWC detection

Cyan diamond is X-ray PWN
NuSTAR-VERITAS-HAWC Legacy Project

• First 2 NuSTAR observations are very interesting: a potential TeV binary of which there are only 6 known, and a high B field Pulsar Wind Nebula with no pulsar detected

• Joint project involves Columbia scientists on VERITAS (Brian Humensky and Reshmi Mukherjee) and on NuSTAR (Kaya Mori and Chuck Hailey)
**Local Cosmic Positrons**

- **AMS-02** on board the International Space Station observes local cosmic rays since 2011
  - excellent charge resolution and particle species discrimination
- TeV $e^+e^-$ lose energy quickly and therefore must be produced locally ($d < \sim 100$ pc)
  - *secondaries* produced by cosmic ray interactions with ISM (spallation)
  - *secondaries* produced by local source
    - local cosmic accelerator (e.g. Geminga)? local dark matter interactions?
- Larger positron flux observed above $\sim 10$ GeV than expected from secondaries
  - First observed by Pamela in 2009, since confirmed by Fermi LAT and AMS-02
  - Are they from a local cosmic accelerator or dark matter?
    - If they are from dark matter, other annihilation products should be produced
AMS Positrons from Pulsars?

- Postulated sources of AMS positron excess are nearby, old pulsars
- Geminga and Monogem are the best candidates
- HAWC detects both as very extended TeV gamma-ray sources
HAWC observations prove that these sources are indeed accelerating electrons and positrons to multi-TeV energies. 

HAWC observations measure the total energy released in electrons and positrons which is much of their measured spin down energy.

HAWC observations of the angular extent of these TeV nebula measures the diffusion coefficient of their propagation in the interstellar medium.
HAWC Diffusion vs. Cosmic Ray Secondary Derived Diffusion

- Diffusion Coefficient, D, Measured by HAWC is much lower than that derived from cosmic ray secondaries
  - The ratio of Boron to Carbon is used to determine D averaged over the ~10 million year lifetime of cosmic rays. However, cosmic rays spend much of their lifetime in the halo of the galaxy where diffusion is probably faster.
- Assuming the HAWC measured D, the positrons from Geminga or Monogem contribute negligibly to the positron flux measured by satellite detectors like AMS-02.
- Hooper & Linden, 2017 argue that the highest energy electrons imply that D cannot be so low.
Other Sources of the Positrons

- Annihilation or Decay of Dark matter into Standard Model Particles
- Other Nearby PWN (perhaps as yet undiscovered)
- Nearby Supernova Remnant Shocks
- Nearby X-ray Binaries
- New Theories about Secondaries Produced by Cosmic Ray Propagation

Linden, et al. 2017

HAWC detection of TeV emission near PSR B0540+23

ATel #10941; Colas Riviere (University of Maryland), Henrik Fleischhack (Michigan Technological University), Andres Sandoval (Universidad Nacional Autonoma de Mexico) on behalf of the HAWC collaboration on 9 Nov 2017; 23:11 UT
Credential Certification: Colas Riviere (riviere@umd.edu)
SS433: Galactic Black Hole in a Binary inside a Supernova Remnant

- Jets are postulated to accelerate particles in many gamma-ray sources and probably in the UHECR sources
  - Acceleration could be due to shocks when the jet slows due to interaction with the external medium or due to magnetic reconnection within the intense fields of the jet
- HAWC observation of SS433 is the direct proof that electrons (not hadrons) are accelerated to >100TeV in jets
  - Jets are observed edge-on so the gamma rays are not Doppler boosted to higher energies or higher luminosities
  - Magnetic field is constrained by the x-ray synchrotron emission now that HAWC determined the electron energy
  - Acceleration does not happen at the black hole because the cooling time of the electrons is too short to make the observed gamma-rays

HAWC significance with the overlay of x-ray contours. The HAWC detection is correlated with the jet lobes and not the black hole.
New Paradigm in Particle Acceleration

- Regions of magnetically dominated plasma accelerate particles efficiently giving hard power law spectra with fast rise AND decay flares

\[ f = f_0 E^{-p} \]
\[ \delta B^2 / B_0^2 = 0.1 \]

\[ \sigma = 6 \]
\[ \sigma = 25 \]
\[ \sigma = 100 \]
\[ \sigma = 400 \]
\[ \sigma = 1600 \]

\[ p = 1.5 \]
\[ p = 4 \]

\( \sigma \) is proportional to \( B^2 \)
The larger \( B \), the more high energy particles are accelerated.
Daily Monitoring of Mrk421, Mrk501, Crab
Conclusion

• HAWC is surveying the TeV sky.
  – Multiple papers recently appeared or are in progress
    “Antiproton Limit”, “GW Search”, “IceCube Neutrino Search”
• More exciting results to come
• Outrigger array upgrade nearly complete which increases HAWC’s
effective area x 4 for gamma-rays > ~20 TeV
Beyond HAWC

- Higher Altitude than HAWC increases low energy sensitivity and larger than HAWC detector also increases high energy sensitivity
- Developing international collaboration for a southern hemisphere, HAWC-like observatory
- Interested US, European, Mexican, and South American collaborators have had several meetings
  - Visited potential sites in Argentina and Chile
  - Formed Southern Gamma-Ray Survey Observatory (SGSO) Alliance
  - Preparing White Paper for Astronomy and Astrophysics Decadal Survey 2020
- Science Objectives are many
  - Discovering rare transient events requires full sky coverage (e.g. Gamma Ray Bursts & Gravitational Wave Sources)
  - Galactic Center Region
  - TeV Source finder for CTA south
The Southern Gamma-ray Survey Observatory Alliance

The SGSO Alliance mission statement

The Southern Gamma-ray Survey Observatory Alliance is a collection of scientists interested in the science and engineering of an extensive air shower detector located at a high-altitude site in the mountains of South America. SGSO will be sensitive to astrophysical gamma rays and cosmic rays in the energy range between 100 GeV and 100 TeV. The purpose of the alliance is the advancement of such a detector.

The member scientists intend to elucidate the expected scientific discoveries of SGSO and the design parameters required to obtain these discoveries; to prototype and test various elements of the detectors; to explore and prototype several detector designs options; to evaluate the suitability of possible sites; to simulate and optimize the sensitivity of different detector designs; and to investigate and make measurements at potential sites. We will work together to communicate our findings among ourselves and the international scientific community.

The alliance will work toward the completion of whitepapers on the scientific capabilities of the detector, pursue funding and promote SGSO for long term planning within the astrophysics community.

Members of SGSO are entitled to access shared documents and participate in workshops and scientific meetings. Membership is informal and carries no obligation or commitment.
Figure 1: The effects of increasing altitude on the effective area of air shower detectors. Below 1 TeV, SGSO can gain an order of magnitude over HAWC by building at higher altitude.
Figure 1: Optical concentrators built from wavelength-shifting scintillating fiber [21] can increase the effective volume of a PMT by over an order of magnitude by collecting light from a large volume of water. These designs may allow SGSO to use $\frac{1}{4}$ of the PMTs and electronics of HAWC for the same detector area.
"Outrigger" extension project

- We will increase the sensitivity to the highest energy events by determining the core position for showers that fall off the array.
- The 350 small WCD outrigger detectors cover an area 4x HAWC and will increase by 3-4x the sensitivity at 50 TeV.
- LANL funded with additional contributions from Mexico and Germany Max Planck Institute

Funded and Soon complete

Simulated event
Illustration of the face-on view of the observed region and the Earth. The color circles correspond to the diffusion distance of leptons of three different energies from Geminga (for readability only the highest energy is shown for PSR B0656+14).

Particles diffuse farther with higher energy until cooling effects dominate, as a result TeV particles diffuse the farthest.

\[ r_d = 2\sqrt{D(E_e)t_E} \]

\[ D(E_e) = D_0(\frac{E_e}{10 \text{ GeV}}) \]

\( t_E \) is the smaller of the cooling time (depends on \( E \)) and the injection time (pulsar age).
HAWC Monitors Active Galactic Nuclei for Flaring Daily

Most recent IAU Atel “HAWC observation of Mrk421 reaching peak TeV flux in month-long enhanced activity” last week. Plus many notifications to atmospheric Cherenkov telescopes via MOU in preceding days.
HAWC, TeV gamma rays

Daily Monitoring of Markarian 421

FACT, TeV gamma rays

Fermi-LAT, MeV-GeV gamma rays

SWIFT-BAT, keV gamma rays

http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc

http://swift.gsfc.nasa.gov/results/transients, Krimm et al., 2013, ApJSS 209,1

http://www.fact-project.org/monitoring, H. Anderhub et al. JINST 8 P6008
CR: small scale anisotropy

- $86 \times 10^9$ events in 181 transits with large scale anisotropy removed ($\geq$ octupole): scales below $60^\circ$.
- Median E of 2 TeV has gyroradius in 3 microG field of $<0.001$ pc = 200 AU.
- What can focus cosmic rays at that distance?

Search for HAWC Counterparts to IceCube astrophysical $\nu$

- We have looked for $\gamma$ sources in the direction from where the 28 highest energy $\nu_\mu$ arrived.

- No sources detected
  - sources opaque to $\gamma$?
  - sources too far away?
  - too many sources?

Also searching in real time in case they are transient
Search for TeV Counterparts to Gamma Ray Bursts

- HAWC effective area 
  ~100m² at 100GeV
- Fermi with ~1m² has detected ~100 GeV $\gamma$-rays from GRBs
- Still waiting for a big one!
  - HAWC Upper Limits from 64 GRBs in ApJ 2017
  - HAWC observation of GRB 170206 is most constraining
Fermi has observed Gamma Ray Bursts that HAWC could detect

- HAWC effective area
  ~100m$^2$ at 100GeV and grows rapidly with energy
- Fermi has ~1m$^2$ area at 100GeV.

HAWC Simulated lightcurve for Fermi GRB 090510
Known TeV Sources AND New TeV sources

Pulsar ~8kpc (26,000 ly) away, but no PWN detected by NuSTAR

Association unclear

Supernova remnant with very energetic pulsar
Complex Cygnus Region

VERITAS source

HEGRA Source

PWN in x-ray binary

Fermi’s

Cygnus Cocoon

New TeV Source

Multiple VERITAS sources
Search for HAWC Counterparts to Gravitational Wave Detections

GW170817
- Neutron Star Merger with electromagnetic counterpart
- Not in HAWC’s field of view at the time, but TeV upper limit was placed 9 hours later (ApJ Lett 848, L12, 20 Oct 2017)

GW151226
- 2015 Dec 26 03:38:53.6 UTC
- >5 sigma
- 14.2M☉ + 7.5M☉ → 21.8M☉
- z=0.09 ±0.03 -0.04
Calculate spectra for different DM mass and annihilation channels with Pythia 8, then determine counts upper limit from HAWC maps vs # of hit PMTs, then use Corsika & GEANT4 to convert to limit on $<\sigma v>$. 
HAWC’s DM Limits Are Better than other Gamma-Ray Observatories above a few TeV

Note that HESS Galactic Center limits are better than HAWC’s if the dark matter distribution is known to not be cored.
Outriggers for HAWC

- Increases sensitivity at highest energies
- Shower cores can be located when they hit off the main array, so that direction and energy can be measured
- 350 outriggers funded by LANL, MPIK Heidelberg, and CONACyT (Mexico)
Search for North FERMI Bubble

Preliminary

Energy [GeV]

$E^2dN/dE [\text{GeV cm}^{-2} \text{ sr}^{-1} \text{s}^{-1}]$

HAWC 108 transits

Fermi Data
HAWC UL Power Law $\alpha=2.75$ 90%
Power Law $\alpha=2$
Power Law $\alpha=2.75$
$N_\mu \propto p^{-2.2}$
$N_\mu \propto p^{-1.7} \exp(-p/13.7 \text{ TeV})$
ICS, z=5kpc
ICS on CMB

Fermi data reveal giant gamma-ray bubbles
Electrons emit TeV gamma-rays and keV x-rays

X-ray energy depends on the magnetic field, so with TeV observations to constrain the electron energy, the magnetic field can be measured!
HAWC Rejects Background Cosmic Rays

HAWC detects a few thousand $\gamma$ rays per day and 20,000 hadronic cosmic rays per second ($\sim$2 billion/day)