Sensitivity and Status of HAWC
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Abstract: The High Altitude Water Cherenkov (HAWC) Observatory, under construction at Sierra Negra, Mexico will detect energetic air showers from primary hadrons and gamma rays with energies from 100 GeV to 100 TeV. The first stage of the instrument, HAWC-30, with 10\% of the channels deployed has been completed and is performing as expected. We anticipate HAWC-100 will be operational by summer 2013 with the full HAWC Observatory (with 300 detectors) being completed in 2014. HAWC complements existing Imaging Atmospheric Cherenkov Telescopes and the space-based gamma-ray telescopes with its extreme high-energy reach and its large field-of-view (\(\sim\)2sr). The full HAWC instrument will be used to study particle acceleration in Pulsar Wind Nebulae, Supernova Remnants, Active Galactic Nuclei and Gamma-ray Bursts.

Keywords: High Altitude Water Cherenkov Observatory, gamma rays

1 Introduction
The High Altitude Water Cherenkov (HAWC) observatory is a multi-TeV photon detector under construction at a high-altitude site in Mexico. Eventually covering some 20,000 square meters, the instrument is sensitive to 100 GeV - 100 TeV photon signals from astrophysical sources. It will be used to study high-energy emission from typical high-energy photon sources: Galactic pulsar wind nebulae (PWN) \[1\], supernova remnants (SNR), diffuse emission in the galactic plane \[2\], as well as active galactic nuclei (AGN)\[3\] and gamma-ray bursts (GRBs) \[4\]. We will also use it to search for TeV photons from dark matter annihilation in our Galaxy \[5\] as well as constrain the evaporation of primordial black holes \[6\]. Here we describe the simulation of the instrument and determination of the sensitivity to steady high-energy sources.

2 HAWC Instrument
The instrument consists of 300 water Cherenkov detectors (WCDs): 4.5-meter tall, 7.3-meter diameter steel water tanks lined with a plastic bladder, filled with clear water, and instrumented with four photo-multiplier tubes (PMTs) in each. The WCDs are deployed close-packed over 20,000 square meters on a 4100-meter plateau near the Sierra Negra at +19°N in Mexico (Figure 1). The WCDs measure the timing and density of air shower particles reaching the ground. Custom front-end electronics partially re-used from the Milagro experiment are used to record the leading-edge time and total charge seen by each PMT during an air shower. The particles from an air shower arrive in a thin planar sheet propagating at the speed of light which washes over the instrument and the arrival time of light is used to determine the direction of the original primary particle.

Air showers are modeled using the CORSIKA program developed for the KASCADE experiment. The ground detector components are modeled using a Geant 4 simulation. The simulation was validated against data from the Milagro experiment and comparison to early HAWC data suggests the simulation is sufficient to estimate the sensitivity of the whole instrument. Reconstruction algorithms developed for Milagro are applied to the simulated output.

The HAWC angular resolutions varies between \(\sim\) 1° to 0.1° depending on how many channels are hit in the event. The requirement that the core be accurately identified practically limits the instrument to observe particles with a core within the geometric area of the instrument.

The challenge in detecting photon sources is the large background of hadronic cosmic rays. Due to randomization by Galactic magnetic fields, cosmic-ray particles are nearly isotropic where photon sources are well-localized. Gamma-ray sources appear as a small bump on the nearly-smooth cosmic-ray background. Additionally, cosmic rays produce a hadronic air shower where gamma rays produce a nearly pure electromagnetic shower. The penetrating particles (primarily muons) and clumpy structure (from sub-showers with high transverse momentum) of a hadronic shower
Fig. 2: Compactness (nHit/CxPE) distribution for photon/hadron discrimination for a photon source at 35 degrees declination for events with more than 700 PMTs hit. CxPE is the number of PEs detected in the hardest-hit PMT outside of a radius of 40 meters. The separation, particularly good for photons over 1 TeV, is evident.

differs from the smooth distribution produced by a pure electromagnetic shower and we exploit this difference to suppress the hadronic background. Figure 2 exhibits some sample simulated signal and background events. We utilize a parameter, the compactness, defined as nHit/CxPE where nHit is the total number of PMTs participating in an event and CxPE is the number of PEs recorded in the hardest-hit channel outside of a radius of 40 meters from the shower core to distinguish photons from hadrons. The background rejection is strongly dependent on the shower energy but rejections of $10^{-2}$ are attainable while maintaining a signal efficiency of 50%. Figure 2 shows characteristic distributions of CxPE for photon events and hadron backgrounds.

In order to estimate the sensitivity to a localized source of gamma rays at a specified declination, we consider following a small angular bin of some angular radius around a potential source as the source transits through the HAWC field of view. The simulated output of the detector is weighted by the amount of time a source at the supposed declination will spend at each zenith angle in the detector. The data are divided into bins of nHit and log10(nPE), the number of hit PMTs in an event and the number of photoelectrons seen during in all PMTs during the event, as a proxy for the primary particle energy. Within each bin, we determine optimal cuts on the angular bin used and on the compactness.

3 Sensitivity Results

Figure 3 shows the effective area of the HAWC instrument to photons. The effective area rises with energy up to 1 TeV. This rise is due to the increasing probability for a particle to produce a detectable number of energetic particles at the ground. If a photon randomly were to interact higher in the atmosphere (since at 4100 meters we are lower than the peak particle production in the air shower) the resulting shower would be smaller. Up to 1 TeV we detect particles which randomly fluctuate to interact deeper in the atmosphere. At 1 TeV this probability is nearly 1.0 and the effective area plateaus at nearly the geometric area of the instrument. This plateau is due to the requirement that the air shower core be identified for accurate correction of the air shower curvature. When the core lies off the detector the core location is ambiguous with the current generation of algorithms and hardware. This limits the effective area to the geometric area at high energies.

To characterize the instruments sensitivity to sources we consider source differential energy spectra of the form $\frac{dN}{dE} = \phi_0 \left( \frac{E}{\text{TeV}} \right)^{-\alpha} \exp\left( \frac{E}{E_{\text{cut}}} \right)$ where $\phi_0$ is the source overall flux, $\alpha$ is the spectral index and $E_{\text{cut}}$ is the exponential cutoff energy.

High-energy showers landing off the detector trigger the instrument but the core, with the current generation of hardware and algorithms, cannot be accurately determined meaning the curvature correction fails. This results in the
Fig. 4: Differential sensitivity per quarter decade of HAWC (for 1 and 5 years and 1 year of HAWC 100) is shown compared to other existing and future IACTs. Note that sensitivity of HAWC and Fermi-LAT is for a sky survey while IACTs are 50 hours on a source.

uncertainty of our differential sensitivity estimate at high energies and is seen in the bands in figure. Figure shows the HAWC sensitivity vs source declination, cutoff energy and source radius.

4 Discussion

The HAWC instrument is designed to study particle acceleration in Galactic and extra-Galactic sources as well as the propagation of high-energy particles through the Galaxy and the extra-Galactic background light (EBL).

Pulsar Wind Nebulae (PWN) are the most common Galactic source of TeV gamma rays. The central pulsar drives a flow of energetic electrons into the surrounding material lighting it up with synchrotron radiation. Further acceleration is possible in shocks created when the flow interacts with surrounding material. Perhaps the most intriguing current topic in PWN science is the detection of flares from the Crab Nebula, challenging our understanding of these objects. It is currently unknown how high in energy these flares go or whether any other PWN flares.

Additionally, electrons and positrons accelerated in PWN constitute a background to dark matter searches. The most striking example of this is the anomalous positron excess discovered by PAMELA. While most attention has been focused on an interpretation as positrons from the annihilation of dark matter, interpretation via conventional pulsar physics is more likely. Developing an unbiased high-sensitivity survey of PWN is crucial to understanding energetic particle backgrounds for more exotic searches.

Supernova remnants (SNR) are also known to produce TeV photons. SNR accelerate particles at shock boundaries by the conventional Fermi mechanism. To date, the strongest positive evidence that SNR are responsible for the Galactic cosmic-ray population is due to TeV emission near SNR coincident with molecular clouds with which the SNR is interacting. More recently, evidence of characteristic spectral features from pion decay has been seen in these objects, strengthening the case that they are hadron accelerators. Nevertheless, while we have a few demonstrated examples of hadron acceleration in SNR, we still have not yet seen evidence of PeV hadron acceleration to fully account for the believed Galactic cosmic-ray population. HAWC’s unbiased survey out to 100 TeV will help identify or constrain instances of PeV hadron acceleration.

Furthermore, HAWC will be used to study Active Galactic Nuclei (AGN), one of the leading candidates for UHE cosmic-ray acceleration. While AGN are very well-established TeV sources much remains to be learned. Some are known to flare by an order of magnitude or more in a matter of hours meaning very small regions of emission. Furthermore, no long-term monitoring of AGN at TeV energies is possible because TeV Cherenkov telescopes are constrained in the number of hours they can look at a source and may only observe when the source is up on dark moonless nights. HAWC will conduct an unbiased survey of the TeV sky every night and can search for transient and high-energy emission from AGN.

5 HAWC-30 Results

The modular design of HAWC allows us to take data even as counters are still being deployed. Starting in October 2012...
we began operating the HAWC detector with 30 WCDs. An observation of the cosmic-ray Moon shadow with HAWC-30 serves as a diagnostic test of the resolution and pointing in the detectors angular reconstruction. (see Figure 6). We observed the Moon shadow from 2012 October 22 to 2013 March 08 and accumulated 35 billion cosmic ray events over 104 days of livetime [7]. Using the data quality cut of nHit32, seven billion events survive. The peak significance is -14.1 and is centered at (179.6° ± 0.1°, 0.1° ± 0.1°).

![Fig. 6: 104-days of the HAWC-30 Moon map.](image1)

6 HAWC Construction and Schedule

HAWC construction began in February 2011. As of May 22, 2013, 106 WCD Tanks have been built, with 77 WCDs and 283 PMTs in the data stream. Although we have been operating the detector more or less continuously since HAWC-30 in October 2012, we will begin physics operations of HAWC-100 (more likely HAWC-110) in August 2013. HAWC-250 is on schedule for completion in August 2014 and HAWC-300 should be completed by the end of 2014.

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![Fig. 7: Two simulated air showers in HAWC. The color and size scale show the number of PEs detected in each PMT. The photon event (top panel) has most of the high light deposition in the central core of the air shower whereas the proton event (bottom panel) shows significant localized charge deposition outside of the shower core region.](image2)

References

[1] Observations of the Crab Nebula with HAWC, J. Braun (this conference)
[2] HAWC Sensitivity to Diffuse Emission, P. Huentemeyer et. al. (this conference)
[3] Real-time AGN Flare Monitor for the HAWC Observatory, A. Imran et. al. (this conference)
[4] Search for high energy emission from GRBs with the HAWC Observatory, K. Sparks et. al. (this conference)
[5] Limits on Indirect Detection of WIMPs with the HAWC Observatory, B. Baughman et. al. (this conference)
[6] HAWC Sensitivity to Primordial Black Holes T. Ukwatta et. al. (this conference)
[7] Observation of the Moon Shadow and Characterization of the Point Response of HAWC-30, D. Fiorino et. al. (this conference)