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Observing the universe at TeV energies with the HAWC observatory

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Abstract: The HAWC (High Altitude Water Cherenkov) observatory is a proposed experiment that combines a very high altitude site with the developed and proven Milagro water Cherenkov technology. HAWC is a 150m x 150m pond of water located above 4100 m over see level with a large field of view and a duty cycle higher than 95%. When completed HAWC will be sensitive to gamma-ray induced air showers from $\sim$100 GeV to 100 TeV with a median energy around 1 TeV. After two years of operation it will have surveyed $\sim 2\pi$ sr of the northern sky with a sensitivity of 40mCrab and will be able to see transient signals of 1 Crab at 5σ in a single day. This sensitivity will likely result in the discovery of new sources as well as allow to follow up observations of detectors such as GLAST, VERITAS/HESS and IceCube. In this work, the observatory design, performance, capabilities and possible sites will be discussed.

Recently ground-based telescopes have revealed a sky rich with objects that emit TeV gamma rays. Atmospheric Cerenkov Telescopes (ACT) have proved their remarkable sensitivity to discover and study individual sources and to perform surveys over a limited area of the sky. For instance, more than 40 TeV-sources with energy spectra reconstructed from about 100GeV up to almost 100TeV have been discovered and, HESS has surveyed [1] the central part of our galaxy showing a large number of new sources that line up with the galactic plane. On the other hand, all-sky telescopes have shown their capabilities to perform all-sky surveys, to discover extended sources and to monitor the sky for TeV transients. For instance, Milagro has achieved the first detection of TeV gamma-ray emission from the Galactic plane [2], and the discovery of sources of TeV gamma rays in the Galactic plane of which several sources appear to be extended [3, 4]. The mapping of the diffuse Galactic gamma-ray emission at TeV energies including the Cygnus Region has also been shown by Milagro at recent conferences.

The communities of both types of telescopes (ACTs and all-sky) have realized the need of a telescope with higher sensitivity in a broader energy range with large field of view. In order to achieve this, the ACT community is designing the future generation of ACT telescopes as one or two arrays of tens of individual atmospheric Cerenkov telescopes. The sensitivity is expected to be improved by a factor of 5-10 in the current energy range and the energy range will be extended below 100GeV and up to 100TeV. However, the duty cycle will remain low to look for transients, the total cost is above hundred of millions of dollars and the construction time might be beyond 6 years (considering that the construction time of the actual ACTs is $\geq$3years). The High Altitude Water Cerenkov Observatory, HAWC, is the next generation of all-sky telescopes. HAWC combines the all-sky Milagro water Cerenkov technology with a very high altitude site to achieve an improvement in sensitivity of a factor of 15 over Milagro. The estimated cost is 6 million of dollars and the construction time is 3 years. In this paper HAWC design, capabilities, science goals and possible sites are discussed.

The HAWC detector is designed as a 150m x 150m x 5m deep reservoir lined with a polypropylene-nylon liner to contain and isolate the $\sim$115 Ml of filtered water from the ground below. Nine hundred 8" Hamamatsu R5912 photomultiplier tubes (PMTs) are secured on a 30 x 30 grid with 5m spacing and 4m deep. Stretching between the PMTs is an opaque curtain designed to optically isolate each PMT. The reservoir is covered with a lighttight building made from prefabricated steel components. The whole observatory will be situated at an altitude of 4100m over sea level, in Sierra Negra, Puebla, México.

The gain in sensitivity of HAWC over Milagro is result of the higher altitude, larger physical area and the optical isolation of the PMTs. Since there are about ∼6 times more electromagnetic particles in an extensive air shower (EAS) at 4100m than at 2600m (Milagro altitude), the energy threshold is reduced giving significant effective area at energies below a TeV and down to 100GeV for low trigger multiplicities, see Figure 1. The larger size results in an improved angular resolution of 0.25^o-0.4^o depending on the number of PMTs hit because of a better determination of the shower front curvature and core location. The background rejection and efficiency also improves significantly, especially at low energies, because penetrating particles such as muons can be detected over a much larger area. The hadron rejection efficiency increases with energy so that at energies above 10 TeV our observations are nearly background free and only limited by flux. Currently, the small size of the Milagro pond causes us to have poor efficiency for gamma showers which hit the pond. In HAWC, we can exclude the area around the core and still have a large area for detecting muons and hadrons. Finally, the optical isolation decreases the number of PMTs hit by light traveling horizontally across the reservoir. Then, the number of PMTs hit not related to the shower decreases resulting in a better angular resolution and a lower trigger multiplicity.

This paper describes the capabilities of HAWC based on an extension of the Milagro simulation software package using CORSIKA and GEANT software. The simulation has been throughly tested by comparing it with Milagro data. And while the agreement with Milagro is very good, gamma-rays and background rates are scaled from measured values in Milagro by comparing the predictions of the HAWC and Milagro simulations. By doing this, potential systematic errors internal to the simulation from the air shower modeling, optical model, detection efficiency and in the measurements of gamma-ray fluxes and hadronic backgrounds provided by other experiments are removed giving us a high level of confidence in our results for HAWC.

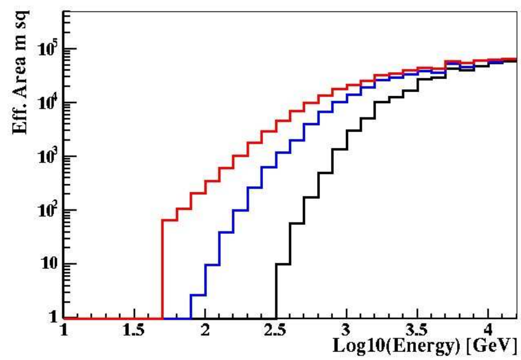

Figure 1: HAWC effective area versus gamma-ray energy for three different levels of trigger multiplicity (20(upper red line), 80(blue line) and 200(lower black line) PMT trigger) for a zenith angle $< 30^o$ after applying the cosmic ray background rejection cut and requiring a reconstructed direction within 1^o

The position of the shower core on the ground is determined by fitting the distribution of the PMT pulse amplitudes to a Gaussian profile. Then, the PMT hit times are adjusted to account for the curvatures of the shower front and fit again to determine the incoming shower angle. The curvature correction is $\sim 0.5^o$-1.0^o. Then, the correct identification of the core location highly impacts the angle reconstruction. Therefore, the angular resolution depends on the event size given by the number of PMT hit.

Hadronic showers are identified through the pattern of energy deposition in the detector. While gamma-rays induced showers have compact cores with smoothly falling density, hadronic showers typically deposit large amounts of energy in distinct clumps far from the shower core. The Milagro compactness parameter, C, have been extended for HAWC. C is defined as the total number of PMTs hit with amplitudes greater than 2PEs divided by the largest pulse amplitude that is more than 30m from the reconstructed core position. Gamma-ray and hadron induced showers have large and low values of C respectively. The hadron rejection efficiency increases with energy.

The energy resolution is limited by shower fluctuations in the atmosphere, as only the tails of EM showers are detected. When the effective area is less than the physical detector area, fluctuations in the shower development begin to dominate the response of the detector. It is impossible to distinguish between a low energy gamma ray that interacted deep in the atmosphere and a higher energy gamma ray that interacted higher in the atmosphere. Therefore the energy resolution of HAWC is strongly dependent upon the primary gamma ray energy. Showers with energies near or above the median (1TeV) can be reconstructed with ∼30-40% resolution. Figure 2 demostrates the ability of Milagro to measure the Crab spectrum.

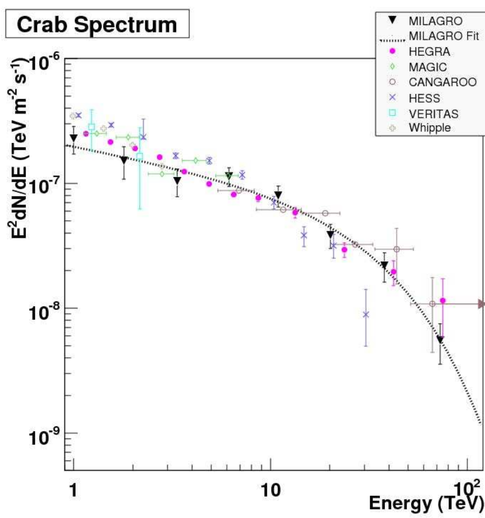

Figure 2: Milagro Crab spectrum and comparison with other observations. The dashed line is the measured Milagro spectrum with an exponential cutoff. The Milagro data are indicated by black triangles. Our data are in good agreement with the recent measurement of a high-energy cutoff by HESS

HAWC will monitor for >4 hours every day, every point in $\sim 2\pi$sr of the sky. Over a 2 year observation period HAWC will perform an unbiased sky survey with a detection threshold of 40 mCrab (see Figure 3), enabling the monitoring of known sources, the discovery of new sources of known types, and the discovery of new classes of TeV gamma ray sources.

The HAWC sensitivity depends on the source spectrum as shown in Figure 4. HAWC sensitivity to extended sources surpasses that of atmospheric Cherenkov telescopes when the sources extent is

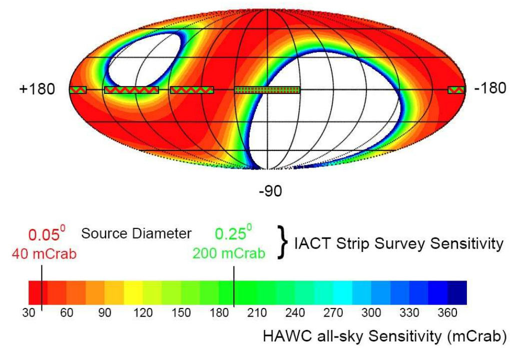

Figure 3: Flux limits for HAWC versus the HESS sky survey and the proposed VERITAS sky survey over the next two years. HAWC is assumed to be located in Mexico (19^{o}N). IACT sensitivity is shown for point (red) sources and for sources extended by 0.25^o (green). A crab-like spectrum is assumed. The HAWC limits will be lower for harder sources.

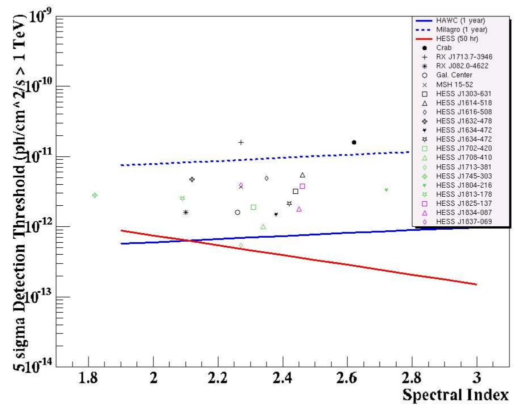

Figure 4: Sensitivity above 1TeV of Milagro (dotted line), HAWC (blue line parallel to Milagro's), and VERITAS or HESS (red line) versus the spectral index of the differential photon spectrum. The Milagro and HAWC observations are for 1 year and 2πsr. The VERITAS or HESS observation is for 50 hours on a single source.

larger than 0.25^o (see Figure 5) and for energies above 10 TeV. The brighter HESS detected sources tend to be of larger extent than the dimmer sources pointing to the likelihood of more extended objects. With HAWC sensitivity at high energies, we will probe the knee of the cosmic ray spectrum answering questions about the origin and propagation of cosmic rays.

HAWC will observe many flares from AGN with the sensitivity to detect a flux of 5 times that of the Crab in just 10 minutes over the entire overhead sky. These TeV flares provide strong constraints on emission mechanisms and Lorentz invariance, plus this will also enable many multi-wavelength observations of these flares. IceCube sensitivity can be significantly enhanced by knowing the location and time of TeV gamma-ray flares which are likely to produce TeV neutrino flares, for more details refer to [5].

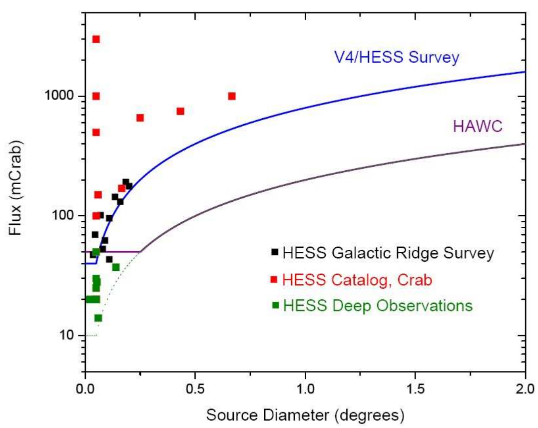

Figure 5: Comparison of γ-ray sensitivity between the IACT and HAWC 2 year sky surveys as a function of the source angular diameter. The HESS detected Galactic sources are shown as well as the Milagro source in the Cygnus region.

The HAWC sensitivity to the prompt emission from gamma-ray bursts is unique. With HAWC low energy threshold, GRBs with a TeV fluence comparable to their keV fluence will be detectable to a redshift of $\sim$1, while for closer GRBs much lower fluences can be detected. HAWC sensitivity to transient phenomena will extend the field of time-domain astrophysics to TeV energies.

Figure 6 demonstrates the ability of HAWC to observe shorter time scale variations than GLAST and to extend the energy range of observations beyond those of GLAST.

HAWC is an all-sky telescope with duty cycle $\sim$95% with sufficient sensitivity to discover new sources and to monitor the sky and known sources for transient emission.

There is strong synergy between the better flux sensitivity of HAWC to extended sources and the superior angular resolution of IACTs over their narrow field of view. HAWC will reuse the Mila-

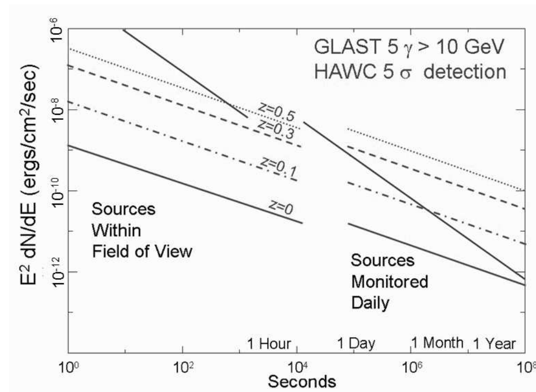

Figure 6: Comparison of the flux necessary for a GLAST detection of 5 γ-rays above 10 GeV with the HAWC 5σ detection threshold for a source differential photon flux of spectral index -2 that is cut off due to extragalactic background absorption. The absorption is calculated assuming the model of Kneiske [6], and the energy at which the flux is attenuated by 1/e is 700, 260, and 170 GeV for z=0.1, 0.3, and 0.5, respectively. The gap between the lines on the left and right is due to the Earth blocking the view of the source.

gro PMTs and much of the Milagro's data acquisition system resulting in a relatively quick construction at low cost.

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