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THE HIGH ALTITUDE GAMMA RAY OBSERVATORY, HAWC

M. M. González[1] for the HAWC Collaboration

RESUMEN

El volcán Sierra Negra en Puebla, México fue seleccionado para albergar a HAWC (High Altitude Water Cherenkov), un observatorio de gran apertura (2π sr), único en el mundo, capaz de observar contínuamente el cielo a energías de 0.1 a 100 TeV. HAWC consiste en un arreglo a una altitud de 4100 m sobre el nivel del mar de 300 contenedores de 7.3 m de diámetro y 5 m de altura llenos de agua pura y sensores de luz que observan partículas sumamente energéticas provenientes de los eventos más violentos del universo y será 15 veces más sensible que su antecesor Milagro. Las aportaciones científicas de Milagro han demostrado las capacidades únicas de este tipo de observatorios. En este trabajo se presentará HAWC y se discutirá brevemente su caso científico y capacidades.

ABSTRACT

The Volcano Sierra Negra in Puebla, Mexico was selected to host HAWC (High Altitude Water Cherenkov), a unique obervatory of wide field of view (2π sr) capable of observing the sky continously at energies from 0.5 TeV to 100 TeV. HAWC is an array of 300 large water tanks (7.3 m diameter $\times$ 5 m depth) at an altitude of 4100 m. a. s. l. Each tank is instrumented with three upward-looking photomultipliers tubes. The full array will be capable of observing the most energetic gamma rays from the most violent events in the universe. HAWC will be 15 times more sensitive than its predecesor, Milagro. We present HAWC, the scientific case and capabilities.

Key Words: acceleration of particles — cosmic rays — gamma rays: general — intrumentation: detectors

1. INTRODUCTION

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. 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 (Atkins et al. 2005), and the discovery of sources of TeV gamma rays in the Galactic plane of which several sources appear to be extended (Abdo et al. 2007a,b). The mapping of the diffuse Galactic gamma-ray emission at TeV energies (shown by Milagro) including the Cygnus Region will help us to understand the origin of the cosmic rays.

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 100 GeV and up to 100 TeV. However, the duty cycle will remain low to look for transients, the total cost is of several tens of millions of dollars and the construction time might be beyond 6 years (considering that the construction time of the actual ACTs is $\geq$3 years). 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. In this paper HAWC design, capabilities and science goals are discussed.

The gain in sensitivity of HAWC over Milagro is the result of the higher altitude, larger physical area and the optical isolation of the PMTs. Since there are about $\sim$6 times more electromagnetic particles in an extensive air shower (EAS) at 4100 m than at 2600 m (Milagro altitude), the energy threshold is reduced giving significant effective area at energies below a TeV and down to 100 GeV for low

[1]Instituto de Astronomía, Universidad Nacional Autónoma de México, Apdo. Postal 70-264, México, 04510 D. F., Mexico (magda@astro.unam.mx).

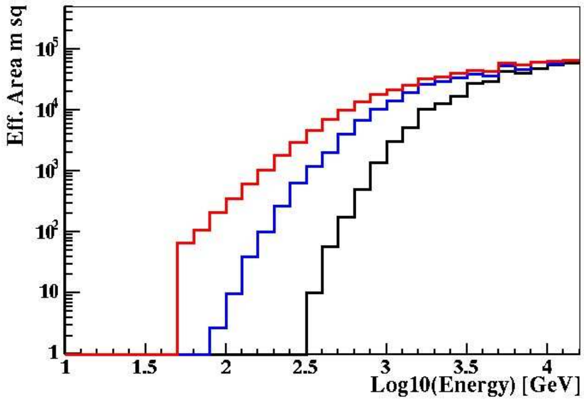

Fig. 1. HAWC effective area versus gamma-ray energy for three different levels of trigger multiplicity [20 (upper red line), 80 (blue line) and 200 (lower black line) PMT trigger] for a zenith angle $<30°$ after applying the cosmic ray background rejection cut and requiring a reconstructed direction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

trigger multiplicities, see Figure 1. The larger size results in an improved angular resolution of two dimensional Gaussian sigma of 0.25°–0.4° 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 we can detect penetrating particles such as muons over a much larger area. The hadron rejection efficiency increases with energy so that at energies above about 2 TeV, HAWC will detect Crab-like sources with a S:B ratio of better than 1:1 which is unprecedented for an EAS detector. Finally, the optical isolation decreases the number of PMTs hit by light traveling horizontally across the array. 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 capability 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.

2. CAPABILITIES

The position of the shower core on the ground is determined by fitting the distribution of pulse amplitudes to a standard lateral distribution profile. After the core is located, the PMT hit times are adjusted to account for the curvature of the shower front. The curvature is treated as a cone of slope $\sim$0.5°-1.0°, so misidentification of the core position leads to degraded angular resolution. The corrected PMT hit times are then fit to a plane to determine the incoming shower angle. The estimated angular resolution reaches a minimum of $\sim$0.1° above 5 TeV.

Hadronic showers are identified through the pattern of energy deposition in the array. 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 divided by the largest pulse amplitude that is more than 40 m 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 (1 TeV) can be reconstructed with $\sim$30–40% resolution. Figure 2 demostrates the ability of Milagro to measure the Crab spectrum.

3. SCIENTIFIC GOALS

HAWC will monitor for $>$4 hours every day, every point in $\sim 2\pi$ sr of the sky. Over a 1(4) year observation period HAWC will perform an unbiased sky survey with a detection threshold of $\sim$40(20) 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 imaging

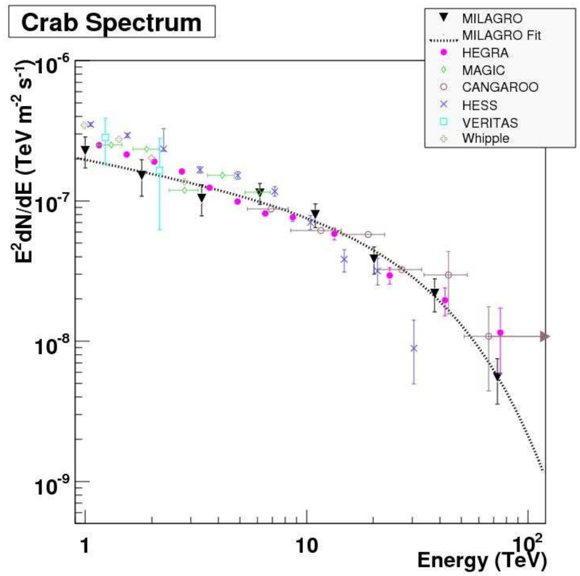

Fig. 2. Milagro Crab spectrum and comparison with other observations. The dashed line is the measured Milagro spectrum with an exponential cut-off. The Milagro data are indicated by black triangles. Our data are in good agreement with the recent measurement of a high-energy cut-off by HESS.

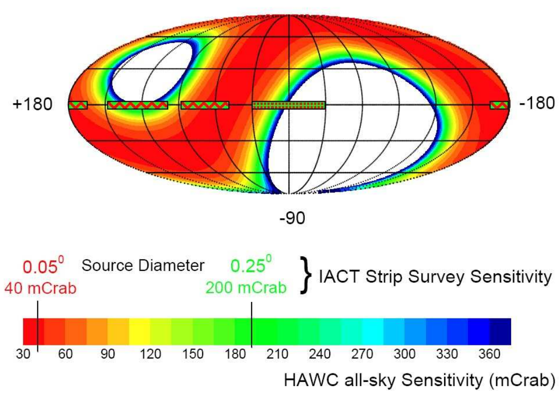

Fig. 3. Flux limits for HAWC versus the HESS sky survey and the proposed VERITAS sky survey over the next two years. HAWC is assumed to be located in Mexico (19°N). IACT sensitivity is shown for point (red) sources and for sources extended by 0.25° (green). A crab-like spectrum is assumed. The HAWC limits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

atmospheric Cherenkov telescopes when the sources extent is larger than 0.25° (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 an-

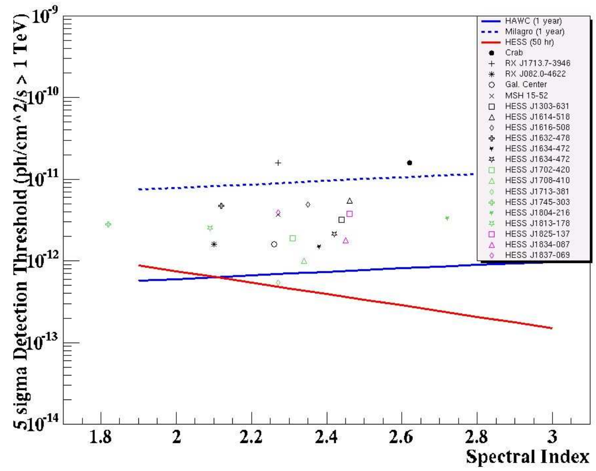

Fig. 4. Sensitivity above 1 TeV of Milagro (dotted line), HAWC (blue line parallel to Milagro's), and VERITAS or HESS (red line) versus the spectral index of the differential photon spectrum. The Milagro and HAWC observations are for 1 year and 2π sr. The VERITAS or HESS observation is for 50 hours on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

swering 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 Goodman et al. (2007).

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 $sim1$, 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. The effective area of HAWC at 100 GeV is more than 100 times that of the Fermi-LAT.

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

The HAWC deep survey of the TeV gamma-ray sky will provide an unbiased survey necessary to characterize the properties of the astrophysi-

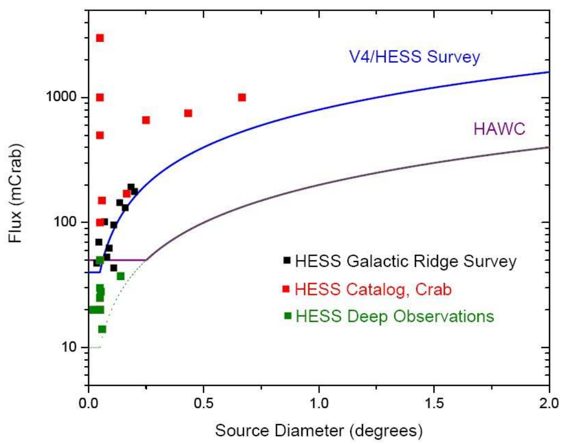

Fig. 5. Comparison of γ-ray sensitivity between the IACT and HAWC 2 year sky surveys as a function of the source angular diameter. The HESS detected Galactic sources are shown as well as the Milagro source in the Cygnus region.

cal sources in order to search for new fundamental physics effects. Examples of possible HAWC investigations include: (1) Constraining the existence of nearby dark matter. HAWC will detect Geminga at nearly 100σ resolving its spatial structure on parsec scales to better understand pulsar wind nebulae and determining Gemingas contribution to the electron, positron, and hadronic flux at Earth. HAWC will also better characterize the spectrum, flux, and variability of the cosmic ray anisotropy to better understand cosmic ray propagation. (2) Measuring the attenuation of astrophysical sources due to interactions with the EBL. HAWC will enable multiple sources to be observed in various flaring states to understand the intrinsic TeV spectrum. Current constraints on the EBL make a conservative assumption of a very hard intrinsic spectrum and are very close to the maximum allowed from galaxy counts. These observations have led to postulations of the existence of axions (Hopper & Serpico 2007) in order to reduce the attenuation of TeV emission from EBL.

The construction of HAWC has been planned in four consecutive stages of 7, 30, 100 and 300 tanks compleating construction in 2014. The first construction stage of HAWC, with 7 tanks, has officially started, see Figure 7.

HAWC is an all-sky telescope with duty cycle ∼95% with sufficient sensitivity to discover new sources and to monitor the sky and known sources for transient emission. It also can help with the understanding of the astrophysical background in order to determine if deviations from this background could be due to new physics.

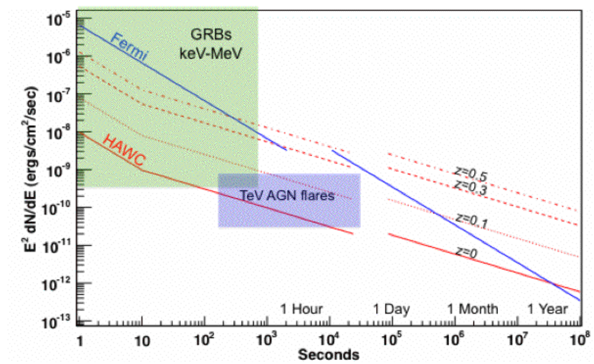

Fig. 6. HAWC sensitivity (red) to extragalactic transients at different redshifts for a 5σ detection threshold. The y-axis is k where dN/dE= k $E^{-2}\exp^{-\tau(z,E)}$ and τ(z,E) is the optical depth due to absorption by the extragalactic background light from the model of Gilmore (2009). Also, shown is the flux necessary for a Fermi detection of 5 gamma rays above 10 GeV.

Fig. 7. Picture shows the construction status of HAWC.

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