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The HAWC TeV gamma-ray Observatory

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Summary. — Ground-based gamma-ray astronomy has historically implemented two dramatically different techniques. One method employs Imaging Atmospheric Cherenkov Telescope(s) (IACT) that detect the Cherenkov light generated in the atmosphere by extensive air showers. The other method employs particle detectors that directly detect the particles that reach ground level—known as Extensive Air Shower (EAS) arrays. Until recently, the IACT method had been the only technique to yield solid detections of TeV gamma-ray sources. Utilizing water Cherenkov technology, Milagro, was the first EAS array to discover new gamma-ray sources and demonstrated the power of and need for an all-sky high duty-cycle instrument in the TeV energy regime. The transient nature of many TeV sources, the enormous number of potential sources, and the existence of TeV sources that encompass large angular areas all point to the need for an all-sky, high duty-factor instrument with even greater sensitivity than Milagro. The High Altitude Water Cherenkov (HAWC) Observatory will be over an order of magnitude more sensitive than Milagro. In this paper we will discuss the design and sensitivity of HAWC.

PACS `95.85.Pw` – γ-ray.
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PACS `95.85.Ry` – Neutrino, muon, pion, and other elementary particles; cosmic rays.

1. – Introduction

Very-High-Energy gamma-rays (100 GeV–100 TeV) were first observed from the Crab Nebula in 1989 [1]. Since that time the field has developed with major advances in Imaging Atmospheric Cherenkov Telescopes. The discoveries by Whipple, HEGRA, HESS, MAGIC, and VERITAS have been truly impressive. There are now over 100 known sources of VHE gamma-rays and a planned advanced large array of IACTs (CTA) has the potential to detect over a thousand sources of VHE gamma-rays. See [2] for a detailed review. Despite this impressive history, certain limitations of the IACT technique (small field-of-view and limited duty cycle) have encouraged the development of alternate technologies. While extensive air shower arrays have been in existence for as long as or longer than ACTs, their usefulness as gamma-ray telescopes has, until recently, been limited. The key limitation of EAS arrays has been their low sensitivity relative to the source fluxes, mainly driven by the high energy threshold of traditional EAS arrays and the moderate background rejection capability (both angular resolution and cosmic-ray rejection) compared to IACTs.

Traditional EAS arrays [3, 4] were typically sparse arrays of scintillation detectors distributed over large areas. Thus, in addition to the fact that many fewer particles reach the ground than Cherenkov photons generated by the EAS, these arrays sampled only a small fraction, typically 1–2%, of the particles that did reach the ground. They were also located at moderate altitudes, where most of the shower particles have been absorbed by the atmosphere. With Milagro [5], we developed water Cherenkov technology for EAS arrays. In a water detector, the EAS particles generate Cherenkov light in the water, which provides an amplification effect, making the particle visible to photomultiplier tubes (PMTs) that do not intersect the particle's trajectory. Water is also an excellent medium for converting the gamma-rays in the EAS (which outnumber electrons and positrons by roughly 6:1) to charged particles, that can then be detected. Finally, a deep (4-6 meters) pool of water acts as a shield to electromagnetic particles, providing a conceptually simple method to detect muons that are present in EAS of hadronic origin.

Milagro was the first EAS array to discover new sources of TeV gamma-rays. Milagro detected the Galactic diffuse emission in the northern hemisphere [6]—a feat that still eludes IACTs (due to the large angular size of the emission region), TeV gamma-rays from the Cygnus region [7], discovered an intermediate-scale anisotropy in the cosmic rays [8], and observed TeV emission from 14 of 34 Fermi Bright Source List sources [9], including the Geminga pulsar wind nebula. These and other discoveries have lead us to develop a proposal for a significantly more sensitive VHE gamma-ray observatory based upon the water Cherenkov technology—the HAWC (High Altitude Water Cherenkov) Observatory. By building the detector at significantly higher altitude (4100 meters asl vs. 2650 meters for Milagro), having a muon detection area an order of magnitude larger than in Milagro, and providing optical isolation between detector cells, HAWC will have over an order of magnitude improved sensitivity relative to Milagro.

2. – HAWC experimental configuration

HAWC is located on the volcan Sierra Negra in Mexico at an altitude of 4100 meters above sea level (asl). The latitude of the site is 19° and the longitude is West 97 degrees. With this latitude the Galactic Center is visible (transits at a zenith angle of 48 degrees), the Crab Nebula (an important calibration source) transits within 3 degrees of zenith, and the array will have $\sim 90\%$ overlap with the IceCube sky and a $\sim 40\%$ overlap with the H.E.S.S. Galactic Plane survey. The longitude of the site is such that we will be capable of simultaneous observations with VERITAS (for example if HAWC detects flaring emission) and other Pan-American observatories.

HAWC will consist of 300 large steel water tanks. The tank dimensions are 7.3 m (diameter) × 4.5 m (height). Each tank will have a plastic bladder to contain the water and be instrumented with 3 Hamamtsu 20 cm PMTs (reused from Milagro). A rendition and potential layout for the array are shown in fig. 1. The complete array will cover an area of roughly 22000 m^2. While details of the trigger system have yet to be determined a simple multiplicity trigger (30 PMTs) yields an effective area as a function of energy as given in fig. 2. For comparison the same figure also shows the Milagro effective area as a function of energy. While the two instruments have a similar area at high

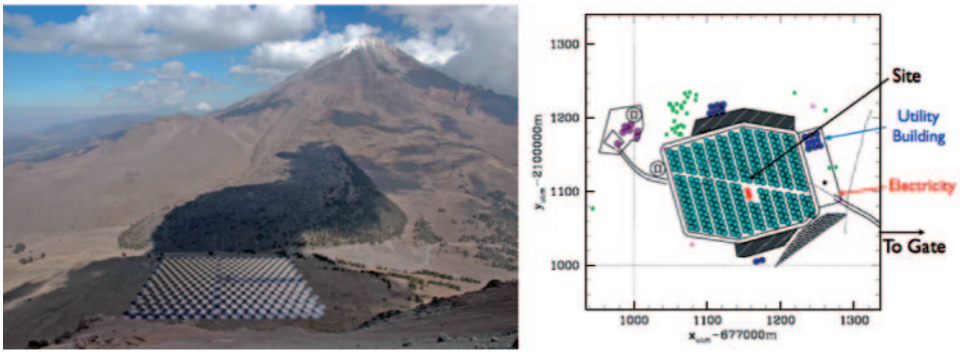

Fig. 1. – On the left a visualization of the completed HAWC array on the slopes of volcan Sierra Negra. Pico de Orizabo is visible in the background. On the right a detail of a potential array design.

energy, HAWC has substantially more area at low energies. For example, at 100 GeV HAWC has roughly a factor of ~ 50 more area than Milagro. Even more dramatic is the behavior of the effective area after the application of a cut to reject the cosmic-ray background. This will be discussed in more detail in the next section.

3. – HAWC performance

3˙1. *Background rejection.* – As in Milagro the background rejetion in HAWC is based upon the identification of EAS with a penetrating component. Though HAWC has only a single layer of PMTs, they are placed at a depth well below the typical path length of electromagnetic particles and are sensitive to the passage of a through-going muon. One of the major improvements relative to Milagro is simply the size of the muon detection area. In Milagro the muon detector was the deep section of the central reservoir which

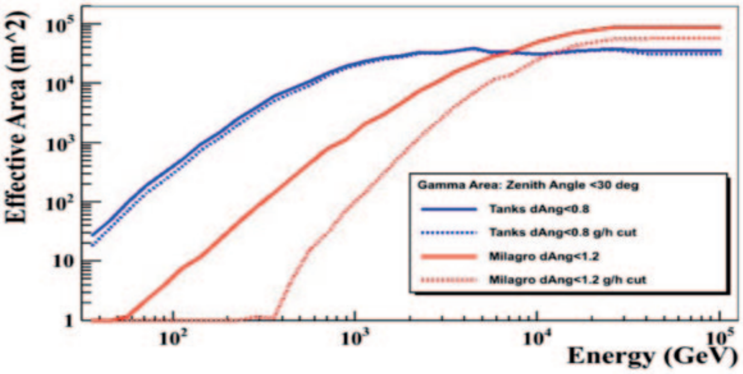

Fig. 2. – The effective area as a function of energy for HAWC and Milagro. The solid lines show the area after a cut on the reconstructed angle is applied (so that the gamma-ray is reconstructed within the angular resolution element of the detector). The dotted lines show the effective area after a cut to remove the cosmic-ray background is applied. Note the dramatic effect in the case of Milagro, while there is essentially no decrease in area for HAWC (see text for details).

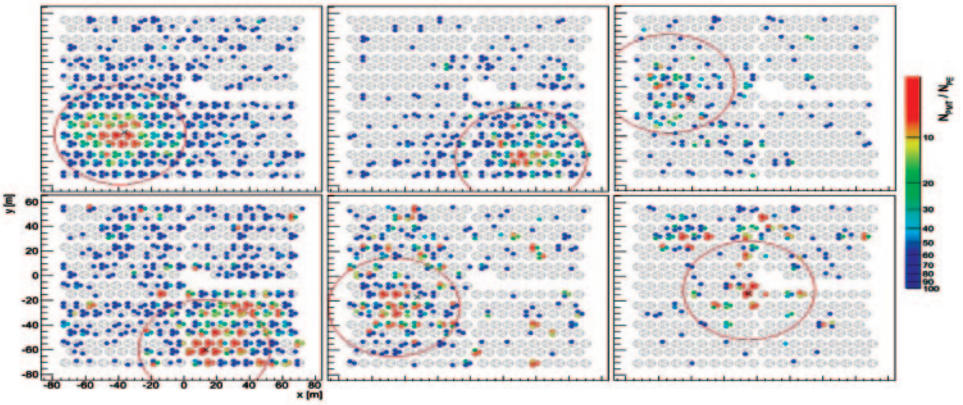

Fig. 3. – (Color online) Six events in HAWC. The top 3 events are gamma-ray and the bottom 3 proton initiated events. Each dot represents a PMT in HAWC and the color scale is proportional to the ratio of the number of PMTs struck in the event to the number of PEs measured in that PMT. Red (light gray) means the PMT has a high level of PEs relative to the event size and blue a low level of PEs relative to the event size. The circle is drawn with a radius of 30 meters and center at the reconstructed shower core. Note that for gamma-ray events there are no red (light gray) PMTs outside of this circle, while for proton events there are numerous red (light gray) PMTs outside of the circle.

had an area of $\sim 2200\,\text{m}^2$. In HAWC, the muon detector is the entire detector area, $\sim 22000\,\text{m}^2$. In Milagro the effect observed in fig. 2 (the large decrease in the low-energy response after the application of a cut on the background) is due to the fact that near the core of an EAS (even one initiated by a gamma-ray) the e-m particles have a higher energy and a large density. This led to large light levels in the bottom layer of Milagro near the core of an EAS. This behavior is similar to that observed by the passsage of a through-going muon. Therefore, in Milagro we rejected most of the low-energy gamma-rays—as only low-energy gamma-rays with cores intersecting the main reservoir could trigger the detector. Because the HAWC muon detection area is so large we can fit the core of the air shower and apply the background rejection cut to only those PMTs that lie outside of a large region (30 m) around the core. This is illustrated in fig. 3. (In Milagro such a cut would have encompassed the entire muon detection area and therefore could not be applied.) The background rejection cut is based on the identification of PMTs outside of a 30 meter radius from the reconstructed shower core with a large number of PEs relative to the event size (as determined by the number of PMTs struck in the event)—the red PMTs in the figure.

3˙2. *Gamma-ray burst sensitivity.* – Observations by the Fermi LAT have demonstrated that GRBs emit photons with energies at least up 90 GeV (after correction for the redshift of the source). This is an energy range that overlaps with that of HAWC. From fig. 2 we see that HAWC will have over $200\,\text{m}^2$ of effective area at 100 GeV and therefore will be substantially more sensitive than Fermi (which has an area of $\sim 1\,\text{m}^2$) to the highest energy emission from gamma-ray bursts. While detailed predictions of the number of GRBs that HAWC will detect have not been carrried out—we have simulated the response of HAWC to some of the GRBs detected by Fermi. In fig. 4 we show the simulated response of HAWC to a GRB at a redshift of 0.9. While we have assumed that

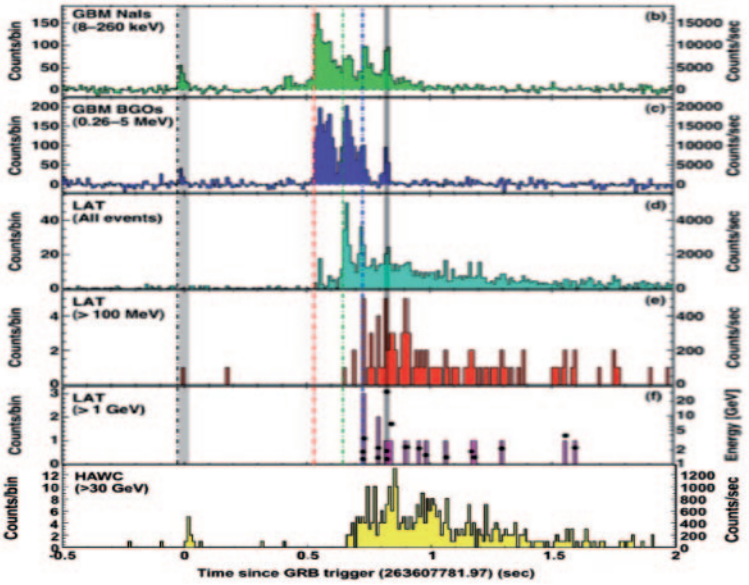

Fig. 4. – Fermi observation of GRB090510 at a redshift of 0.9 (top 5 panels) and the simulated lightcurve from HAWC (including background), bottom panel. For the given redshift the cutoff energy is ∼ 125 GeV. If the zenith angle of the GRB is less than 25 degrees this would result in roughly 200 detected events in the first second of the GRB.

the GRB spectrum is only cutoff by interactions with the extragalactic background light (EBL), even if the inherent spectrum cutoff at 50 GeV, HAWC would detect this burst with a significance of 5 standard deviations. Together with Fermi, HAWC can map the energy spectra of GRBs to the highest energies and thereby probe the conditions in the acceleration region (bulk Lorentz factor, radiation fields, etc.). In addition, HAWC will search for GRBs autonomously. We will implement a real-time search of the data and alert other observatories such as VERITAS to the occurrence of a GRB.

3˙3. *DC survey sensitivity.* – Every source within the field-of-view of HAWC (roughly 2πsr of the sky) will be observed for ∼ 1400 hours per year. Such large observation times enable HAWC to peform a sensitive unbiased survey of an entire hemisphere of the sky. In addition, the long exposure time will give HAWC excellent sensitivity to the highest energy gamma-rays, where the paucity of signal is the main determinant of experimental sensitivity. In fig. 5 we show the DC sensitivity of HAWC after 1 and 5 years of data taking. This corresponds to a sensitivity of roughly 20 mCrab over the entire hemisphere after 5 years of operation.

4. – Conclusions

With the success of the Milagro observatory, the role of EAS detectors in ground-based gamma-ray astronomy has been well established. HAWC is a second-generation water Cherenkov detector that will have 10-15 times the sensitivity of Milagro. The large field-of-view, high duty factor, and improved sensitivity will make HAWC an excellent instrument to study both transient and steady emission in the Universe. Within the Galaxy

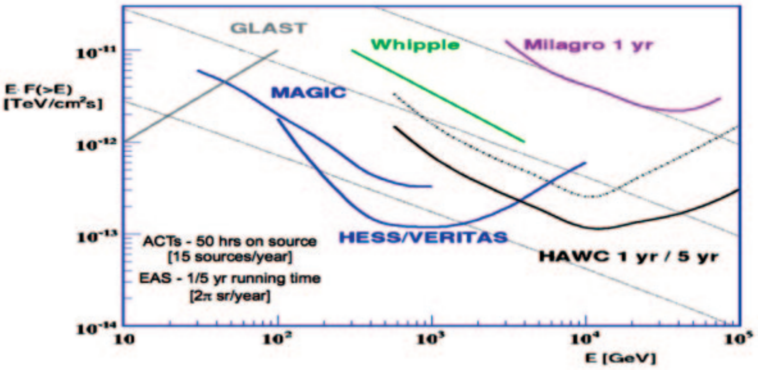

Fig. 5. – The sensitivity of HAWC, compared to other gamma-ray instruments, to a steady signal with a Crab-like spectrum. The solid line shows the HAWC sensitivity after 5 years of operation and the dotted line after a single year of observation. For IACTs the sensitivity is given for a 50 hour observation period (observation of 15 sources per year).

HAWC will have unparalleled sensitivity to the highest energy gamma-rays (due to the long integration times available), excellent sensitivity to the Galactic diffuse emission at TeV energies, and other large sources. In the extragalactic realm, with a substantially lower energy threshold than Milagro, HAWC will detect many transient events from known AGN and have good discovery potential for AGN as yet undetected in the VHE energy band. Finally, as a gamma-ray burst detector HAWC will have a unique role to play, together with the Fermi instrument we will measure the highest energy emission from gamma-ray bursts, the key to our understanding of the emission mechanism and environment. As of this writing HAWC has been funded by the U.S. National Science Foundation and Department of Energy, and the Mexican Conacyt. Given the current funding profile we expect to be taking data with the full array in 2014.

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