HAWC in the Fermi Era

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***Abstract*. The High Altitude Water Cherenkov (HAWC) gamma-ray observatory will be a wide field of view, continuously operated, TeV gamma-ray observatory. HAWC is a natural extension of Milagro, which has demonstrated the ability to detect, at TeV energies many of the galactic sources which have been observed by the Fermi LAT in the GeV energy range. Since Milagro was a first generation detector constructed in a preexisting reservoir at a relatively low elevation (2640m), what Fermi was able to see in several months took Milagro ∼5 years to see. HAWC will be constructed as a joint Mexican-US collaboration on the Sierra Negra Mountain in Mexico at an elevation of 4100m. The design of HAWC was optimized using the lessons learned from Milagro and will be ∼15 times more sensitive than Milagro when completed. This improvement in sensitivity will allow HAWC to measure or constrain the TeV spectra of most of the Fermi discovered GeV sources. In addition, above 100 GeV HAWC will be more sensitive than the Fermi and be the only ground-based instrument capable of detecting prompt emission from gamma-ray bursts in this energy regime.**

***Keywords*: HAWC, Fermi, TeV Gamma Rays**

I. INTRODUCTION

High energy gamma rays probe the most extreme astrophysical environments including those that produce the highest energy cosmic-ray particles. The Milagro observatory has demonstrated that a detector with a wide field of view (2sr) and nearly 100% duty cycle can discover new sources of TeV gamma rays at energies between 1 and 100 TeV[1] [2], and map the diffuse emission from the plane of our Galaxy[3]. Now that the Fermi Gamma Ray Telescope is surveying the sky with unprecedented sensitivity in the GeV energy range, a next generation wide-field telescope with comparable sensitivity to Fermi in the TeV will allow us to measure or constrain the high energy behavior of most of the Fermi discovered GeV sources.

The HAWC (High Altitude Water Cherenkov) observatory builds on the experience and technology of Milagro to make a second-generation high-sensitivity detector. This unique detector will be capable of continuously surveying the TeV sky for steady and transient sources from 100 GeV to 100 TeV with a sensitivity ∼ 15 times that of Milagro.

HAWC will be built on a plateau at Sierra Negra in Mexico at an altitude of 4100 meters above sea level (See Figure 1). The baseline detector design calls for 900 large water tanks (4m diameter x 5m depth) each instrumented with a single 20 cm photomultiplier tube looking up at the water volume from the bottom of the tank. The tanks will be densely packed to cover an area of ∼20,000 m^2. (See Figure 2). The increased dense area (especially the deep area used for background rejection, which is 10x that of Milagro), the increased detector altitude, and the optical isolation of the detector elements lead to the large increase in sensitivity relative to Milagro.

Fig. 1: HAWC depicted on the Sierra Negra with the Pico de Orizaba in the forground. The LMT can be seen just above HAWC.

II. KEY SCIENCE GOALS OF THE HAWC OBSERVATORY

The key science goals of HAWC will be to:

1) Map the Galactic diffuse gamma-ray emission from 1 TeV to 100 TeV (spatially and spectrally resolved) and thereby measure the cosmic-ray flux and spectrum throughout the Galaxy. Regions with emission above that expected from the observed matter density are prime candidates for cosmic-ray acceleration sites.
2) Measure the spectrum of Galactic sources to the highest energies up to and beyond 100 TeV. Such emission is a clear indication of proton acceleration.
3) Perform an unbiased sky survey with a detection threshold of ~ 30 mCrab in two years over 2π sr of the sky.

Fig. 2: HAWC 900 tank baseline configuration depicted on the Sierra Negra site

4) Study transient emission from AGN. With the sensitivity to detect a flux of 5 times that of the Crab in 10 minutes HAWC will monitor all AGN with Declinations between 60 and -20 degrees. This data set will enable multi-wavelength campaigns and opens the possibility of discovering orphan TeV flares.
5) Study the local anisotropy in the cosmic radiation in particular determine the gamma-ray fraction of the anisotropy and measure the energy spectrum of the anisotropy. These measurements are important in understanding if there is a local source of cosmic rays or perhaps a more exotic mechanism responsible for the observed anisotropy.
6) Monitor the sky for VHE emission from gamma-ray bursts. Above 100 GeV HAWC will be more sensitive than the Fermi telescope and be the only ground-based instrument capable of detecting prompt emission from gamma-ray bursts in this energy regime. This capability will provide an excellent complement to IACTs which will be sensitive to emission occurring 40 seconds after the burst onset.

III. Milagro and Fermi

Recently, the Fermi collaboration released their Bright Source List[4]. Of the 34 sources in the Milagro field of vew 14 have signficances greater than 3σ [1]. Figure 3 shows the Milagro sky maps in the regions of Fermi LAT bright sources. Also 9 of the 16 Fermi bright source list pulsars in the Milagro field of view are seen at greater than three sigma in Milagro. (Several others are seen at greater than 2 sigma. The Fermi exposure was approximately three months compared to about five years for Milagro. Thus Fermi had ∼20 times less exposure implying that for the same significance Fermi was $\sqrt{20} \sim 4.5$ more sensistive than Milagro. The ratio of the significance for Fermi on galactic sources to Milagro is shown in Table I. From this table we see that for many sources Fermi has ∼3 times the signficance of Milagro. Combining this we estimate that Fermi has between 10-20 times the sensitivity in the GeV that Milagro has above 10 TeV.

TABLE I: Milagro Fermi comparison

Fermi Source	Ratio of $\frac{Fermi\ \sigma}{Milagro\ \sigma}$	Milagro σ's
0FGL J2021.5+4026	16.	4.2
0FGL J2020.8+3649	3.7	12.4
0FGL J1907.5+0602	3.5	7.4
0FGL J2032.2+4122	3.1	7.6
0FGL J2229.0+6114	4.9	6.6
0FGL J0633.5+0634	16.0	1.4
0FGL J1953.2+3249	> 9.0	0.0
0FGL J1958.1+2848	2.7	4.1
0FGL J0631.8+1034	2.8	3.7
Crab	7.8	17

IV. HAWC Performance

The simulation of the HAWC detector is an extension of the Milagro simulation14 software package. CORSIKA is used to simulate gamma-ray and hadron induced atmospheric showers, and a custom detector simulation using GEANT4 is used to propagate the secondary shower particles that reach the detector elevation through the detector. Cherenkov light production is simulated and individual Cherenkov photons are tracked. Detailed optical modeling of the water (absorption and scattering), reflection and absorption at surfaces, and the PMT response are included. The simulation has been thoroughly tested through comparison with Milagro data, and predicts the cosmic-ray background rate consistent with balloon measured fluxes and predicts the Crab flux consistent with the IACT measured fluxes. The simulation provides a complete end-to-end simulation of the detector performance. Details of the performance and sensitivity estimation can be found on the HAWC web site.[5]

To further reduce potential systematic errors in the simulation or in measured gamma-ray or cosmic-ray background rates, we estimate signal and background rates in HAWC relative to Milagro and anchor the results to the Milagro measurements of the Crab flux and the background rate. As both experiments share many of the same potential systematic errors, the ratio is nearly systematic free. The detector simulation shows that the sensitivity of the HAWC detector is ∼15 times that of Milagro. Since the time it takes to see a source depends on the sensitivity squared HAWC will see the Crab at 5 every day. Figure 4(a) shows the effective area of HAWC and Milagro and Figure 4(b) shows the angular resolution of HAWC and Mialgro. We find that the angular resolution of HAWC reaches a minimum of $\sim 25°$ above 5 TeV. One would expect that the angular resolution would improve as the energy rises. The flattening is a

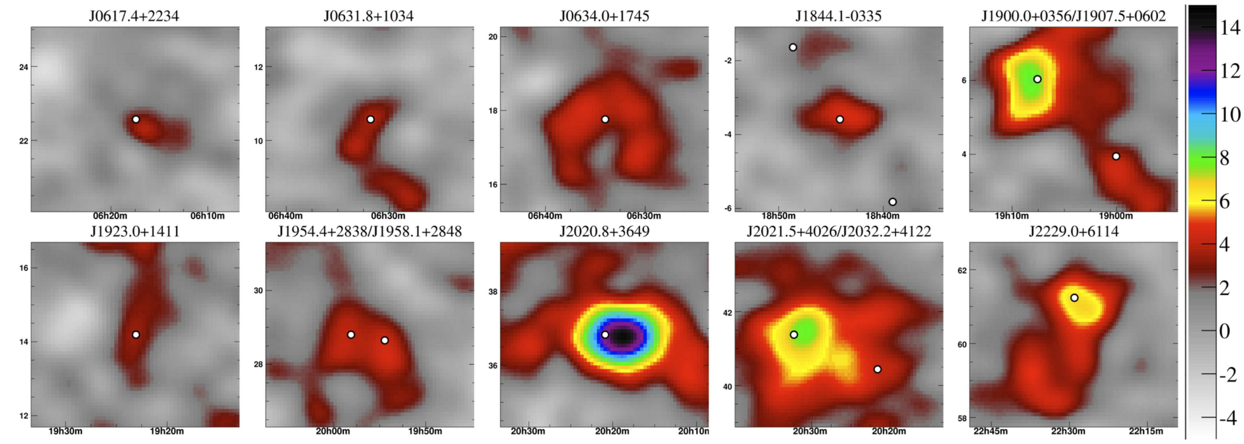

Fig. 3: Shown above are Milagro sources with $> 3\sigma$ corresponding to the Fermi LAT bright source list. Each frame shows a $5° x\ 5°$ region with the LAT sources indicated by white dots. Horizontal axes show Right-Ascension and vertical axes show Declination. The colors indicate the statistical significance in standard deviations.

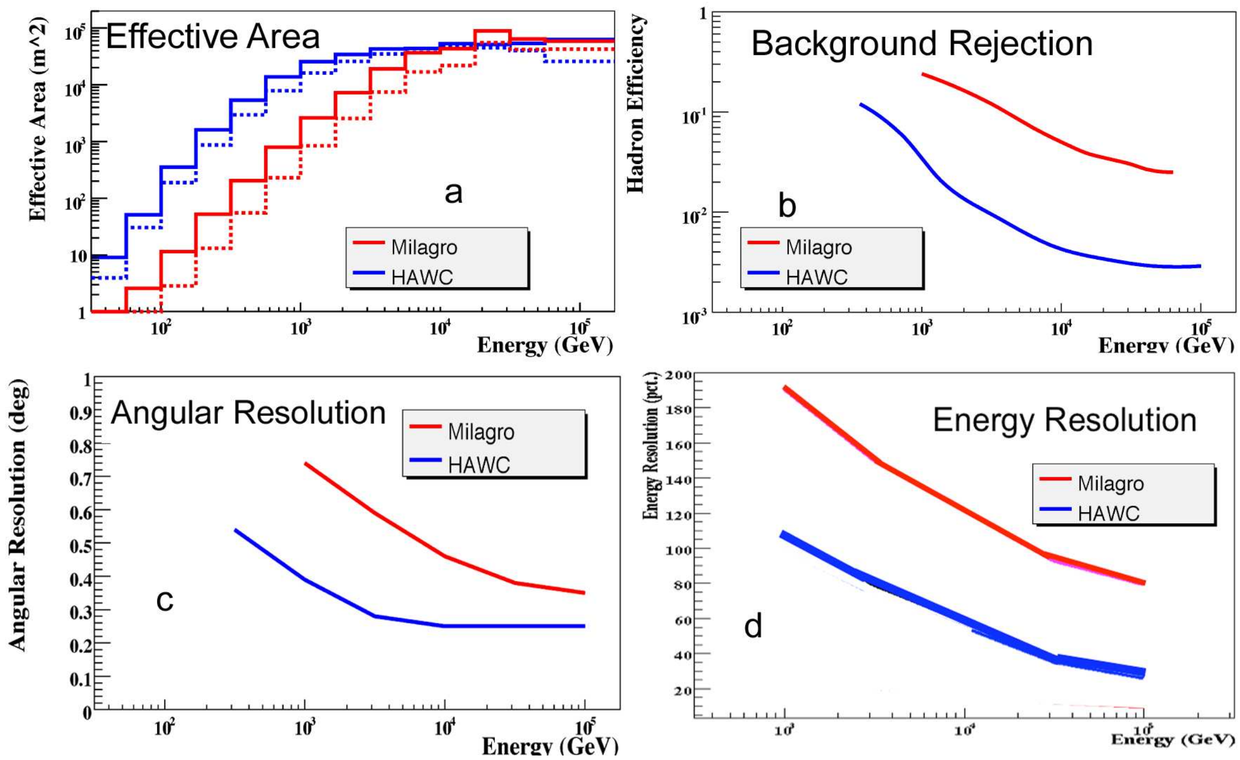

Fig. 4: (a) Effective area, (b) Background rejection, (c) Angular resolution and (d) Energy resolution capability of HAWC and Milagro. Figure 6b is the efficiency for retaining hadrons with the gamma-hadron cut when the gamma-ray efficiency is 50%. The overall sensitivity of the detector depends on all of these quantities.

consequence of systematic errors in the parameterization of the curvature correction as a function of energy. The curvature correction used here was optimized for Milagro and has not been re-optimized for HAWC. As we improve the reconstruction algorithms we expect the angular resolution to improve, however, for estimation of sensitivity, we conservatively characterize the angular resolution as depicted in Figure 4. Notice that HAWC has a substantial effective area well below the nominal threshold. This is a phenomenon that is not unique to HAWC, but common to all EAS gamma-ray detectors due to the well-understood probability that the first interaction will occur lower in the atmosphere. This low energy effective area allows us to see both AGN and GRBs out to a redshift between 0.1 and 0.5

V. HAWC AND FERMI

Fermi will provide a vast number of targets for HAWC to study. As as already been shown, many of these sources extend into the TeV energy range. HAWC will be the ideal instrument to measure the high energy

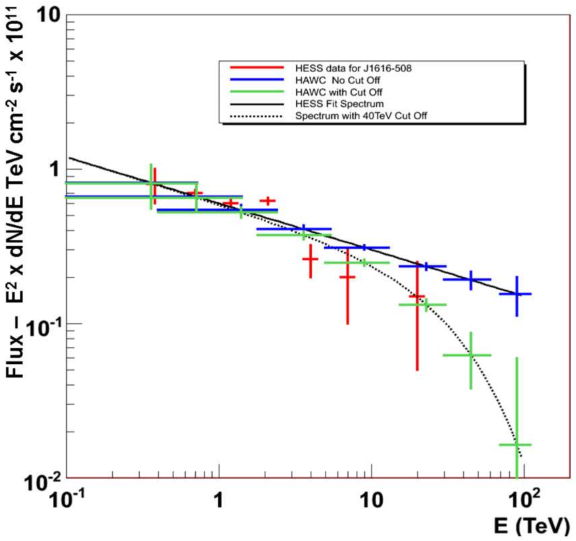

Fig. 5: HESS data is shown (in red) for J1616-508. The two lines show a spectrum with slope -2.3 one (solid) unbroken and one with an exponential cutoff at 40 TeV. A simulation of 1 yr of HAWC data is shown in green (blue) with (no) cutoff demonstrating that HAWC will distinguish between these spectra.

behavior of these sources. HAWC will be vastly superior to Milagro for the measurement of gamma-ray spectra both due to improved sensitivity and energy resolution. The superior energy resolution is achieved through the increased elevation, which allows us to sample showers closer to their maximum, and also because HAWC is larger and more uniform than Milagro, which allows us to isolate the shower core and integrate the EM component. Most of the sources detected in surveys by air Cherenkov telescopes are not detected above 10 TeV. Figure 5 shows the spectra of a typical HESS source and the capability of HAWC to clearly discern the difference between a continuation of this spectra and an exponential cut off of 40 TeV. This combined with the sensitivity of HAWC will allow HAWC to measure or constrain the TeV spectra of most of the Fermi discovered GeV sources.

VI. GRBs

Fermi-LAT observations suggest that the emission extends to high photon energies for both long and short GRB, and the brightest LAT-detected GRB emitted gamma rays up to energies of 70 GeV[6]. To pursue a full study of the highest energies at the prompt phase of a GRB one must use a high FoV instrument to catch GRB, although observations of the latter part of the prompt phase can be performed by rapidly slewing a small FoV instrument to the location of a well-localized GRB. HAWC can search independently for GRBs, but its sensitivity improves by $\sim$2x when a satellite trigger is available and the scientific return from simultaneous observations is far greater. The rate of GRBs observed by SWIFT is $\sim$100/yr in 1 sr, by Fermii-GBM is $\sim$225/yr in 9 sr, and by Fermi-LAT is $\sim$12/yr in 2.5 sr. At any time HAWC observes 2 sr, so 1/6 of the satellite detected GRBs ($\sim$50/yr) will be within HAWCs field of view. The strongest constraints on VHE emission will come from nearby GRBs because VHE -rays are attenuated by interactions with the extragalactic background light. 7% of the SWIFT detected GRBs are within $z<0.5$, so in the 2 sr field of view of HAWC, there will be $\sim$14/yr within $z<0.5$ of which $\sim$1/4 will also be detected by satellites. While an IACT can slew within 3 sr, the reduced duty cycle requiring clear, dark nights gives only 2-3/yr that are observable and fewer than 1/4 will be localized sufficiently by satellites in order to slew to the GRB location.

The number actually detected at TeV energies depends on the (as yet unknown) high energy emission mechanisms. However, we do know that only ap 7% of Swift bursts lie at $z<0.5$, so the large number of observations possible with HAWC are likely the only way to systematically study TeV emission from GRBs. Advanced LIGO (in 2014) is likely to open a new era in multimessager astrophysics, with sensitivity to binary mergers within 200 Mpc. HAWC can make TeV observations of GRB emission produced in these mergers resulting in two powerful new tools in the study of short bursts.

VII. Summary

HAWC will be a second generation wide-field gamma-ray telescope that will be synergistic with IACTs, neutrino detectors and especially the Fermi Gamma Ray Telescope. HAWC's sensitivity in the TeV is well matched to Fermi in the GeV. This will allow us to measure or constrain the high energy behavior of most of the Fermi discovered GeV sources. In addition, HAWC will have a unique capability to detect transient TeV emission of both AGN and GRBs.

References

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