HAWC: A Next-Generation All-sky Gamma-Ray Telescope

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Abstract

The High-Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory is currently under construction 4,100 m above sea level on the slope of Pico de Orizaba in Mexico. HAWC is a high-duty cycle, large field-of-view instrument capable of monitoring the gamma-ray sky between roughly 50 GeV and 100 TeV. The detector will be used to record both steady and transient gamma-ray sources and to provide an unbiased survey of the northern sky with $2\pi$ sr daily coverage. Upon completion in 2014, HAWC will comprise 300 large light-tight water tanks arrayed over an area of 20,000 square meters. Each tank will be instrumented with four photomultipliers to detect particles from extensive air showers produced by gamma rays and cosmic rays. With 15 times the sensitivity of its predecessor experiment Milagro, the HAWC Observatory will enable significant detection of Crab-like fluxes each day at a median energy of 1 TeV. We present the scientific case for HAWC and describe its design and sensitivity.

Keywords: TeV gamma-ray astronomy, cosmic rays, extensive air showers, HAWC

1. Introduction

The High-Altitude Water Cherenkov (HAWC) Observatory near Pico de Orizaba in Mexico (N 18°59′, W 97°18′) is a detector designed to observe gamma rays and cosmic rays in the energy range from about 50 GeV to

\textsuperscript{1}http://www.hawc-observatory.org

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100 TeV. The study of these high energy particles provides us with a better understanding of some of the most extreme astrophysical objects, from supernova remnants in our Galaxy to extragalactic objects like active galactic nuclei (AGN) and gamma-ray bursts (GRBs).

High-energy gamma-ray emission correlates with sites of cosmic ray acceleration, so the observation of the sky in high-energy gamma rays is a promising approach to understanding the origin of Galactic and extragalactic cosmic rays. Charged cosmic rays cannot be expected to point back to their sources at all but the highest energies (some $10^{19}$ eV and above) because of deflection in magnetic fields. Gamma rays, however, point back to their source. By locating and studying high-energy gamma ray sources, we ultimately hope to understand where and how cosmic rays are accelerated. The measurement of the energy spectrum of gamma ray sources in the HAWC energy range from TeV to 100 TeV is a key to understanding whether cosmic ray acceleration takes place in these sources.

High-energy gamma-ray astronomy is by now a well-established field of astronomy. In the MeV to GeV energy range, NASA’s Fermi Gamma-Ray Space Telescope has discovered about 2000 gamma-ray sources above 1 GeV (Nolan et al., 2012). Many of these sources have spectra that extend to even higher energies, up to several tens of TeV. As of late 2012, the catalog of TeV gamma-ray sources consists of 143 sources, of which 87 are Galactic and 56 are extragalactic. The source catalog includes many different types of sources, from AGN to pulsar wind nebulae, starburst galaxies, supernova remnants, globular clusters and star-forming regions.

Unlike the Fermi catalog, the TeV catalog is not an all-sky survey, but a strongly biased source list. This difference is a result of the experimental techniques currently applied to detect TeV sources. Satellite experiments like Fermi have an area of about 1 m$^2$ and are too small to detect the faint fluxes of sources much above 100 GeV. At TeV energies, detectors therefore have to be ground-based and the gamma-ray primaries are no longer detected directly. On entering the Earth’s atmosphere, TeV gamma rays interact with air molecules and induce large cascades of secondary particles, so-called extensive air showers. The properties of the gamma-ray primary have to be reconstructed from the air shower cascade it induces. Several techniques to detect and reconstruct air showers have been developed. By

\begin{footnote}{http://tevcat.uchicago.edu}\end{footnote}
far the most sensitive to date is the atmospheric Cherenkov technique, which uses large mirrors and cameras of photomultiplier tubes (PMTs) to image the Cherenkov light that is produced when relativistic particles of the air shower cascade travel through the Earth’s atmosphere. These imaging atmospheric Cherenkov telescopes (IACTs) are pointed instruments with a small field of view and can observe only a limited region of the sky during the night. Consequently, a large fraction of the TeV sky remains unexplored.

In addition, many gamma-ray sources are highly variable, and some are known to flare by orders of magnitude in flux on short time scales, sometimes down to a few minutes. There is therefore a strong case for an instrument with a large field of view and a high duty cycle which can create an unbiased map of the TeV sky and continuously monitor the sky for transient sources. The HAWC observatory is an instrument conceived to fill this need. Its design is based on technology proven at the Milagro experiment which was operated near Los Alamos from 2000-2008.

There are strong indications that a more sensitive next-generation instrument like HAWC will uncover many additional TeV gamma-ray sources. One of the most striking results from the Milagro experiment is the discovery that a significant number of strong GeV sources from the Fermi Bright Source List (Abdo et al., 2009b) are also observed at multi-TeV energies with Milagro (Abdo et al., 2009c). Many of the Milagro sources that correlate with objects from the Bright Source List are marginal in the Milagro sky survey, with significances between \( 3\sigma \) and \( 5\sigma \) after accounting for the statistical penalty associated with the search for sources over the entire sky, and could therefore not be claimed as sources based on Milagro observations alone. A similar result was found in an analysis of data taken with the Tibet-III air shower array (Amenomori et al., 2009).

The discovery that many marginal TeV sources are correlated with objects from the Bright Source List is strong evidence that bright Galactic 100 MeV to 100 GeV sources are also TeV gamma-ray emitters and that there are potentially many more TeV sources whose flux falls just below the sensitivity of the current generation of instruments. A next-generation all-sky instrument like HAWC is bound to discover many additional sources.

2. The HAWC Observatory

Unlike the IACTs, HAWC does not detect atmospheric Cherenkov radiation, but rather the particles of the air shower cascade that hit the ground.
Since the particles are relativistic, they can be detected by the Cherenkov light they produce in water. HAWC will comprise a large \((150 \times 150 \, \text{m}^2)\) array of 300 light-tight water tanks, each 4.7 m high and 7.3 m in diameter. Fig. 1 (left) shows the planned layout of the detector.

Each water tank will be instrumented with 4 PMTs which record the Cherenkov light produced when the particles of the extensive air shower reach the ground and traverse the detector (Fig. 1 (right)). Since the air shower particles arrive nearly in a plane, the relative time of light arriving in the PMTs can be used to determine the direction of the particle that initiated the shower. HAWC can be operated in all weather conditions and ambient light levels and therefore has a theoretical duty cycle close to 100\%. It has a large effective area and an instantaneous field of view of about 2 sr (or 16\% of \(4\pi\)), with a daily sky coverage of \(2\pi\) sr. Simulations show that the angular resolution of HAWC is about 0.1° for energies greater than 10 TeV. Another crucial parameter for achieving the physics goals of HAWC is the energy resolution. We expect an energy resolution of around 30\% above 10 TeV.

HAWC marks an improvement in sensitivity over Milagro by about a factor of 15. The operation of the detector at high altitude, closer to the shower maximum, also lowers the energy threshold of the detector. This is important, as the source flux drops sharply with energy, and many sources appear to exhibit high-energy cutoffs in their spectra.

HAWC uses two different data acquisition (DAQ) systems. The primary
**Figure 2:** Example for a simulated gamma shower (left panel) and proton shower (right panel) as observed by the full HAWC detector. The color code indicates the number of photoelectrons per PMT.

DAQ system records individual events caused by air showers once a trigger condition is met. In this DAQ mode, HAWC is sensitive to showers with energies larger than about 300 GeV. In addition, a secondary “ scaler DAQ system” operates in a PMT pulse counting mode to detect sudden increases in the counting rate. The scaler system is meant to improve the sensitivity of HAWC to transient phenomena at the lowest energies. It lowers the energy threshold of the detector to about 50 GeV, but it does not provide directional information, since it does not record individual showers. Transient phenomena like solar flares and (potentially) GRBs are observed as detector-wide increases in the counting rate.

Ground-based instruments have to detect gamma-ray sources against the background of charged cosmic rays, which are more than 1,000 times more abundant than gamma rays at TeV energies. Separation of gamma-induced showers from hadron-induced showers is therefore one of the most crucial tasks of data analysis in gamma-ray astronomy. Cherenkov telescope arrays like VERITAS, MAGIC, and H.E.S.S. have developed excellent background rejection by analyzing the shower image on the PMT cameras.

Gamma/hadron separation is more difficult for HAWC, as it is not an imaging detector. However, the background from hadronic cosmic-ray air showers can be reduced significantly by analyzing the two-dimensional pattern of triggered PMTs and their charge. The lateral profile of gamma show-
ers is relatively smooth due to their almost purely electromagnetic nature. Hadron-induced showers have a messy profile with “hot spots” from penetrating particles far from the shower core. Typical examples for simulated proton and gamma showers are shown in Fig. 2. Simulations show that by tagging all events with a large amount of charge far away from the core as hadronic, it is possible to reject more than 99% of the background for events above 10 TeV. The remaining cosmic-ray background is irreducible and needs to be estimated to identify gamma-ray sources (see e.g. Atkins et al. (2003) for a description of the background estimation method).

3. HAWC Science Goals

The science topics that can be addressed with HAWC data range from gamma-ray astronomy to direct studies of TeV cosmic rays to a variety of topics in astrophysics and particle physics. In this section, we discuss a selection of these topics in more detail.

3.1. Gamma-Ray Astrophysics with HAWC

3.1.1. Galactic Sources and Galactic Diffuse Emission

It is generally believed that supernova explosions are responsible for the cosmic-ray flux up to about $10^{15}$ eV. There is currently no direct evidence for this scenario, but we know that supernova remnants provide the environment and the energy to explain the Galactic cosmic-ray flux: the observed energy density of Galactic cosmic rays, $10^{-12}$ erg/cm$^3$, can be sustained by an energy release of $10^{51}$ erg for a Galactic supernova every 30 years.

Gamma rays can be generated when accelerated cosmic rays interact in or near their source. However, the observation of gamma rays is not necessarily a “smoking gun” for cosmic-ray acceleration, because high-energy gamma rays can also be produced by electron acceleration and subsequent inverse-Compton scattering of gamma rays. This mechanism, for instance, is believed to generate the multi-TeV gamma-ray emission seen in the Crab Nebula. Potential cosmic-ray accelerators can be identified by measuring the energy spectrum of sources. A typical electron-produced gamma-ray spectrum would cut off earlier than typical cosmic-ray-produced spectra because of Klein-Nishina effects in the inverse-Compton cross section.

HAWC can build on the success of the Milagro survey of the Galactic Plane, which has revealed sources within the Galaxy that were not seen by other instruments (Abdo et al., 2007). HAWC will perform a survey of the
Figure 3: Sensitivity as a function of energy for HAWC and other gamma-ray observatories (Fermi, Whipple, VERITAS, MAGIC, and H.E.S.S.). The HAWC sensitivity is shown for one year (dashed black line) and 5 years of operation (solid black line). For the IACTs, we assume 50 hours of on-source observation. The grey lines indicate 0.01, 0.1, and 1.0 times the flux of the Crab Nebula.

Galactic Plane and measure the spectrum of Galactic sources up to 100 TeV to address the question of whether the source spectra exhibit a cutoff or continue to energies well beyond the reach of inverse-Compton upscattering. The sensitivity of HAWC to TeV gamma-ray sources is compared to other gamma-ray detectors in Fig. 3. Given that the IACTs are pointed instruments, the sensitivities of HAWC and the IACTs are notoriously difficult to compare. Here, the HAWC sensitivity is estimated for a full year and five years of observation, and the IACT sensitivity assumes 50 hours of on-source time (approximately several months of observing time).

Galactic diffuse emission is produced when cosmic rays interact with interstellar gas and produce pions, which subsequently decay into gamma rays, and when high-energy electrons interact with gas and radiation fields. The measurement of the diffuse flux can therefore be used to find regions of cosmic-ray acceleration in the Galaxy. Milagro has measured an excess of diffuse emission throughout the Galaxy at energies around 10 TeV (Abdo et al., 2008b) with a flux about 8 times higher than predictions based on the
GALPROP model (Strong & Moskalenko, 1998). The largest excess comes from the Cygnus region of the Galactic Plane, and Milagro was able to resolve the emission inside and outside of this region. HAWC will refine these observations and measure the diffuse gamma-ray spectrum at energies above 10 TeV, spatially resolve the diffuse emission, and extend the measurements to 100 TeV.

3.1.2. Active Galactic Nuclei

AGN were among the first extragalactic sources discovered at TeV energies. They show extreme variability, with flares of up to 50 times their quiescent flux. Their study can provide information on the acceleration mechanisms that produce TeV gamma rays. High-energy gamma rays from AGN are produced by the interaction of accelerated charged particles with ambient matter or radiation fields. Current models differ in whether electrons or hadrons are accelerated in the sources. In leptonic models, electrons produce high-energy gamma radiation via inverse-Compton scattering of ambient photons; for example, from synchrotron emission, from the accretion disk, or from the cosmic microwave radiation. Hadronic models assume that protons and nuclei are accelerated in the source and interact with interstellar material in an astrophysical beam dump. The charged and neutral pions produced in this process decay and give rise to a flux of high-energy gamma rays and neutrinos. AGN can also be used to probe the extragalactic background light (EBL) (see e.g. Dwek & Krennrich (2012) for a recent review) and the intergalactic magnetic field (IGMF) which the gamma rays have to traverse from the sources to us (see e.g. Dolag et al. (2009); Neronov & Semikoz (2009); Arlen et al. (2012) and references therein). Such measurements of the EBL and the IGMF are of considerable importance for cosmology.

HAWC observations will contribute to multi-wavelength campaigns that study a selected object at various wavelengths, from radio to TeV gamma rays, at the same time.

3.1.3. Gamma-Ray Bursts and Other Transient Phenomena

The sensitivity of HAWC to GRBs has been extensively studied and summarized in Abeysekara et al. (2012). Fig. 4 shows an example for the expected sensitivity of HAWC using data from the primary DAQ system. The sensitivity depends on the location and duration of the burst and the shape of the burst emission spectrum. Fig. 4 shows the sensitivity as a function of the spectral index $\gamma$, assuming a spectrum of the type $dN/dE \propto E^\gamma$, for various
values of a sharp high-energy cutoff of the spectrum. The burst location is
at zenith angle $20^\circ$ and the burst duration is 1 s. The left panel assumes
a trigger condition of $n_{\text{Hit}} > 70$, the right panel has a lower threshold of
$n_{\text{Hit}} > 30$, where $n_{\text{Hit}}$ is the number of hit PMTs in the event. Two GRBs
observed by Fermi, GRB090510 (Ackermann et al., 2010) and GRB090902b
(Abdo et al., 2009d), are also shown for comparison. These bursts are of par-
ticular interest to HAWC, as for both bursts, the Fermi Large Area Telescope
(LAT) detected a photon with energy in excess of 30 GeV. The burst fluxes
are scaled to account for the dependence of the sensitivity on the burst du-
ration. The example shows that HAWC will be able to detect GRBs such as
these two bright Fermi GRBs with high significance if their spectrum extends
to about 60 GeV.

In addition to studies that use prior information on burst location and
time, for example from satellites, HAWC will also perform “untriggered”
searches that require no prior information. Such searches are less sensitive,
as the large statistical trial factor from searching over the entire visible sky at
all times needs to be taken into account. This leads to a loss in sensitivity of
about a factor of 2. In this mode, HAWC will be able to provide TeV alerts
for other instruments, for example IACTs, that can follow up with detailed
observations of any flare region discovered by HAWC.

In addition to the main DAQ system, GRB searches can also be performed
with the scaler DAQ system or with a combination of both systems. This
extends the energy range of HAWC’s sensitivity down to several tens of GeV.
Details and examples are described in Abeysekara et al. (2012).

3.2. Cosmic-Ray Physics with HAWC

The high rate of cosmic rays detected in HAWC forms an undesir able
background in the search for gamma-ray sources, but it also makes HAWC a
very sensitive cosmic-ray detector. With HAWC, precision measurements of
small deviations of the cosmic-ray flux from anisotropy, at the $10^{-4}$ to $10^{-5}$
level in relative intensity, are possible in the next few years.

Anisotropy in the flux of charged particles at TeV energies is not what one
would readily expect. Galactic magnetic fields should scramble the arrival
direction distribution of charged primaries in this energy range. Neverthe-
less, over the last decade, several experiments in the northern and southern
hemisphere have reported anisotropy in the arrival direction distribution of
cosmic rays at TeV energies. The anisotropy has two main features: a large-
scale structure with an amplitude of about $10^{-5}$ usually described as a dipole
Figure 4: Sensitivity to GRBs as a function of spectral index for various values of a sharp high-energy spectral cutoff. The left panel shows the 5σ discovery potential for a trigger threshold of \( n_{\text{Hit}} > 70 \), the right panel for a trigger threshold of \( n_{\text{Hit}} > 30 \), where \( n_{\text{Hit}} \) is the number of hit PMTs in the event. Taken from Abeysekara et al. (2012).

or a sum of low-order multipoles (Amenomori et al., 2005, 2006; Munakata et al., 1997; Guillian et al., 2007; Abdo et al., 2009a; Aglietta et al., 2009; Abbasi et al., 2010), and a small-scale structure with a few cosmic-ray excesses and deficits of angular size 10° to 30° (Abdo et al., 2008a; Vernetto et al., 2009; Abbasi et al., 2011). Fig. 5 shows the small-scale structure as observed by Milagro in the northern hemisphere and the IceCube detector in the southern hemisphere.

The measurements clearly imply that the propagation of cosmic rays from their sources to us is not understood. There is still no theoretical explanation for the observed anisotropy, but several models can at least qualitatively explain it. Cosmic rays in this energy range are assumed to be accelerated in Galactic sources, most likely in shocks from supernova explosions. The transport of cosmic rays at these energies in the Galactic magnetic field is diffusive. The flux from a nearby source would be observed on Earth as a dipole, so if a few supernova remnants from recent nearby supernovae were responsible for the Galactic cosmic-ray flux (Erlykin & Wolfendale, 2006), we would observe a superposition of these individual dipoles. The observed large-scale structure can qualitatively be described by the sum of the contributions from a few nearby sources and from the large-scale distribution of supernova remnants in our Galaxy (Blasi & Amato, 2011). A more quantitative prediction for the amplitude, phase, and shape of the large-scale anisotropy is not possible, since it would require detailed knowledge of the time and location of recent
(10 to 100 k years) nearby supernovae. However, the model predicts sudden changes in the phase of the anisotropy as a function of energy, and there are indeed first indications of a strong energy-dependence of the anisotropy (Aglietta et al., 2009; Abbasi et al., 2012; Aartsen et al., 2012).

The small-scale structure shown in Fig. 5 is more difficult to explain. Given the energy of the particles and our current knowledge of the strength of magnetic fields in our Galaxy (see for example Han et al. (2006)), the cosmic rays cannot point back to their sources (the Larmor radius of a 10 TeV proton in a $\mu$G field is about 0.01 pc). However, the small-scale structure can be the result of cosmic-ray propagation in turbulent magnetic fields within a few tens of parsecs from Earth (Giacinti & Sigl, 2011).

A direct identification of Galactic cosmic-ray sources from the observed charged cosmic-ray anisotropy is probably impossible. Their study can nevertheless help in understanding cosmic-ray propagation and diffusion, and can potentially provide information about Galactic magnetic fields.
Figure 6: Top: Recent picture of the HAWC site (October 2012), with about 30 completed tanks (HAWC30). Bottom: HAWC30 event display showing an event taken from one of the first runs. The colors indicate the timing of the tube hits. Only 3 tubes per tank were installed for this early run.
3.3. Astrophysics and Particle Physics

Examples of other HAWC science topics include tests of Lorentz invariance with transient sources, searches for exotic signals such as massive relic particles (SUSY Q-Balls, WIMP dark matter, Kaluza-Klein dark matter), and primordial black holes. For a recent review of dark matter searches with gamma-ray telescopes, see e.g. Porter et al. (2011).

4. Current Status and Outlook

As of December 2012, more than 30 tanks have been built and instrumented, and data taking in this configuration (HAWC30) has started. The top panel of Fig. 6 shows a recent picture of the detector, and the bottom panel shows an event taken from one of the first HAWC30 runs. HAWC30 data will be used for first studies of the new detector, including a study of the shadow of the Moon, which will enable us to verify pointing and angular resolution of the detector. By summer of 2013, we expect to operate HAWC in a 100-tank configuration (HAWC100). The full detector (HAWC300) is expected to be completed in late 2014.

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