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First results from HAWC: monitoring the TeV gamma-ray sky

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Abstract. The High Altitude Water Cherenkov (HAWC) Observatory is a wide-field gamma-ray detector sensitive to primary energies between 100 GeV and 100 TeV. The array is being built at an altitude of 4100 m a.s.l. on the Sierra Negra volcano near Puebla, Mexico. Data taking has already started while construction continues, with the completion projected for early 2015. The design is optimized to detect extended air showers induced by gamma rays that pass through the array and to reconstruct the directions and energies of the primary photons. With a duty cycle close to 100% and a daily coverage of ~ 8 sr of the sky, HAWC will perform a survey of TeV emissions from many different sources. The northern active galactic nuclei will be monitored for up to 6 hours each day, providing unprecedented light curve coverage at energies comparable to those of imaging air Cherenkov telescopes. HAWC has been in scientific operation with more than 100 detector modules since August 2013. Here we present a preliminary look at the first results and discuss the efforts to integrate HAWC in multi-wavelength studies of extragalactic jets.

Keywords. gamma rays, cosmic rays, galaxies: active, gamma ray bursts

1. Introduction

Gamma-ray astronomy has become a field of rapid progress and provides unprecedented insights into different astrophysical phenomena. Concerning the study of extragalactic jets in active galactic nuclei (AGN), the main objective is the investigation of particle acceleration that leads to gamma rays with TeV energies, as observed in some blazars. Different gamma-ray detectors cover many orders of magnitude in photon energy and contribute to a complementary picture. Satellite instruments can continuously monitor large regions of the sky but are limited by their size to the higher photon statistics in the MeV to GeV energy range. Ground-based Imaging Air Cherenkov Telescopes (IACTs), on the other hand, have sensitivity to TeV gamma rays, though with a small field of view of $O(1°)$ and a low duty cycle due to the restriction that they run only at nights.

The Milagro Collaboration (Milagro (2004)) proved that a water Cherenkov detector (WCD) optimized for reconstructing gamma-ray air showers can provide observations of TeV gamma rays with a wide field of view and high duty cycle. Milagro was used to successfully map bright galactic sources, but the detector had very limited sensitivity below an energy of 1 TeV. The High Altitude Water Cherenkov (HAWC) Observatory is a direct successor to Milagro with a lower energy threshold down to ~ 100 GeV. It will deepen the survey of gamma-ray emitters in our Galaxy and provide unique insights into extragalactic sources.

The HAWC Observatory is being built on the slope of the Sierra Negra volcano in the state of Puebla, Mexico. Construction and operation is the work of a collaboration of scientists from more than 20 institutions from Mexico and the United States. HAWC is an

Figure 1. A photo of the HAWC Observatory, taken in September 2014, with more than 250 tanks built.

array of individual WCDs, housed in tanks as seen in Fig. 1. This modular design made it possible to start preliminary data-taking with 30 WCDs in the fall 2012 and scientific operation with 111 WCDs in August 2013. While data taking and construction continues, sets of new WCDs will be added over the following months. The start of operations with the full array of 300 WCDs is projected for early 2015.

HAWC can be used to monitor more than 2 steradians (sr) of the sky above it at any time, independent of environmental factors and with an expected downtime on the order of only a few percent due to maintenance. These detector properties will make it possible to run an extensive monitoring program of bright transient gamma-ray sources and to survey a large fraction of the sky with HAWC. The research program of HAWC also includes several other topics, for example the search for gamma-ray signatures from dark matter annihilation or exotic transient phenomena at TeV energies. Charged cosmic rays, a background for gamma ray detection, can be mapped to explore their anisotropy or used to study the interaction with solar particle acceleration.

2. The HAWC Observatory

2.1. *Water Cherenkov detectors*

HAWC is a WCD array located at an altitude of $4,100$ m above sea level. In the final configuration, 300 WCDs housed in commercial steel tanks of 7.3 m diameter and 4.5 m height will cover an area of approximately $22,000$ m^2. The design was explored in a pathfinder experiment at the same location (Abeysekara *et al.* (2015)). A light-proof bladder in each tank is filled with $\sim 200,000$ liters of purified water. At the bottom, three $8''$ PMTs and one central high quantum efficiency $10''$ PMT are facing upwards to detect Cherenkov light from relativistic particles, produced as secondaries in extensive air showers.

Every PMT signal is transmitted to a central counting house via electrical cables that also provide high voltage. Custom front-end electronics translate the voltage pulses into digital time-over-threshold (ToT) records with sub-nanosecond precision for each time stamp. The relative timing of all PMTs can be calibrated to nanosecond precision with

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a central calibration laser. Short laser pulses of 300 ps are transmitted via optical fibers into each WCD, providing measurements of the delay of the electronic PMT responses to photon signals. By varying the laser intensity over four orders of magnitude, the system is also used to provide a charge calibration for each PMT, resulting in translation functions of ToT values into hit charges. A trigger, fully configurable via software on the local computers, reduces the data rate from several hundreds to O(10) MB per second, thus providing a data stream for reconstructing air showers.

2.2. *Reconstruction and event selection*

By measuring the "footprint" of secondary air shower particles penetrating through HAWC, the characteristics of the primary particle can be reconstructed in two steps. First, the charge distribution of an event is fitted to determine the shower core. Then, a log-likelihood algorithm is used to fit a curved shower front to the arrival times of all PMT hits in the event. The resulting incident angle is then recorded as the direction of the primary particle. The angular resolution improves with the shower size and thus with the primary's energy and will be around $0.1°$ for gamma rays exceeding 10 TeV in the final HAWC configuration.

The discrimination of events induced by gamma rays from the much larger background of air showers due to charged cosmic rays relies mainly on the fact that the the latter hadronic showers are much more likely to contain individual muons. By rejecting events with large charge depositions outside the core region, as expected from muons passing near a PMT, a large fraction of events induced by hadronic primaries can be filtered out. The reconstructed directions of the remaining signal and background events are collected in a pixelated sky map. The expected background rate at any point can then be estimated via direct integration of the background outside the region of interest and is used to calculate significances of excesses or deficits. Flux values are determined by comparing excess counts to those of simulated gamma-ray sources.

2.3. *Sensitivity*

Since showers coming from local zenith have the shortest path through the atmosphere, the sensitivity to gamma rays decreases with increasing zenith angles. While there is no hard cut-off, a typical aperture for HAWC is defined as $< 45°$ in zenith angle. Given these constraints and a location at $19°$ northern latitude, the instantaneous field of view of HAWC is $\sim 1/2$ sr and the daily sky coverage ~ 8 sr, or 2/3 of the whole sky.

Compared to its predecessor Milagro, HAWC is located at an altitude about 1750 m higher, bringing the detector closer to the maximum of secondary particles in an air shower and thus reducing the energy threshold by an order of magnitude. Together with the larger densely sampled area for observing air showers, this leads to a projected sensitivity for HAWC being better by a factor 15 than that of Milagro. The energy range accessible by HAWC has a large overlap with those of IACTs, as shown in Fig. 2. A full description of this sensitivity projection for steady gamma-ray point source searches is described in HAWC Collaboration (2013). By characterizing source strengths via the integrated flux above 2 TeV to reduce the dependence on spectral parameters, the full HAWC detector is sensitive to pure power law spectra at a level of $5 \times 10^{-13}\mathrm{cm}^{-2}\mathrm{sec}^{-1}$ over 5 sr (or 40%) of the sky.

The Crab nebula is the strongest steady TeV gamma-ray emitter in the sky and a good reference source, since it transits every day close to zenith in HAWC's field of view. With the completed detector, this source will be observable with a daily significance of about 5σ and thus serve as a continuous performance verification.

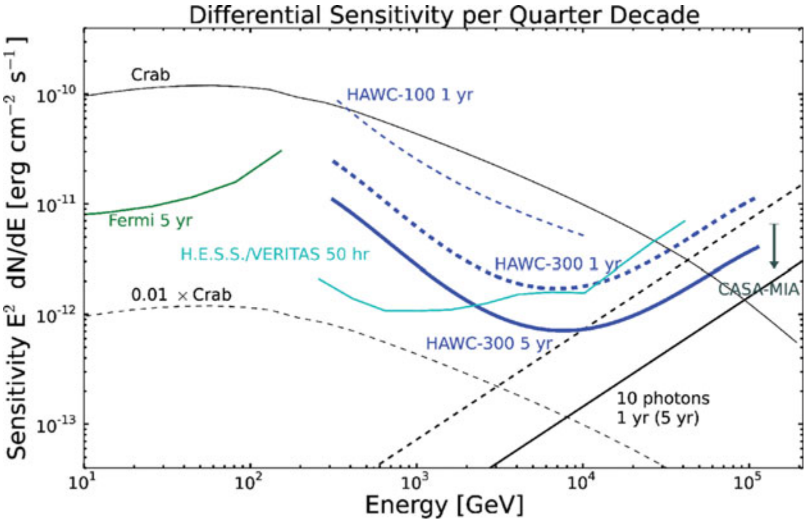

Figure 2. The differential sensitivity of HAWC to point sources.

3. Monitoring Active Galactic Nuclei

AGN are possible sources of the highest energy cosmic rays and a number of AGN, in particular blazars, have been observed to emit TeV gamma rays. Measurements from IACTs have highlighted the variability of these fluxes over very different time scales. By correlating the characteristics of such gamma-ray flares over multiple wavelengths, it is possible to test and refine the models of how and where relativistic particle acceleration can occur in the jets of these objects.

For IACTs, both the duty cycle and field of view limit AGN observation in a way that external alerts are often required to capture flaring activity. The unique capability of HAWC to observe the transits of AGN in the northern and part of the southern hemisphere each day for up to 6 hours will provide unprecedented data on the transient behavior of these sources. The resulting light curves of daily flux measurements can be used in an unbiased study of the frequency of flaring states and will form a database for time-dependent, multi-wavelength studies of AGN, as well as other sources.

The sensitivity of HAWC will also make it possible to detect bright flares, on the order of several Crab flux units, down to time scales of less than one transit. An automated flare monitoring program is being tested on the computers at the HAWC site, where all HAWC air shower data are constantly reconstructed in real time. The program traces the event counts from a list of source directions and produces alerts whenever a significant high state is identified. Such alerts can then be promptly passed to IACTs or other observatories to potentially trigger a follow-up observation with better sensitivity or in a different energy band. Additionally, a more detailed analysis targeting longer flares will also be performed at the site and provide results with a delay of about one day. It will have the potential to detect transients of day-scale length, with fluxes below one Crab unit, that can be identified by updating a sky map of gamma-ray events after every sidereal day and comparing it to a cached average.

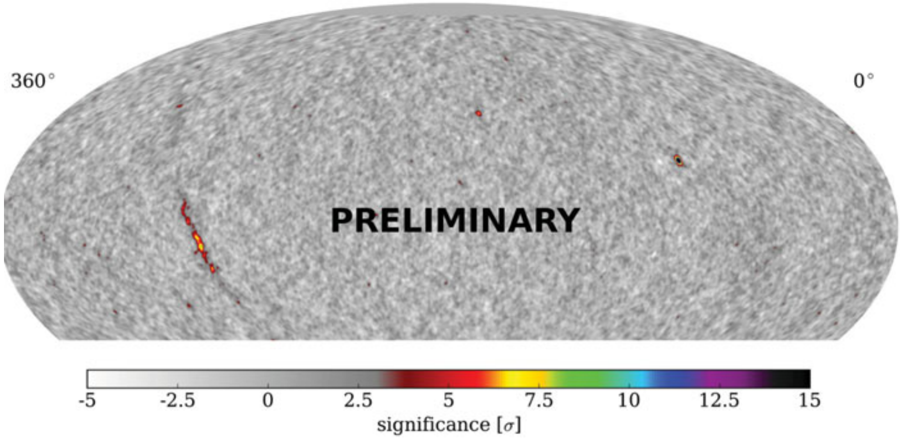

Figure 3. A preliminary sky map of gamma-ray excess significances in equatorial coordinates for HAWC data taken during 260 live days between August 2013 and June 2014.

4. First results

4.1. *Sky map*

Scientific operation of the first 106 HAWC WCDs began in August 2013 and a preliminary analysis, following the basic steps outlined in section 2.2, combined the data taken over 260 live days up to June 2014, while the array size increased to 133 WCDs. The resulting significance map of the TeV gamma-ray sky is shown in Fig. 3. The instrument response is still under investigation and uncertainties on the energy scale and separation of individual sources remain. The event selection is partly optimized on the signal from the Crab nebula, which is observed at a significance exceeding 20σ. The inner part of the Galactic plane is visible as an extended region, partly due to gamma-ray emission from the interaction of cosmic rays with the interstellar gas. The strong TeV blazar Markarian 421 can also be clearly identified in the upper center of this map.

4.2. *Gamma-Ray Bursts*

The Fermi-LAT catalog of gamma-ray bursts (GRBs) in Fermi-LAT Collaboration (2013) shows the extended energy spectra of some events, but due to the limited effective area of a satellite experiment, the actual cut-off for such extended energy spectra remains unknown. As discussed in detail in HAWC Collaboration (2012), the HAWC Observatory has good chances of detecting GRBs if their high energy cutoffs are on the order of $\sim$ 50 GeV or higher. The large field of view and high duty cycle of HAWC make it possible to follow up on many GRB alerts from external satellite monitors with different methods. On the one hand, reconstructed air shower data for the exact time window of the burst can be examined in detail with a predetermined analysis prescription. On the other hand, a second data acquisition system in HAWC monitors all PMT scaler hit rates for a significant excesses in coincidence with a GRB, improving the detector's threshold towards lower energies. An analysis of GRB 130427 with the latter method is discussed in HAWC Collaboration (2014c). HAWC data will also be promptly analyzed for significant gamma-ray flares at any point in the sky, with the aim to find potential GRB candidates and send timely alerts to other experiments.

4.3. *Cosmic rays and dark matter*

The majority of air shower events in HAWC are caused by charged cosmic rays with an average energy of a few TeV. While they are rejected as background for a gamma-ray

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search, they can also be studied to understand their spatial distribution over the large field of view of HAWC. A first analysis of data taken between June 2013 and February 2014 confirms and extends previous measurements of small-scale anisotropic features and has been published in HAWC Collaboration (2014a).

The annihilation of dark matter with itself has been predicted to produce a gamma-ray signal from regions with a high ratio of dark to luminous matter, like it is expected in dwarf galaxies. The sensitivity of HAWC for such an indirect detection of multi-TeV dark matter particles is discussed in HAWC Collaboration (2014b).

5. Conclusions and Outlook

The HAWC Observatory, a second generation water Cherenkov detector, located in Mexico, is now taking data and growing towards completion in early 2015. The design is optimized for gamma-ray astronomy above an energy threshold of $\sim$ 100 GeV and complements existing imaging Cherenkov telescopes by surveying more than 2/3 of the whole sky with its wide field of view. A duty cycle close to 100% allows HAWC to monitor Galactic and extragalactic objects for transient phenomena and search for GRB emission beyond currently established energies. Various analyses are under development to perform real-time searches for AGN flares that will greatly enhance the availability of TeV data for multi-wavelength studies of extragalactic jets. Preliminary data, taken with a partial detector configuration of about 1/3 of the final size, have already been used to study charged cosmic ray distributions and to verify the observation of the brightest known gamma-ray sources. This is the beginning of an unprecedented deep survey of TeV emissions in the Universe.

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