Surveying the TeV sky with HAWC

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The High altitude Water Cherenkov (HAWC) Observatory has been completed and began full operation in early 2015. Located at an elevation of 4,100 m near the Sierra Negra volcano in the state of Puebla, Mexico, HAWC consists of 300 water tanks instrumented with 4 PMTs each. The array is optimized for detecting air showers produced by gamma rays with energies between 100 GeV and 100 TeV and can also be used to measure charged cosmic rays. A wide instantaneous field of view of $\sim 2$ steradians and a duty cycle $> 95\%$ allow HAWC to survey two-thirds of the sky every day. These unique capabilities make it possible to monitor variable gamma-ray fluxes and search for gamma-ray bursts and other transient events, providing new insights into particle acceleration in galactic and extra-galactic sources. In this contribution, we will present first results from more than one year of observations with a partial array configuration. We will discuss how HAWC can map the gamma-ray sky as well as probe other physics including cosmic ray anisotropies and the search for signatures of dark matter annihilation.

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1 Introduction

Gamma-ray astronomy at TeV energies has opened a new window into the most energetic processes in our universe, including galactic particle acceleration sites like supernova remnants and the extremely variable extra-galactic emission from gamma-ray bursts (GRB) and active galactic nuclei (AGN). On the one hand, this allows us to probe astrophysical phenomena in a new way, and, on the other hand, provides the means to study fundamental aspects of TeV-scale physics. Bright extra-galactic flares can be used to understand cosmological features or test the laws for photon propagation beyond energies achieved in laboratories. Furthermore, it is possible to search for gamma rays emitted in processes involving hypothetical particles, in particular candidates for dark matter, and thus provide invaluable experimental constraints for particle physics models. In order to move TeV gamma-ray astronomy towards such precision measurements, it is imperative to focus more on surveys and statistically analyze classes of objects instead of individual case studies. This contribution highlights how the High Altitude Water Cherenkov (HAWC) observatory has started to pursue these goals as the most sensitive TeV survey instrument.

2 The HAWC Observatory

HAWC is an array of 300 water Cherenkov detectors (WCDs). Completed in March 2015, 300 WCDs housed in commercial steel tanks of 7.3 m diameter and 4.5 m height cover an area of approximately 22,000 m². A light-proof bladder in each WCD is filled with 180,000 liters of purified water. At the bottom, three 8′′ photo-multiplier tubes (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. HAWC is located at an altitude of 4,100 m above sea level and thus closer to where the maximum number of secondary particles occur during shower evolution than the predecessor MILAGRO [1]. This results in a lowered threshold of ~ 100 GeV for HAWC and a gain in sensitivity to the steeply falling power-law spectra of astrophysical gamma rays.

Signals from every PMT in HAWC are transmitted to a central counting house via the same cables that provide the 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 an optical calibration system. Short laser pulses of 300 ps are sent via a network of 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. A trigger, fully configurable via software...
on the local computers, reduces the data rate to about 25 kHz.

Reconstructing the characteristics of the primary shower particle for a triggered event includes two steps: first, the charge distribution of an event is fitted to determine the central axis of the shower (shower core), then, a function describing a curved shower front is fitted to the arrival times of all PMT with hits in the event. The resulting incident angle is then recorded as the direction of the primary particle. The angular resolution improves with the size of the shower “footprint” on the detector, and thus, on average, with the primary’s energy. In the preliminary analysis, the resolution changes from $\sim 2^\circ$ to $< 0.5^\circ$ over HAWC’s energy range and is expected to be as low as $\sim 0.1^\circ$ for the highest energies with a fully matured analysis.

Most air shower events that HAWC records are induced by hadronic, charged cosmic rays. Studying the angular distribution has confirmed and expanded the observations of a small-scale ($O(10^\circ)$) anisotropy in the arrival directions at the level of $10^{-4}$ in relative intensity, see [2]. The discrimination of events induced by gamma rays from this background relies mainly on the fact that the hadronically induced showers typically include muons, while gamma-ray showers generally do not. By rejecting events with large charge depositions outside the core region, as only expected from muons passing near a PMT shielded by $\sim 4$ m of water, a large fraction of events induced by hadronic primaries can be filtered out.

HAWC gamma-ray analyses are typically performed as binned analyses, where events are sorted depending on the fraction of PMTs that are hit by an air shower. This variable is a proxy of energy. After applying individual gamma-hadron separation cuts in each analysis bin, 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 [3]. The resulting sensitivity of HAWC to point-like sources of gamma rays is discussed in detail in [4].

Due to the larger path lengths through the atmosphere for air showers arriving from directions closer to the horizon, the sensitivity of HAWC to TeV gamma rays is strongly suppressed beyond zenith angles of $45^\circ$. This defines an instantaneous field of view of about 2 steradians. Since HAWC is operating with a duty cycle $> 95\%$, this wide angular acceptance allows HAWC to scan about two-thirds of the entire sky every day.

3 First Results

During ongoing construction, HAWC took data with an array growing from 90 to 135 active WCDs between August 2013 and July 2014. In November 2014, a configuration of 250 WCDs became operational and the full array of 300 WCDs started taking data
in March 2015. Figure 3 shows a significance sky map of the data from 283 live days of the former configuration (called \textit{HAWC-111}) and 105 days of the latter. Among the most prominent features is an accumulation of TeV gamma-ray sources along the galactic plane. In the inner part of this region, a deconvolution assuming multiple point-like sources with overlapping event distributions, due to HAWC’s limited angular resolution, revealed 10 sources with $> 3\sigma$ post-trial significance, as discussed in [5]. The brightest spot on the right of the map is the Crab Nebula, the brightest steady TeV gamma-ray source. It serves partially as a calibration source for HAWC, for example for optimizing the gamma-hadron separation cuts [6].

The survey capabilities of HAWC provide an excellent opportunity to perform an indirect search for dark matter with HAWC, motivated by models in which annihilation or decay of dark matter produce gamma rays. In regions where an over density of dark matter is expected, for example around the center of our galaxy, a search could reveal such gamma rays if dark matter consists of WIMPs with masses in the TeV range. A dark matter search in the galactic center is complicated by the presence of many baryonic astrophysical sources of gamma rays and will require a more detailed mapping of that region first. Meanwhile, a simpler TeV dark matter study focusing on dwarf spheroidal galaxies that contain no other TeV gamma-ray sources has already been performed with early HAWC data. Limits on the dark matter annihilation cross section are presented in [7], based on the non-observation of significant gamma-ray
excesses from 14 dwarf spheroidal galaxies.

Figure 2: Flux light curve of Markarian 421 for the time between June 13, 2013, and July 9, 2014, in intervals of 7 days, based on fits with a fixed spectral shape with power law index 2.2 and exponential cut-off at 5 TeV and are shown as divided by the average Crab flux observed by HAWC on the right axis. The large uncertainties in the flux around day \( \sim 90 \) are due to a period of construction and maintenance in September 2013 during which HAWC was shut down during day time for several days in a row.

With its ability to scan two-thirds of the sky every day, HAWC provides unparalleled data to search for variability at TeV energies in many different objects simultaneously. For the early HAWC-111 data, light curves of bright and highly variable extra-galactic objects were obtained by binning the data into 7-day intervals and fitting a gamma-ray flux value for each such bin. Figure 3 shows the light curve for AGN Markarian 421. An X-ray flare reported by the MAXI detector happens at the onset of the interval in HAWC data with the highest flux measurement [8]. The chance probability of the HAWC measurement alone to occur as a fluctuation over a constant average flux, with a trial factor for 56 time bins, is \( 1.4 \cdot 10^{-5} \) (4.3\( \sigma \)). This establishes HAWC as a tool to monitor day-scale TeV flaring from AGN and these observations will be used to constrain acceleration models for such sources. By collecting data of extra-galactic gamma-ray emission from many flares and different AGN, it will be possible to systematically probe photon propagation and attenuation and thus study cosmological features like the extra-galactic background light [9] or inter-galactic magnetic fields [10]. Further examples and details about this analysis are provided in [11] and the same methods will be used to search for gamma-ray variability over the whole field of view of HAWC. A separate search for much shorter flares (seconds) of TeV gamma rays from GRBs revealed no significant excesses in early HAWC data, see [12, 13].

The analyses of the galactic plane sources, dark matter annihilation and light curve measurements discussed above were performed within an analysis framework
developed specifically for the wide range of HAWC science topics \[14\]. It is based on convoluting model descriptions of sources with a detector response, established through simulation and reference sources, and comparing those with the observed data via the likelihood formalism. A maximum-likelihood procedure can then yield best-fit results for the parameters of the models. The HAWC analysis software uses the same model interface as that implemented in the more general Multi-Mission Maximum Likelihood (3ML) framework \[15\]. The latter software is designed to support direct joint analyses of data from different experiments. This feature will allow us to perform studies over a much wider energy range than HAWC alone covers, for example by including Fermi-LAT data in a joint spectral fit for any of the above source classes.

4 Conclusions and Outlook

The HAWC observatory has been continuously taking data for two years, first with a partial configuration and then with the completed array since March 2015. The wide field of view and > 95 \% duty cycle provide unprecedented observations of TeV gamma-ray emission from galactic and extra-galactic sources and their spectra and variability. First results include a scan of dense clustering of gamma-ray sources in the galactic plane, a search for TeV dark matter annihilation and the first day-scale TeV light curves obtained with a wide-field water Cherenkov detector. More sensitive analyses based on the most recent data taken with the completed HAWC array will soon reveal many new insights into the TeV sky.

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