Abstract

The High Altitude Water Cherenkov (HAWC) Observatory is a TeV gamma-ray detector located at an altitude of 4100 meters on the northern slope of the Sierra Negra volcano in the state of Puebla, Mexico. The detector will consist of 300 water Cherenkov detectors spread on a 22,000 square meter area, and is expected to be fully constructed by the end of 2014. Thanks to its large field-of-view, good angular resolution and >90% duty cycle, HAWC will allow us to study the Galactic sources at high energies (100 GeV - 100 TeV), diffuse gamma-ray emission, and transient emissions from active galactic nuclei and gamma-ray bursts. The detector started its continuous operation in August 2013 with a fraction of the array, and its size has been increasing since then. The first results of the experiment, with almost one year of data from the partial array, are reviewed in this proceedings.

Keywords: astro-particle, gamma rays, cosmic rays, water Cherenkov array

1. Gamma-ray astronomy

Gamma-ray astronomy studies the cosmic sources that are able to emit electromagnetic radiation of energies above 100 keV. Unlike lower energy photons, like optical and radio, gamma rays are absorbed in the atmosphere. Therefore, in order to detect the primary gamma rays, satellites like the Fermi Gamma-Ray Space Telescope are needed. The size of the satellites limits their sensitivity to energies up to hundreds of GeV due to the low expected fluxes at high energies.

Another way to perform gamma-ray astronomy is to use ground-based experiments which are able to detect the shower of secondary particles produced after the interaction of the primary gamma ray in the atmosphere. These experiments are sensitive to TeV energies. Currently there are two main techniques to perform TeV gamma-ray astronomy from the ground. One consists on collecting the Cherenkov light induced in the air by the secondary particles in the shower, with the goal of inferring the direction and energy of the primary. These detectors are called Imaging Atmospheric Cherenkov Telescopes (IACTs). Current examples of IACTs are H.E.S.S., MAGIC, and VERITAS. Another detection technique consists on using an array of particle detectors. For instance, Water Cherenkov Detectors (WCDs). In this case, the Cherenkov light is produced in water. Examples of experiments using this technique are: Milagro [1], based at Los Alamos National Laboratory in New Mexico (USA), was the pioneer experiment. Milagro ended its operations in 2008. Presently HAWC [2], with an improved design compared to Milagro, is the most sensitive experiment using this technique. Both types of experiments complement each other in the exploration of the TeV gamma-ray sky.

2. The HAWC detector

The HAWC collaboration is about to finish the construction of a water Cherenkov array at 4100 m.a.s.l. on the northern slope of the volcano Sierra Negra in the state of Puebla, Mexico (N 19° latitude). The complete detector will consist of 300 WCDs spread on a 22,000 square meter area. Every WCD is a tank made of steel with 4.5m high, 7.5m diameter, and contains 200,000 liters of purified water. At the bottom of the tank there...
are three 8-inch PMTs arranged in a triangular layout, plus one high quantum-efficiency 10-inch PMT at the center of this triangle. The 8-inch PMTs were reused from the Milagro experiment and the 10-inch are brand-new.

The detector is calibrated by means of a laser calibration system which delivers light pulses to all the WCD in the array using optical fibers. This laser signal allows the timing and charge calibration of the individual PMTs, which are crucial for an accurate reconstruction of the air shower.

By the time of the conference more than a half of the WCDs were already operational. The construction of the HAWC detector is expected to be completed by the end of 2014.

3. Detector performance

HAWC is a second generation Water Cherenkov experiment which has several design improvements with respect to Milagro. The most important is that the instrumented area is larger. In addition, HAWC is located at higher altitude (Milagro was located at an altitude of 2600 m), which allows the reduction of the energy threshold and improve the energy estimation, since the experiment is closer to the maximum of the shower. Another improvement is the optical isolation since the PMTs are separated in WCDs instead of being deployed all together in a pond like Milagro. This improves the hadron rejection which is one of the challenges of this kind of detectors. At an energy of 10 TeV, HAWC will reject 99% of the hadrons while still keeping more than 50% of the gamma rays. With all the improvements, the sensitivity of HAWC will be approximately a factor of fifteen greater than to Milagro. HAWC will be able to the detect the Crab at 7σ level in every transit of the source.

The HAWC sensitivity [3] is compared to other gamma-ray experiments in Figure 2. Above 4 TeV, one year of HAWC data will be equivalent to 50h observation from an IACT. One of the main strength of HAWC is its large field of view which is 2 sr instantaneously, and 8 sr daily (60% of the sky). HAWC surveys the gamma-ray sky and is expected to detect 40 of the already know TeV sources\(^1\). Also, being at N 19°N makes the Galactic Center visible for HAWC. Moreover, since HAWC does not need to point to the source, it has the potential of discover new sources and identify regions of interest that may have been missed by IACTs.

4. First results

Since August 2013, HAWC has been taking data steadily, with one third of the full detector operational\(^2\). This first year of data has produced some interesting results which are summarized in this section.

4.1. Moon and Sun shadow

Both Moon and Sun block the cosmic rays arriving to the Earth producing a deficit from the corresponding location of these objects in the sky. The shape of the cosmic-ray shadow and its position, as well as the angular resolution of the detector is expected to depend on the energy of the cosmic rays. Therefore, the overwhelming flux of cosmic rays that reach the HAWC detector can be also used to check the pointing accuracy of the instrument.

\(^1\)A comprehensive list of known TeV gamma-ray sources can be found in [4].

\(^2\)For the sake of simplicity, the detector configuration will be expressed by “HAWC” plus the number of WCDs taking data. For instance, HAWC111 means 111 WCDs operational, i.e., roughly one third of the complete detector.
Figure 3 shows the Moon-centered equatorial map showing the shadow of the Moon. With 68 days of data, the deficit is seen as a 20$\sigma$ negative significance.

For the data sample analyzed the median energy is around 2 TeV and the angular resolution is 1.2$^\circ$. Also the deficit is not centered at the exact Moon position due to the deflection of the cosmic rays by the Earth’s magnetic field. This deflection is roughly 1$^\circ$. Both the width and the shift of the Moon shadow agrees with the expectations from Monte Carlo simulations.

4.2. All-sky map

The preliminary HAWC all-sky map\(^3\) is shown in Figure 4. The map shows the significance obtained with 260 days of data from a fraction of the detector growing from 106-133 WCDs. The Crab nebula has been already observed by HAWC at a significance greater than 20$\sigma$ even if there are still some caveats to be addressed. For instance, there are absolute energy scale uncertainties, absolute pointing uncertainties, and apparent source confusion. Also it is important to mention that this analysis was partly optimized on the Crab nebula.

Other characteristic TeV sources like Mkr 421 were already visible with significances above 5$\sigma$ level. Also in this map it is easy to observe several significant regions in the Galactic Plane.

4.3. Cosmic-ray anisotropy

The anisotropy of the arrival direction of the cosmic ray, which was first detected by Milagro [5], and later on confirmed by other experiments like IceCube [6], has been also observed with HAWC [7]. Figure 5 shows the sky map obtained with 113 days of HAWC30 data. It contains $5 \times 10^{10}$ cosmic-ray events with a median energy of 1.9 TeV, and a median angular resolution of 1.2$^\circ$. The map shows the significance computed by using a 10$^\circ$ smoothing angle.

There are 3 regions with an excess of cosmic rays above 5$\sigma$ level. Region A and B were already reported by Milagro experiment, and region C was recently announced by the ARGO-YBJ collaboration [8].

The origin of the cosmic-ray anisotropy is unclear. HAWC will shed some light by measuring the spectrum, flux, and variability of the cosmic-ray anisotropy. This will also lead to a better understanding of cosmic-ray propagation.

4.4. Gamma-ray burst

Gamma-Ray Bursts (GRBs) are one of the most energetic processes in the universe. GRBs have been detected up to several GeV by Fermi-LAT [9]. However none of the ground-based experiments have detected one yet. The main problem is that they are unpredictable, and due to the reduced duty cycle of the IACT, it is difficult to detect them. The large duty cycle of HAWC (>90%), together with its large field of view makes HAWC the ideal experiment to detect GRBs at TeV energies. The HAWC expectations for detecting GRBs, under some spectrum assumptions, have been discussed in [10]. HAWC is expected to detect a rate as high as $\sim 1.6$ GRB per year.

One of the brightest GRB in the last years happened while a small fraction of the detector (HAWC30) was taking data, and only the scaler data acquisition system (DAQ) was active. The burst was not detected, and the corresponding upper limits were derived [11] (see Figure 6).

It is important to notice that this burst also happened at low elevation (33$^\circ$) where the detection effective area of the experiment is reduced by two orders of magnitude if compared to the one when the source is at zenith. A similar GRB would be easily detected by the full HAWC detector if it happens close to zenith.

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\(^3\)This is the most up to date version of the HAWC skymap. At the conference it was shown a version with only 154 days of data.
Figure 4: Preliminary all-sky map from HAWC in Galactic coordinates. This map was obtained with 260 days of data from a partial array (see text). The Galactic Plane together with some known TeV sources are clearly visible.

Figure 6: HAWC upper limits on GRB130427A. Together with the complete HAWC sensitivity and the flux measured by Fermi. The full detector (HAWC300) is shown for comparison.

4.5. Dark matter

The HAWC observatory is also a good instrument to perform indirect searches for dark matter [12]. In particular, HAWC will be sensitive to gamma-ray signatures of high-mass (multi-TeV) dark matter annihilation, constraining the mass, annihilation spectrum, and annihilation cross-section. One of the most promising candidates to possess big amounts of dark matter are the so-called dwarf spheroidal galaxies. These galaxies have low luminosity, which means low gamma-ray background. However, they have a relatively large concentration of dark matter, so a gamma-ray signal with hard spectra from one of these objects would be indicative of dark matter annihilation. Figure 7 shows the upper limits for one of the best candidates of dwarf galaxies, Segue1. These limits correspond to the particular case where dark matter annihilates into $\tau^+\tau^-$. The plot has 83 days of data taken with HAWC30 configuration. Also, the predicted limits with 180 days with HAWC111 are shown, together with limits from other experiments on the same source.
5. Outlook and prospects

The HAWC gamma-ray observatory is just a few months away from being completed. Thanks to the non-pointed observations, large field of view, and a high duty cycle it is the perfect instrument for surveying the gamma-ray sky. HAWC is already the most sensitive detector of its type.

Some of the scientific prospects of the experiment include the detection of new TeV sources, measurement of the spectrum of Galactic sources at high energy, detection of GRBs at high energies, detection of transient sources and prompt notification to other experiments, study of the diffuse Galactic emission, cosmic-ray anisotropy, constraints on the existence of the nearby dark matter, evaporation of primary black holes [13], test of Lorentz invariance, and search for exotic signals like SUSY Q-balls.

The HAWC Gamma-Ray Observatory has been running for more than one year now. A selection of the first results were summarized here, and several analysis are ongoing. The collaboration is expected to deliver new and exciting results in the following years.
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References