First scientific contributions from the High Altitude Water Cherenkov Observatory

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Abstract. The High Altitude Water Cherenkov Observatory (HAWC), located at the slopes of the volcanoes Sierra Negra and Pico de Orizaba in Mexico, was inaugurated on March 20, 2015. However, data taking started in August 2013 with a partially deployed observatory and since then the instrument has collected data as it got closer to its final configuration. HAWC is a ground based TeV gamma-ray observatory with a large field of view that will be used to study the Northern sky with high sensitivity. In this contribution we present some of the results obtained with the partially built instrument and the expected capabilities to detect different phenomena with the complete observatory.

1. The HAWC observatory
The HAWC collaboration completed the construction of an array of Water Cherenkov Detectors (WCDs) at around 4100 meters above sea level at the slopes of the volcanoes Sierra Negra and Pico de Orizaba in the state of Puebla, Mexico. The array consists of 300 WCDs that cover an area of approximately 22 000 square meters. Each WCD has a steel structure with dimensions 4.5 m high, 7.3 m diameter and with a volume of around 200 000 liters of purified water contained in a specially designed plastic bladder. Each WCD is instrumented with four PhotoMultiplier Tubes (PMTs) facing towards the water volume. Three of the PMTs (8-inch diameter) are deployed forming an equilateral triangle with a side length of 3.2 m centered at the WCD. A fourth high quantum-efficiency PMT (10-inch diameter) is located at the center of the triangle. The calibration of the detector is done using a laser system that provides light pulses to the whole array using optical fibers. The laser signal is used for timing and charge calibration of each HAWC PMT.

2. HAWC scientific goals
HAWC will survey continuously 60% of the sky in the energy range from approximately 100 GeV up to around 100 TeV. Thus, HAWC will be able to measure the energy spectrum and variability of gamma ray sources up to the highest energies detected so far. Moreover, as it operates with a duty cycle higher than 90%, HAWC will have the ability to search for transient events in the northern sky and allow for follow up observations from other observatories by sending prompt alerts. The science of HAWC is not limited to the study of gamma rays sources, it will also study the cosmic ray anisotropy (the small-scale cosmic ray anisotropy was first detected by...
its predecessor Milagro [1]), solar energetic transient events, and perform fundamental physics studies in topics such as dark matter and primordial black holes.

3. Early results of the observatory

In August 2013 the construction of the observatory had reached 105 WCDs and data was taken in a continuous way. However, even with a tenth of the complete detector, in April 2013, it was possible to use the scaler system to observe a transient event of the Sun activity known as a Forbush decrease, and to place limits on the high energy emission from a gamma ray burst.

3.1. HAWC sky map

Figure 1 shows a preliminary HAWC sky map that was produced with data from 260 days taken from August 2013 to June 2014. The detector configuration was changing so that the number of WCDs taking data varied with time ranging from 106 up to 133 WCDs. The median energy of the reconstructed gamma rays was of approximately 2 TeV. The angular resolution of the shower reconstruction varied with the size of the events, going from approximately 1.4° when the shower produces signals in few WCDs up to around 0.2° for showers that cover almost the whole array.

![Preliminary HAWC skymap](image)

**Figure 1.** First preliminary HAWC significance gamma ray skymap in Galactic coordinates. The map shows clear emission from some of the known sources, and the Galactic Plane.

There are some caveats to consider for this preliminary analysis. The response of the observatory is still under investigation and there are remaining uncertainties on the energy scale, absolute pointing, and in the separation of individual sources. Taking into account these details one can observe on the sky map several known sources of high energy gamma rays such
as the blazar Markarian 421, multiple sources along the galactic plane and the Crab nebula, which is detected with a significance larger than 20 standard deviations.

3.2. GRB 130427A
The most prominent of the transient phenomena that HAWC will explore are the Gamma Ray Bursts (GRBs). GRBs are powerful bursts of gamma rays that occur randomly in the sky about once per day. These events are associated to supernovas and the merging of neutron stars. A detailed description on the sensibility of HAWC to detect GRBs can be found in [2]. GRB130427A featured the highest energy photon ever detected in such phenomena, which is 95 GeV, as well as the longest $\gamma$ ray duration (20 hours) [3]. When this GRB happened, on March 27, 2013, HAWC was in the early stage of construction, with only 29 WCDs instrumented. Unfortunately, the main DAQ was offline, but the scaler DAQ of HAWC was working monitoring 112 PMTs. The second misfortune for the observation of this GRB with HAWC was that the GRB had an elevation of only 33° in the field of view of the observatory. At that location the sensitivity is approximately two orders of magnitude worse compared to that at zenith and also the energy threshold for detection is increased. The decrease in sensitivity with elevation occurs because at zenith the atmospheric showers have the shortest path through the atmosphere, and this path increases with decreasing elevation. The burst was not detected, but HAWC set limits for the flux at high energy [4], these are shown in figure 2.

![Figure 2. Upper limits for GRB130427A obtained with the partially built HAWC [4]. The sensitivity of the complete observatory for an overhead GRB is shown for comparison.](image)

![Figure 3. Dark matter limits for the dwarf galaxy Segue 1 in the $\tau^+\tau^-$ annihilation channel. The upper limit obtained with 30 WCDs of HAWC is compared with the limits from other observatories, as well as to the sensitivity of the complete HAWC after five years of operation.](image)

3.3. Dark matter searches
After null results of the dark matter searches both at the LHC and by the Fermi satellite, high mass Weakly Interacting Massive Particles (WIMPs) are increasingly interesting candidates for dark matter. Due to its large field of view, HAWC is a sensitive instrument to extended sources that are candidates to contain a large amount of dark matter that could annihilate producing standard model particles that in turn would yield gamma ray signatures. The dark matter searches by HAWC will allow, in case of no detection, to constrain the mass and annihilation cross section of high mass WIMPs. For a complete review of the capabilities of HAWC to indirectly detect high-mass dark matter annihilations see [5]. One interesting target to study with HAWC is the dwarf spheroidal galaxy Segue 1, which is a high mass region with few stars.
Segue 1 is expected to be made mostly of dark matter and due to its low luminosity it also has a low gamma ray background. Figure 3 shows the expected limits on the product of the cross section times the relative velocity of the interacting dark matter as a function of the dark matter mass that can be obtained with HAWC after five years of operations with the complete detector. The figure also shows the preliminary limits established using data obtained with only 30 WCDs in a period of 82 days of data taking, as well as the expected limits that will be obtained after analysing 180 days of data taken with 111 WCDs. The limits correspond to the annihilation channel into a pair of tau leptons.

3.4. Primordial black holes

Primordial Black Holes (PBHs) are an hypothetical type of black hole that could have been formed in the early Universe by the gravitational collapse of density fluctuations. Due to Hawking radiation, PBHs with an initial mass of the order of $5 \times 10^{14} \text{ g}$ should be in the present epoch in the final stage of its evaporation. At the end of the lifetime of PBHs, these produce bursts of high energy fundamental particles including gamma rays in the GeV-TeV range. The large HAWC field of view and high duty cycle ($\approx 95\%$) allow for a wide search of PBHs. Figure 4 shows the sensitivity of HAWC to the PBH burst rate density as a function of the burst duration. For comparison, the figure also shows current limits set by different observatories and the expected sensitivity of HAWC after 1, 2 and 5 years of operations as well as the limits set by the predecessor of HAWC, the Milagro observatory. For a detailed study of the sensitivity of HAWC to observe evaporating PBHs see [6]. In case of no detection, with five years of data HAWC will provide the best limits for the evaporation of PBHs.

![Figure 4. Sensitivity of HAWC to the PBH burst rate density compared to other observatories [6].](image)

![Figure 5. Forbush Decrease observed by HAWC when only 30 WCDs were operational in April 2013 [7].](image)

3.5. Solar energetic transient events

HAWC is also able to study transient events from the Sun, such as ground level enhancements and Forbush Decreases (FDs). The FDs occur when coronal mass ejections travel through the interplanetary medium deflecting galactic cosmic rays that would otherwise strike our planet, producing a decrease in the flux of cosmic rays. Figure 5 [7] shows one FD detected when HAWC had only 30 WCDs, in April 2013. The figure shows the rate as a function of time, measured with the partially built HAWC and a comparison with observations done with neutron monitors in three different observatories. The rigidity cut-off at both Athens and Tsumeb are similar to
the one at the HAWC location, so the time profile and maximum decrease are similar. Hermanus is located in South Africa.

4. Outlook

The HAWC observatory was inaugurated on March 20, 2015. Due to its large field of view and high duty cycle, HAWC will be able to survey two thirds of the sky for transient emission and constrain the gamma-ray spectra of sources up to 100 TeV. In this contribution we described some of the scientific studies that will be done with HAWC and showed a selection of preliminary results obtained while the observatory was still in the construction stage: dark matter searches, PBHs, GRBs and solar physics. The description does not cover the whole scientific goals of HAWC that also include the detection of new TeV sources, the study of diffuse Galactic emission, the detailed characterization of the cosmic ray anisotropy, tests of Lorentz invariance and the search for exotic signals like Q-balls. The HAWC collaboration looks forward for exciting new results in the coming years of operations of the observatory.

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