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Recent results from the HAWC observatory

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Summary. — The High-Altitude Water Cherenkov Observatory (HAWC) is a TeV gamma-ray detector located at an altitude of 4100 meters on the slope of the Sierra Negra volcano in Puebla, Mexico. Inaugurated in March 2015, HAWC observes 65% of the sky every day with more than 90% duty cycle and an excellent angular resolution. HAWC plays an important role as a survey instrument for multi-wavelength studies, and presently is the most sensitive instrument to detect transients and extended sources of gamma-rays at multi-TeV energies. In this contribution I present the recent results from the experiment and discuss the future goals of the Collaboration.

1. – Introduction

Gamma-ray astronomy up to GeV energies is performed using space satellites like *Fermi*. However, at TeV energies the satellites run out of statistics due to their limited size and the decrease of the gamma-ray fluxes with energy.

Ground-based experiments have been conceived to extend the gamma-ray detection to TeV energies. Instead of a direct detection of the primary gamma ray, they detect the shower of secondary particles produced after the interaction with the atmosphere. The recorded information from the shower is enough to reconstruct the energy and direction of the primary. The shower can be detected thanks to the Cherenkov light produced in the atmosphere. This is called Imaging Atmospheric Cherenkov Telescope (IACT) technique, and provides good angular and energy resolution, but a limited duty cycle and a small field of view (around 3°). It has been successfully used by experiments like H.E.S.S. [1], MAGIC [2], or VERITAS [3], and it will be the technique used for the future Cherenkov Telescope Array (CTA) detector [4].

Another approach is to detect the shower at the ground. One example is the HAWC observatory which uses an array of water Cherenkov detectors (WCDs). This technique provides a moderate angular and energy resolution. However, with a high duty cycle and large field of view, HAWC can perform deep surveys and study extended sources.

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2. – The HAWC gamma-ray observatory

The HAWC detector consists of 300 WCDs deployed on a 22,000 square meter area, at 4100 m a.s.l. on the slope of the Sierra Negra volcano in central Mexico (N 19°). Each one of the WCD has the shape of a right circular cylinder with 4.5 m high and 7.3 m diameter. The WCDs are made of steel with a roof that protects it from the extreme altitude conditions of the HAWC site. Inside the WCD a large plastic blag is deployed containing 200 000 l of purified water and 4 photo-multipliers (PMTs). The PMTs are calibrated thanks to a laser system that is able to deliver pulsed light to all the PMTs in the array. Fully operational since March 2015, HAWC is detecting gamma-rays in the energy range from ∼0.5 to ∼100 TeV. The experiment has collected around 17 months of good quality data. The highlights from the results are presented in the next section.

3. – Results

3˙1. *Crab Nebula observation.* – The Crab Nebula was detected with high significance by HAWC [5]. Since the Crab Nebula is probably the most studied source in the gamma-ray sky it was used to check the performance of the detector. For instance, analyzing events reconstructed from a direction close to the Crab Nebula, where it is expected a high gamma-ray population, and compare it to events from a region with no sources was used to test the selection cuts applied to the data to discriminate gammas from hadrons.

Also the events reconstructed close to the Crab, that pass all the selection criteria, constitute a perfect sample to test the angular resolution(1) of the experiment. In HAWC the angular resolution for the most energetic events is better than 0.2°.

3˙2. *Differential sensitivity.* – The differential sensitivity(2) of HAWC and other experiments is shown in fig. 1. The HAWC sensitivity is computed for a simulated source with a flux proportional to $E^{-2.63}$ transiting at the declination of the Crab Nebula (22°). Above ∼10 TeV HAWC sensitivity surpasses the current-generation IACTs. This great sensitivity together with the fact of having a large field of view is allowing the discovery of sources that have been unnoticed by IACTs, especially at high-energies.

3˙3. *HAWC Galactic plane survey.* – HAWC is about to publish the first survey of the Galactic plane with the complete detector operational [6]. Figure 2 shows, in two panels, the significance map of the Galactic plane region. A total of 39 sources have been detected with $\sqrt{TS} \approx 7$, which corresponds to 5σ detection after trials. Out of these 39, there are 16 detected more than one degree away from the location of known TeV sources [7], and therefore, excellent candidates to be new TeV gamma-ray sources.

3˙4. *Extended sources.* – Two significant extended sources have been found by HAWC when using a 2° radius disk for the search. One is coincident with the excess around the Geminga pulsar already reported by the Milagro experiment [8]. In the second one the significant extended emission comes from the vicinity of PSR B0656+14. This source is reported for the first time. Both PSR B0656+14 and Geminga are similar in distance,

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(1) The angular resolution is defined as the angular radius around the true gamma-ray direction in which 68% of events are reconstructed.

(2) The differential sensitivity is defined as the required flux to detect a source at 5σ 50% of the time.

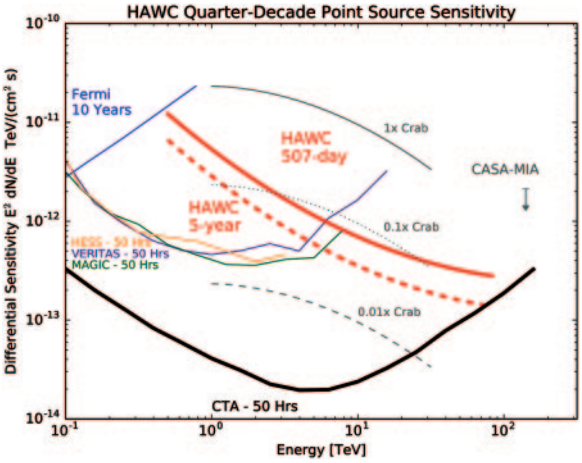

Fig. 1. – Differential sensitivity plot of: HAWC with 507 days of data (red), the HAWC 5-year expected sensitivity (red dashed), IACTs (H.E.S.S., MAGIC, VERITAS, and CTA) for 50-hour observations, *Fermi* LAT satellite for 10 years. The Crab Nebula flux is also plotted as reference.

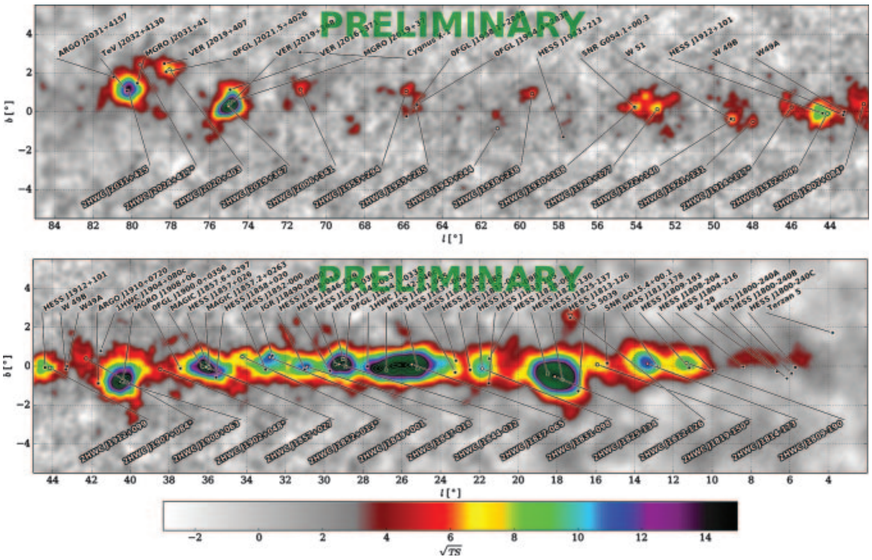

Fig. 2. – Gamma-ray observation of the Galactic Plane by the HAWC observatory.

age, and spindown power. The study of the gamma-ray emission from both sources can provide important information about the electron and positron flux observed at the Earth, and shed some light on the PAMELA positron excess [9].

3˙5. *Extragalactic sources.* – Extragalactic sources are difficult to detect because the gamma-ray flux is attenuated at TeV energies. HAWC has been able to detect two sources: Markarian 421 and 501, which are both well-known TeV blazars. HAWC continuously monitors them providing light-curves and flare alerts [10] to other experiments, so follow-up observations can be performed. HAWC observations show high variability in the measured fluxes over a period of more than a year.

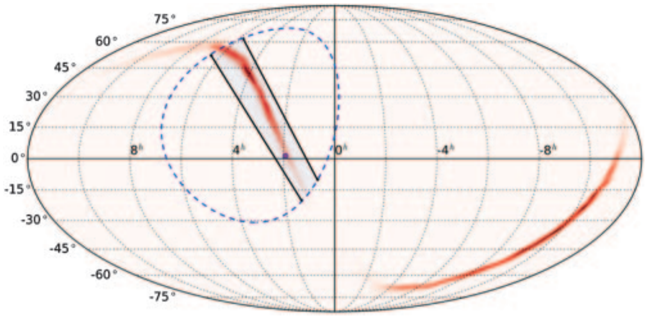

Fig. 3. – Sky map in equatorial coordinates with: the LIGO contours (in red), the HAWC field of view (delimited by the dashed blue line), the HAWC search region (gray area delimited by solid black line), and the most significant gamma-ray event (pink dot) associated with the LIGO event.

3·6. *Gamma-ray bursts.* – HAWC is the only experiment able to observe instantaneously a large fraction of the gamma-ray sky at TeV energies. This permits the search for Gamma-ray bursts (GRBs) with HAWC. The collaboration has developed two search methods. The first one looks for emission from specific coordinates in the sky, triggered by GRB detections from *Fermi* and Swift satellites. The second method is a blind search over all the field of view of HAWC using three different time intervals [11].

Unfortunately there was not successful detection of a GRBs by HAWC yet, and upper limits were derived. The increase of the statistics and the improvement of the analysis and detector performance, especially at low energies, will enhance the chances of detection.

3·7. *Data sharing and multi-messenger astronomy.* – The HAWC collaboration has put a lot of effort on preparing a comprehensive multi-messenger program. Currently HAWC is sharing data via Memoranda of Understanding with the following observatories: IACTs (VERITAS, MAGIC, FACT, H.E.S.S.), space telescopes (Swift, *Fermi*), gravitational waves (GW) detectors (LIGO/VIRGO), and neutrino telescopes (IceCube, ANTARES). Apart is also part of the AMON network [12].

The observation by IACTs of some of the new potential TeV sources reported by HAWC brought the first HAWC source confirmation by VERITAS. The source was in a region already studied but was overlooked in previous observations.

HAWC has also surveyed the position of the HESE IceCube events [13]. The non-detection of a gamma-ray source counterpart has set important constraints on the origin of these neutrinos.

Finally, HAWC is perfectly positioned to search for TeV gamma-rays associated with LIGO GW events, due to the large uncertainties in the localization of the GW event in the sky, and also because HAWC can use archival data in the search. The collaboration has studied in detail the only event that was in the HAWC field of view, *i.e.*, GW151226. The blind GRBs search was used in the analysis of that event, but restricting the region of interest to a 15° wide area centered on the LIGO contour, as can be seen in fig. 3.

The best candidate, occurred 9.98 s after the GW trigger with a post trial p-value of 0.08. Therefore, there was not a significant gamma-ray detection associated. However, the searches will improve with more GW detections and a better localization of the events.

4. – Conclusions and prospects

With 17 moths of data, the HAWC collaboration has started to publish the first results. Some of these results are expected to have a big impact on the gamma-ray astronomy field. The data taking is expected to continue at least for five more years. Moreover, in parallel, the collaboration started the deployment of outrigger stations that will improve the reconstruction and will increase the sensitivity at high-energies.

Finally, the collaboration has started, together with other institutions not in HAWC, to conceive a wide field-of-view TeV observatory for the Southern Hemisphere to be constructed in the near future.

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