Gamma-Ray Astronomy with the HAWC Observatory

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The High-Altitude Water Cherenkov Observatory (HAWC) is a TeV gamma-ray detector located at 4100 m a.s.l. on the slope of the Sierra Negra volcano in Puebla, Mexico. The detector, completed in early 2015, consists of 300 water Cherenkov detectors (WCDs) spread on a 22000 m^2 area. Each WCD is instrumented with four photo-multiplier tubes used to detect energetic secondary particles produced after the interaction of a primary cosmic ray or gamma-ray with the atmosphere. HAWC observes two thirds of the TeV sky every day and it is sensitive to primary particles with energies from several hundred GeV to a hundred TeV. Some of the HAWC scientific goals are to study the Galactic sources at high energies, extended sources, diffuse gamma-ray emission, and transient emission from Active Galactic Nuclei (AGNs) and Gamma-Ray Bursts (GRBs).The recent results from the experiment and the future plans of the collaboration will be discussed in this paper.

1 Introduction

Gamma-ray astronomy allows us to explore the most energetic and violent events in the Universe. A conventional way of performing gamma-ray astronomy implies using space satellites as detectors, since gamma rays are absorbed in the atmosphere. However, due to the decrease of source fluxes with energy, and the limited collecting area of the satellites, ground-based experiments are required to achieve TeV sensitivities.

There are two main detection techniques employed to observe the TeV gamma-ray sky. One is based on the collection of the Cherenkov light induced in the air by the secondary particles in the electromagnetic shower initiated after the interaction of a primary gamma-ray with the atmosphere. This technique is called Imaging Atmospheric Cherenkov Telescopes (IACTs) and it is used by observatories like H.E.S.S., MAGIC, or VERITAS, and will be used for the future CTA observatory. A relatively great angular and energy resolution are some of the main features of the IACT detectors. The second detection technique consists on using an array of particle detectors, for instance WCDs, where the Cherenkov light is produced in the water. This technique is used by the HAWC observatory, which is presently the most sensitive gamma-ray experiment. This type of experiments are characterized by having a large field of view and a high duty cycle.

The HAWC observatory is located at 4100 m a.s.l. on the slope of the volcano Sierra Negra in Puebla, Mexico (N 19° latitude). The array is composed by 300 WCDs. Each WCD is 4.5 m high, 7.3 m 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 the triangle. The PMTs of each tank are calibrated, in time and charge, by a

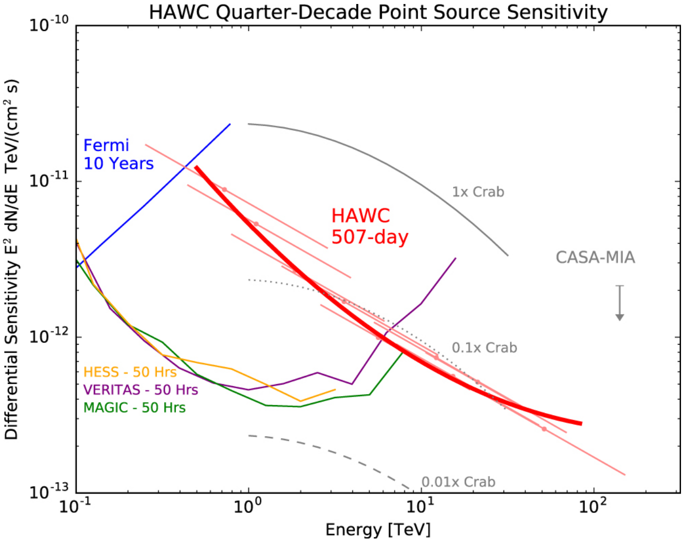

Fig. 1: HAWC differential sensitivity for a source at a declination of 22° compared to other experiments (Abeysekara et al., 2017c). The HAWC flux presented here assumes a source with a differential energy spectrum $E^{-2.63}$ required to produce a $5\,\sigma$ discovery 50% of the time.

laser system which delivers light pulses to all the WCD in the array through optical fibers. A proper calibration is crucial for an accurate air shower reconstruction. By the time of the conference the results of the first 17 months of data were available. The highlight from these results will be presented in the following sections.

2 Crab Nebula observation and detector sensitivity

The Crab Nebula is one of the brightest and probably most studied sources in gamma-ray astronomy. It is detected by HAWC with high significance ($>100\,\sigma$). The analysis of the events reconstructed from a direction close to the Crab Nebula, were used to check the gamma/hadron discrimination capabilities of the detector, as well as the angular resolution at different energies. The Crab Nebula observation and the estimation of the detector sensitivity has been one of the first papers published by HAWC (Abeysekara et al., 2017c). The paper provides detailed information about the analysis process which has been the reference for all the HAWC papers published after it.

From the plot of the sensitivity curve (Fig. 1) one can notice that above 10 TeV the HAWC sensitivity (17 months) surpasses a deep observation (50 h) of the current-generation IACTs. The great sensitivity at high-energies together with the fact of having a large field of view makes HAWC an excellent survey detector in the TeV energy range and above.

3 HAWC catalog

The second HAWC catalog (the first one with data from the complete array) was released by Abeysekara et al. (2017e). The catalog provides the position and flux measured for a total of 39 sources listed, that passed the detection threshold ($5\,\sigma$ post-trial). Out of these sources, 19 are detected at least 0.5° away from another known TeV source as listed in TeVCat[1].

The discovery of new sources by HAWC have triggered follow-up observations from IACTs. By the time when these proceedings were written only one of the new sources from the HAWC catalog was confirmed by VERITAS (Holder, 2017), although follow-up observations are expected to continue.

4 Geminga Region

First HAWC data confirmed one of the most interesting sources discovered by Milagro [2], i.e., the extended emission from the vicinity of the Geminga pulsar (Baughman & Wood, 2015). The large extension of Geminga gamma-ray emission (larger than 2° in radius) made it undetectable for the IACTs so far. HAWC observations with a larger dataset not only confirmed the detection of Geminga but also found a similar source in the vicinity of PSR B0656+14. Both PSR B0656+14 and Geminga are similar in distance, age, and spindown power and are interesting since they have been postulated as one of the main astrophysical candidates to explain the unexpected excess of positrons reported by PAMELA in 2008 (Adriani et al., 2009).

After the study of the gamma-ray emission from both sources, the HAWC collaboration concluded that these sources are unlikely to be the sources of the positron excess, as can be seen in Fig. 2. The analysis details are given in a recent paper (Abeysekara et al., 2017b).

5 Flare monitoring

One of the main features of HAWC is the capability of observing with a high duty cycle (≈ 95%) which, combined with the large field of view, allows for the monitoring of variable sources like AGNs. In a recent publication (Abeysekara et al., 2017a), HAWC has presented the results from the monitoring of two known TeV blazars (Markarian 421 and 501) where clear flux variability on timescales of one day was found for both sources. The highest fluxes observed corresponded to 5 and 3.5 times the Crab Nebula flux for Mrk 421 and Mrk 501, respectively.

Apart from both Markarian blazars, HAWC also monitored in real-time a selected list of gamma-ray sources visible to HAWC every day (Abeysekara et al., 2017f).

Moreover, the collaboration has developed a system that monitors in real-time a selected list of gamma-ray sources in the HAWC visible sky (Abeysekara et al., 2017f). The system automatically sends alerts in real time to other experiments when a source crosses a predefined threshold.

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[1] http://tevcat.uchicago.edu/

[2] http://umdgrb.umd.edu/cosmic/milagro.html

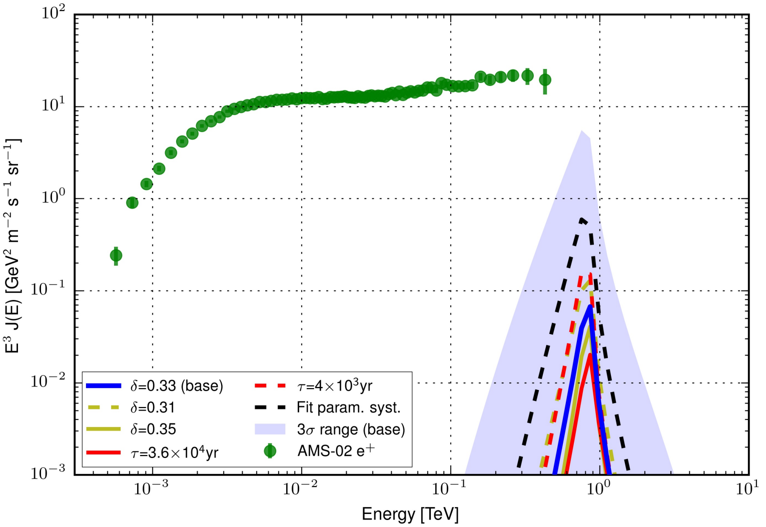

Fig. 2: Positron flux estimated by the HAWC collaboration (blue line) compared with AMS-02 experiment (green points), (Aguilar et al., 2014). The blue shaded region is the $3\,\sigma$ statistical uncertainty. The additional lines reflects the systematics effects of considering different pulsar characteristic: initial spin-down time scale (red lines), the index of the diffusion coefficient (yellow lines), and the parameters of the fitted model (black line).

6 Gamma-Ray Bursts

GRBs are energetic gamma-ray explosions that happen randomly on the sky. The duration of a GRBs is usually of the orders of seconds, although in some times they can last up to several hours. Their short duration and their unpredictability make them difficult to detect by pointing instruments like IACTs. The HAWC collaboration has studied a list of GRBs based on triggers from other experiments. After the first 18 months of data the analysis did not reveal any significant detection of a GRBs by HAWC (Alfaro et al., 2017). Therefore, the upper limits on the gamma-ray emission were set. HAWC chances of detecting a GRB are expected to significantly increase by improvement of the detector sensitivity at low energies, refined analysis techniques, and increase of statistics.

7 Fermi bubbles

Discovered in 2010, the Fermi bubbles are large and symmetrical structures that extend up to about 50,000 light-years up and down from the Galactic center, having the plane of the Galaxy as the symmetry plane. TeV gamma-ray emission from the Fermi bubbles has not been detected yet, but due to its large field of view, HAWC is in a privileged position to observe them. The HAWC collaboration has reported relevant upper limits (Abeysekara et al., 2017d) after the observation of the northern Fermi bubble region.

8 Multi-messenger astronomy

The HAWC collaboration is deeply involved in the multi-messenger program that includes sharing via Memoranda of Understanding with the following observatories: IACTs (VERITAS, MAGIC, FACT, H.E.S.S.), space telescopes (Swift, Fermi), gravitational waves detectors (LIGO/VIRGO), and neutrino telescopes (IceCube, ANTARES).

Triggered by the IceCube collaboration, HAWC already reported the results of the search of some interesting neutrino events (Aartsen et al., 2017). In a similar way, gravitational waves events reported by LIGO/VIRGO are of special interest of HAWC and follow-up observation have been already performed for the most favorable events, e.g. (Abbott et al., 2017).

9 Future

HAWC near-term plans include the deployment of the outrigger array, which consists of 300 extra WCDs that will surround the main HAWC array. These WCDs are 1/80 in size compared to a regular WCD from HAWC and already being deployed at the HAWC site. It is expected that the deployment of the outrigger array will increase the HAWC sensitivity above 10 TeV by more than a factor of 3.

In the more long-term plans, HAWC collaborators together with other external scientists from other experiments have started to discuss about the construction of a wide field-of-view TeV observatory for the Southern Hemisphere. This detector, that will be built from the experience gained from HAWC construction, is expected to complement the future CTA in the south.

10 Conclusion

A summary of the results from the first 17 months of data with HAWC was presented in the conference. Results such as the publication of the HAWC catalog or the observation of the extended emission from Geminga and PSR B0656+14 pulsars have had a big impact on the gamma-ray astronomy field. Apart from keep taking data for several years, the collaboration has started the upgrade of the detector by adding extra WCDs to the main HAWC array that will bring unprecedented sensitivity above 10 TeV, for a survey detector. Finally, together with other institutions, the collaboration is already planning on a wide field-of-view TeV observatory for the Southern Hemisphere to be constructed in the near future.

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