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HAWC: A next-generation all-sky gamma-ray telescope

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Abstract

The High-Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory is currently under construction 4100 m above sea level on the slope of Pico de Orizaba in Mexico. HAWC is a high-duty cycle, large field-of-view instrument capable of monitoring the gamma-ray sky between roughly 50 GeV and 100 TeV. The detector will be used to record both steady and transient gamma-ray sources and to provide an unbiased survey of the northern sky with 2π sr daily coverage. Upon completion in 2014, HAWC will comprise 300 large light-tight water tanks arrayed over an area of 20,000 m^2. Each tank will be instrumented with four photomultipliers to detect particles from extensive air showers produced by gamma rays and cosmic rays. With 15 times the sensitivity of its predecessor experiment Milagro, the HAWC Observatory will enable significant detection of Crab-like fluxes each day at a median energy of 1 TeV. We present the scientific case for HAWC and describe its design and sensitivity.

Keywords: TeV gamma-ray astronomy; Cosmic rays; Extensive air showers; HAWC

1. Introduction

The High-Altitude Water Cherenkov (HAWC) Observatory near Pico de Orizaba in Mexico (N 18°59′, W 97°18′) is a detector designed to observe gamma rays and cosmic rays in the energy range from about 50 GeV to 100 TeV. The study of these high energy particles provides us with a better understanding of some of the most extreme astrophysical objects, from supernova remnants in our Galaxy to extragalactic objects like active galactic nuclei (AGN) and gamma-ray bursts (GRBs).

High-energy gamma-ray emission correlates with sites of cosmic ray acceleration, so the observation of the sky in high-energy gamma rays is a promising approach to understanding the origin of Galactic and extragalactic cosmic rays. Charged cosmic rays cannot be expected to point back to their sources at all but the highest energies (some 10^{19} eV and above) because of deflection in magnetic fields. Gamma rays, however, point back to their source. By locating and studying high-energy gamma ray sources, we ultimately hope to understand where and how cosmic rays are accelerated. The measurement of the energy spectrum of gamma ray sources in the HAWC energy range from several TeV to 100 TeV is a key to understanding whether cosmic ray acceleration takes place in these sources.

High-energy gamma-ray astronomy is by now a well-established field of astronomy. In the MeV to GeV energy range, NASA's Fermi Gamma-Ray Space Telescope has discovered about 2000 gamma-ray sources above 1 GeV (Nolan et al., 2012). Many of these sources have spectra that extend to even higher energies, up to several tens of TeV. As of late 2012, the catalog of TeV gamma-ray sources[2] consists of 143 sources, of which 87 are Galactic and 56 are extragalactic. The source catalog includes many different types of sources, from AGN to pulsar wind nebulae, starburst galaxies, supernova remnants, globular clusters and star-forming regions.

Unlike the Fermi catalog, the TeV catalog is not an all-sky survey, but a strongly biased source list. This difference is a result of the experimental techniques currently applied

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[1] http://www.hawc-observatory.org

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

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to detect TeV sources. Satellite experiments like Fermi have an area of about 1 m^2 and are too small to detect the faint fluxes of sources much above 100 GeV. At TeV energies, detectors therefore have to be ground-based and the gamma-ray primaries are no longer detected directly. On entering the Earth's atmosphere, TeV gamma rays interact with air molecules and induce large cascades of secondary particles, so-called extensive air showers. The properties of the gamma-ray primary have to be reconstructed from the air shower cascade it induces. Several techniques to detect and reconstruct air showers have been developed. By far the most sensitive to date is the atmospheric Cherenkov technique, which uses large mirrors and cameras of photomultiplier tubes (PMTs) to image the Cherenkov light that is produced when relativistic particles of the air shower cascade travel through the Earth's atmosphere. These imaging atmospheric Cherenkov telescopes (IACTs) are pointed instruments with a small field of view and can observe only a limited region of the sky during the night. Consequently, a large fraction of the TeV sky remains unexplored.

In addition, many gamma-ray sources are highly variable, and some are known to flare by orders of magnitude in flux on short time scales, sometimes down to a few minutes. There is therefore a strong case for an instrument with a large field of view and a high duty cycle which can create an unbiased map of the TeV sky and continuously monitor the sky for transient sources. The HAWC observatory is an instrument conceived to fill this need. Its design is based on technology proven at the Milagro experiment which was operated near Los Alamos from 2000–2008.

There are strong indications that a more sensitive next-generation instrument like HAWC will uncover many additional TeV gamma-ray sources. One of the most striking results from the Milagro experiment is the discovery that a significant number of strong GeV sources from the Fermi Bright Source List (Abdo et al., 2009b) are also observed at multi-TeV energies with Milagro (Abdo et al., 2009c). Many of the Milagro sources that correlate with objects from the Bright Source List are marginal in the Milagro sky survey, with significances between 3σ and 5σ after accounting for the statistical penalty associated with the search for sources over the entire sky, and could therefore not be claimed as sources based on Milagro observations alone. A similar result was found in an analysis of data taken with the Tibet-III air shower array (Amenomori et al., 2009).

The discovery that many marginal TeV sources are correlated with objects from the Bright Source List is strong evidence that bright Galactic 100 MeV to 100 GeV sources are also TeV gamma-ray emitters and that there are potentially many more TeV sources whose flux falls just below the sensitivity of the current generation of instruments. A next-generation all-sky instrument like HAWC is bound to discover many additional sources.

2. The HAWC observatory

Unlike the IACTs, HAWC does not detect atmospheric Cherenkov radiation, but rather the particles of the air shower cascade that hit the ground. Since the particles are relativistic, they can be detected by the Cherenkov light they produce in water. HAWC will comprise a large ($150 \times 150\ m^2$) array of 300 light-tight water tanks, each 4.7 m high and 7.3 m in diameter. Fig. 1(left) shows the planned layout of the detector.

Each water tank will be instrumented with 4 PMTs which record the Cherenkov light produced when the particles of the extensive air shower reach the ground and traverse the detector (Fig. 1(right)). Since the air shower particles arrive nearly in a plane, the relative time of light arriving in the PMTs can be used to determine the direction of the particle that initiated the shower. HAWC can be operated in all weather conditions and ambient light levels and therefore has a theoretical duty cycle close to 100%. It has a large effective area and an instantaneous field of view of about 2 sr (or 16% of 4π), with a daily sky coverage of 2π sr. Simulations show that the angular resolution of HAWC is about 0.1° for energies greater than 10 TeV. Another crucial parameter for achieving the physics goals of HAWC is the energy resolution. We expect an energy resolution of around 30% above 10 TeV.

HAWC marks an improvement in sensitivity over Milagro by about a factor of 15. The operation of the detector at high altitude, closer to the shower maximum, also lowers

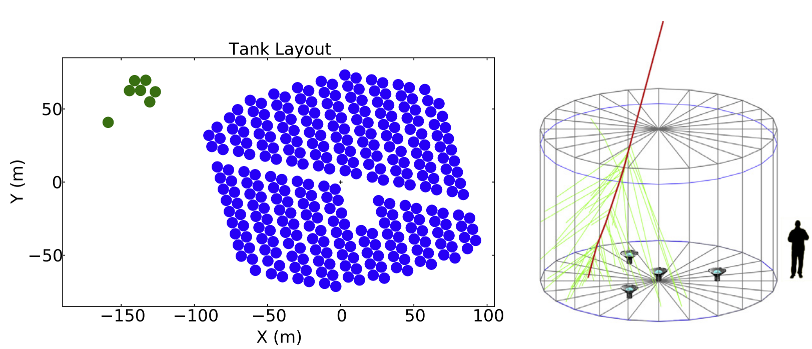

Fig. 1. *Left:* Layout of the full HAWC detector with 300 tanks. Each blue circle indicates the position of a HAWC tank. The green dots on the upper left indicate the location of the VAMOS array, a small test array operated in 2011. The gap in the middle of the HAWC array marks the location of the central electronics building. *Right:* Scheme of a HAWC tank. (For interpretation of the references to colour in this figure legend, the reader is referred to the web version of this article.)