Observation of the Anisotropy of Cosmic Rays with HAWC

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Abstract: The High-Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory is sensitive to the flux and arrival direction distribution of charged cosmic rays in the TeV energy band. While the observatory is only partially deployed, with 30 out of 300 water Cherenkov detectors in data acquisition since September 2012, HAWC is recording air showers from cosmic rays at a rate above 2 kHz. As a result, we have already accumulated one of the largest data sets of TeV cosmic rays ever produced. We have analyzed the data and observed a significant anisotropy at the $10^{-3}$ level in the arrival directions of the cosmic rays on both large scales ($>60^\circ$) and small scales ($<20^\circ$). We present these results and compare our findings to previous observations of anisotropy by experiments such as Milagro, Tibet/ARGO, and others in the northern hemisphere, and the IceCube Neutrino Observatory in the southern hemisphere.

Keywords: cosmic rays, gamma rays, anisotropy

1 Introduction

The HAWC detector is currently under construction 4100 m above sea level on the north slope of Volcán Sierra Negra near Puebla, Mexico. The observatory, located at 19°N latitude, is designed to study the sky in gamma rays and cosmic rays between 50 GeV and 100 TeV.

While cosmic rays are the major source of background in the gamma-ray analysis, the distribution of the arrival directions of the cosmic rays is itself of significant interest. During the past decade a $10^{-3}$ anisotropy in the arrival direction distribution of the TeV cosmic rays has been measured with the Tibet A$\gamma$ array [1], Super-Kamiokande [2], Milagro [3, 4], EAS-TOP [5], MINOS [6], and ARGO-YBJ [7] in the northern hemisphere, and in the southern hemisphere with the IceCube [8, 9, 10] and IceTop [11] detectors.

The anisotropy has been observed on large angular scales ($>60^\circ$) and small scales ($<20^\circ$) by multiple experiments. The large-scale structure is dominated by dipole and quadrupole moments and does not appear to persist above the TeV band [11]. Although the large-scale structure is not well understood, it has long been suggested that weak dipole or dipole-like features should be a consequence of the diffusion of cosmic rays from nearby sources in the galaxy [12, 13]. The small-scale structure, on the other hand, could be the product of turbulence in the galactic magnetic field [14].

Using data from HAWC recorded between January and April 2013, we have measured the cosmic-ray anisotropy in the TeV band. Due to the low latitude of the HAWC site, these data cover a region of the sky previously unobserved by experiments operating in the northern and southern hemispheres. In these proceedings we present the results of a search for anisotropy on large and small angular scales, and compare the observed anisotropy with previous measurements of the northern and southern skies.

2 The HAWC Detector

The HAWC Observatory is a 22,000 m² array of close-packed water Cherenkov detectors (WCDs). Each WCD consists of a cylindrical steel water tank 4.5 m in height and 7.3 m in diameter. A non-reflective plastic liner inside the tank contains 188,000 liters of purified water, and four photomultipliers are attached to the liner on the floor of the tank: one central high-quantum efficiency Hamamatsu 10” PMT and three Hamamatsu 8” PMTs. The PMTs face upward to observe the Cherenkov light produced when charged particles from air showers enter the tank. The signals from each PMT are transferred via analog cables to a counting house in the center of the array, where the data are digitized using custom front-end electronics and CAEN VX1190A 128-channel TDCs. Between September 2012 and April 2013, the observatory was operated with 30 WCDs in data acquisition (HAWC-30). When construction is complete, the observatory will comprise 300 water Cherenkov detectors with 1200 photomultipliers.

Triggers for gamma-ray and cosmic-ray air showers are formed with a simple multiplicity trigger which requires $\geq 10$ PMTs to be above threshold within a sliding time window of 100 ns. The trigger rate in HAWC-30 is approximately 5 Hz. The data are reconstructed offline, and with 30 WCDs the angular resolution of the air shower reconstruction is approximately 1.5°. We note that this is about an order of magnitude worse than in the complete array, but it is sufficient to observe the anisotropy of the cosmic rays.

The analysis presented in this paper uses the data collected during the operation of HAWC-30 between January 1, 2013 and April 15, 2013. Cuts in zenith angle of $<45^\circ$ and number of hit PMTs $\geq 15$ are used to remove poorly reconstructed events from the data. During this period the detector collected $2.2 \times 10^{10}$ well-reconstructed events and exhibited a livetime of 95 days. Using the detector simulation we estimate that the median energy of the data set is about 2 TeV.
3 Analysis

To produce residual maps of the anisotropy of the arrival directions of the cosmic rays, we must estimate the expected rate of events in the detector assuming an isotropic flux. In order to account for random fluctuations in the observed rate due to atmospheric effects and the detector geometry, we calculate the expected flux from the data themselves. The sky map is plotted in equatorial coordinates; the solid and dashed lines correspond to lines of galactic latitude. The galactic center is shown as a solid black circle.

3.1 Large-Scale Anisotropy

For the HAWC-30 data we estimate the large angular scale fractional deviations from isotropy using the technique of forward-backward asymmetry [4]. In this technique we assume that the normalized intensity $I_\delta$ of the flux of cosmic rays at a fixed declination $\delta$ can be expressed as a three-term harmonic expansion in right ascension $\alpha$:

$$I_\delta(\alpha) = \frac{R_\delta(\alpha)}{R_\delta(\alpha)} = 1 + \sum_{n=1}^{3} \gamma_{n,\delta} \cos(n(\alpha - \phi_{n,\delta})). \tag{1}$$

To estimate the harmonic coefficients $\gamma_{n,\delta}$ and calculate the residual intensity, we divide the arrival directions of the data along the local meridian into positive and negative hour angles $\pm \xi$. For a fixed time interval characterized by the local sidereal time $\theta_0$, we can define the relative asymmetry of the arrival directions in the “forward” and “backward” directions (along and against the rotation of the Earth) by

$$FB_\delta(\theta_0, \xi) = \frac{N_{\theta_0,\delta}(+\xi) - N_{\theta_0,\delta}(-\xi)}{N_{\theta_0,\delta}(+\xi) + N_{\theta_0,\delta}(-\xi)}. \tag{2}$$

Since $\alpha = \theta_0 \pm \xi$ and the residual coefficients $\gamma \ll 1$, the asymmetry can be expressed as

$$FB_\delta(\theta_0, \xi) \approx -\sum_{n=1}^{3} \gamma_{n,\delta} \sin n\xi \sin(n(\theta_0 - \phi_{n,\delta})). \tag{3}$$

In practice, we use the data to produce a two-dimensional table of $FB$ as a function $\alpha$ and $\xi$ for a fixed declination $\delta$. Fitting eq. (3) to the table provides the fit coefficients $\gamma_{n,\delta}$ for the different declination bands.

This procedure has been applied to the HAWC-30 data and the result is shown in Figure 1. In our analysis we performed the fits in 18 independent declination bands. The fits were performed on data taken when the detector had at least 102 active PMTs, covering a subset of the period between January 1 and April 15, 2013.

While the data are independent for each band in $\delta$, we note that all bands exhibit a relative deficit of events in the interval $120^\circ < \alpha < 240^\circ$ and a relative excess outside this region. The fit results closely match those of Milagro, which were produced using the same technique [4]. In addition, the amplitude of the fit in each band is approximately $10^{-3}$, which is in agreement with the scale of the large dipole and quadrupole anisotropies reported in the northern and southern hemispheres by other experiments.

3.2 Small-Scale Anisotropy

To search for anisotropy on small angular scales, we directly compute the relative intensity as a function of equatorial coordinates $(\alpha, \delta)$. We begin by binning the sky into an equal-area grid with a resolution of 0.1° per bin using the HEALPix library [16]. A binned data map $N(\alpha, \delta)$ is used to store the arrival directions of air showers recorded by the detector, and a binned reference map $\langle N(\alpha, \delta) \rangle$ is computed to describe the arrival direction distribution if the data arrived isotropically at Earth.

The reference map is produced using the direct integration technique described in [15], adapted for the HEALPix grid. In brief, we proceed by collecting all events recorded during a predefined time period $\Delta t$ and integrate the local arrival direction distribution against the detector event rate. The method effectively smooths out the true arrival direction distribution in right ascension on angular scales of roughly $\Delta t \cdot 15^\circ \cdot h^{-1}$ such that the analysis is only sensitive to structures smaller than this characteristic angular scale. The direct integration procedure also compensates...
for variations in the detector rate while preserving the event distribution in declination. Once the reference map is obtained, we calculate the deviations from isotropy by computing the relative intensity

\[ \delta I_i(\alpha, \delta) = \frac{N_i(\alpha, \delta) - \langle N_i(\alpha, \delta) \rangle}{\langle N_i(\alpha, \delta) \rangle}, \]

which gives the amplitude of deviations from the isotropic expectation in each angular bin \(i\). The significance of the deviation can be calculated using the method of Li and Ma [17].

The analysis was carried out on HAWC-30 data using \(\Delta t = 2\) hr to obtain sensitivity to features smaller than \(30^\circ\) in right ascension. The results are plotted in Figure 2, with the relative intensity shown on the top and the significance shown on the bottom. The data have been smoothed using a \(10^\circ\) top-hat function to make the clustering of arrival directions readily apparent.

Several prominent features are visible in the sky map, notably the regions of excess flux at \(\alpha = 60^\circ\) and \(\alpha = 120^\circ\). The number of independent pixels in the sky map is of order \(10^5\), and after accounting for trial factors only these two regions of excess are significant at \(> 5\sigma\). These hot spots correspond to the \(10^\circ\)–\(20^\circ\) regions of cosmic-ray access observed by Milagro (Regions A and B in [3]) and ARGO-YBJ [7].

An inspection of the sky maps in Figure 2 also shows that every region of excess is associated with a neighboring deficit in the cosmic ray flux. If these small-scale features are produced by turbulence in the galactic magnetic field, as proposed in [14], then there is no reason for us to favor hot spots over cold spots in the analysis. However, we do find that none of the deficit regions is currently more significant than \(-5\sigma\) after trial factors are taken into account. In addition, the estimation of reference maps with direct integration can be biased by a strong anisotropy, leading to artificial deficits or excesses next to regions of true excess or deficit [3]. For this reason we cannot currently rule out the possibility that the deficit regions are artifacts of the analysis rather than real features in the residual cosmic ray flux.

**4 Discussion**

While the HAWC-30 data are still not highly significant when compared to published observations of the cosmic ray anisotropy, it is still instructive to compare our results (particularly the small-scale structure) with other measurements in the northern and southern hemispheres.

When comparing Fig. 2 to published results from the northern hemisphere, two features stand out. The first is the weak hot spot at \(\alpha = 250^\circ\). This region of excess does
We will investigate this possibility with future data. Sky.

The second feature of interest is the elongated excess at $\alpha = 120^\circ$, which is visible at all declination angles observed by HAWC. The extension of the excess to high northern declinations is notable because this is not observed in the Milagro data, even though Milagro was located at $35^\circ$N latitude. However, the significance maps published by ARGO-YBJ also extend to high declinations, and these maps indicate that the Region B excess extends to the northern edge of the ARGO exposure.

With the present data it is not clear if these differences and similarities are significant. However, if we take them at face value then there are several possible explanations for the features we observe. HAWC and ARGO-YBJ have a similar energy threshold (which is lower than that of Milagro), and both detectors are at similar geomagnetic latitudes. Therefore if there is a significant contribution to the anisotropy from events at the energy threshold it could explain the similarity between observations at the two sites. We will investigate this possibility with future data.

A comparison between data from HAWC-30 and IceCube is very interesting because the HAWC data cover declinations down to $-25^\circ$, which is the edge of the exposure region in the published IceCube results. When comparing the data sets we find that the gross features of the cosmic ray sky maps, such as a significant large-scale deficit near $\alpha = 180^\circ$ and the presence of $10^\circ-20^\circ$ structures, are visible in both hemispheres. In particular it is interesting to observe that the elongated Region B excess at $\alpha = 120^\circ$ extends into the southern hemisphere with a similar relative intensity as that observed in the northern sky.

There are some differences between the data sets. Both the large and small-scale structures appear to be misaligned in $\alpha$, with the structures observed in IceCube appearing at higher right ascensions by $\sim 15^\circ-20^\circ$. In addition, the Region A excess, which is the most prominent feature in the HAWC-30 sky maps, does not appear to have a counterpart in the IceCube data.

The source of these differences is unclear but there are several possible explanations. First, the IceCube data are of relatively high energy with respect to other measurements of the anisotropy. The median energy of the low-energy IceCube cosmic-ray analysis is 20 TeV, as compared to 2 TeV for HAWC-30. As a result the differences in the sky maps could be due to the different energy scales of the data sets. As HAWC accumulates large statistics it should be possible to check this assumption by producing a high-energy sky map.

A second source of difference could be a composition/trigger bias between the two detectors. For example, the IceCube detector observes cosmic-ray air showers via the TeV muons which travel 1.4 km into the south polar ice sheet. Hence, at the energy threshold of the cosmic-ray analysis the IceCube detector will preferentially trigger on proton events over heavier nuclei (which produce lower-energy muons on average) [9]. Recent data indicate that the TeV band is a complex region of changing cosmic-ray composition, with protons becoming the sub-dominant primary type at energies above 10 TeV [18, 19]. As a result, IceCube and HAWC may not be observing a completely equivalent population of cosmic rays.

5 Conclusions

Using the 30-tank configuration of HAWC we have observed a significant large-scale and small-scale anisotropy in the arrival direction distribution of the cosmic rays in the TeV band. Our observations are largely in agreement with previous measurements of the anisotropy in the northern and southern hemispheres. The areas of disagreement, such as the possibility of a third region of significant small-scale excess and discrepancies between HAWC and IceCube, may be due to the presence of unaccounted energy and composition effects in the anisotropy. Both possibilities will be the subject of a future detailed investigation.

References