Study of HAWC Sensitivity to Active Galactic Nuclei

ASIF IMRAN¹ FOR THE HAWC COLLABORATION²
¹Los Alamos National Laboratory, Los Alamos, NM 87545, USA
²For a complete author list, see the special section of these proceedings
aimran@lanl.gov

Abstract: HAWC (High Altitude Water Cherenkov) is the next-generation particle shower detector designed for high energy observations of astrophysical sources. Currently under construction in Mexico, the wide field of view observatory will combine high duty cycle with unprecedented sensitivity up to very high energy gamma rays to push the boundaries of our observable TeV universe. Here, we present a study of HAWC sensitivity to active galactic nuclei (AGN) over a broad range of intrinsic source strengths and redshifts. Recent observations of strong TeV flares by atmospheric Cherenkov detectors indicate that a number of AGNs will be observable by the HAWC observatory. HAWC will greatly enhance multi-wavelength studies of AGN, particularly above 20 TeV, where observations by other experiments remain unavailable.

Keywords: galaxies: active — gamma rays: galaxies — instrumentation: detectors — methods: observational

1 Introduction

Recent advances by ground-based very high energy (VHE; E > 350 GeV) gamma-ray detectors have revealed a new view of the universe—one that is teeming with AGNs, one of the most extreme objects in the universe characterized by their non-thermal emission spanning nearly ~ 20 decades of energy. AGNs also exhibit rapid variability at all wavelengths over minutes to day timescale. A small fraction of these violent emitters are associated with relativistic outflows (or jets) which are thought to be powered by accretion onto a super massive black hole (10⁸ − 10¹⁰ M☉). The mechanisms for the acceleration of particles to the highest energies near or within the jets are an active field of research. Hence, observational information about AGN is valuable to constrain competing models for particle acceleration and radiation in the jets. Furthermore, short-term variability information can be used to probe the environment around the central black hole. Finally, VHE gamma-rays are attenuated by the soft photons in the diffuse cosmological radiation field (extragalactic background light or EBL). Therefore, direct observations of VHE radiation from AGN may be used to constrain cosmological parameters in particular related to primordial radiation in the universe [1].

The broadband continuum spectral energy distribution (SED) of AGNs are marked by a double-humped structure with two distinct peaks: The first peak at UV/X-ray energies and a higher energy peak at GeV/TeV energies. The low-energy component of the SED is attributed to synchrotron emission from highly relativistic electrons in the jets. Competing models exist to account for the high energy emission. In the typical leptonic scenario, the same population of electrons Compton-scatter soft photons to gamma-ray energies (where the seed photon are produced previously as a result of synchrotron radiation [2]). Whereas, hadronic scenarios predict protons being accelerated to relativistic energies within the jets in the presence of strong magnetic fields. Subsequently, these protons are subjected to photopion losses that develops into cascades of photons, leptons, neutrons and neutrinos. Hence, both direct proton and muon synchrotron radiation are responsible for the high-energy bump in the hadronic scenario [3].

A characteristic feature of the VHE emission from AGN is extreme flux variability, i.e., large magnitude and shortest timescale. During flaring episodes, the observed flux levels can easily vary by more than one order of magnitude. Mrk 421, a nearby and prominent AGN known for frequent giant flares has been observed at 15 times its quiescent flux, accompanied by variations in spectral shape during increased emission levels [4]. Furthermore, H.E.S.S. observation of PKS 2155-304 in 2006 revealed flux variability on time scales of ~ 3 minutes, the fastest variation recorded from any AGN [5]. Furthermore, VHE emission from the radio-galaxy M87 has been shown to vary over a range of time scales from yearly to just over days [6]. Flux variability along with spectral variability plays a crucial role in understanding the non-thermal emission mechanisms in AGN jets. These features can also test theoretical models sensitive to changing initial conditions such as source environments or injection parameters close to the jets. Broadband coverage of the emission from AGNs can be used to
constrain the size, strength of magnetic field, and Doppler factor of the emission region. Additionally, detailed modeling of the intrinsic emission spectra of AGNs are important for the study of the measurement of the EBL density.

2 HAWC Observatory

Built upon the design and success of Milagro [7], the HAWC observatory is the second-generation particle shower detector suited for high energy observations of astrophysical sources. Currently under construction in the Sierra Negra mountains in Mexico, the observatory is situated at an elevation of 4100 m above the sea level (20° N 97° W). Once completed in 2014, HAWC will comprise of 300 water detectors, each standing at 4.5 m tall, 7.3 m in diameter, and instrumented with three 8 inch photomultiplier tubes (PMT). The final array of detectors will roughly cover an area of ~ 150 m \times 130 m. Incoming high energy particles will interact with the atmosphere and generate a shower of secondary and tertiary particles moving at nearly relativistic speeds. The penetrating particles in the cascade will interact with the water in detectors near the ground level to produce Cherenkov photons. The HAWC instrument will operate by detecting and timing these brief flashes of Cherenkov photons and measuring their charges to reconstruct the arrival direction of the primary high energy particle. The improved sensitivity of this new detector (corresponding to ~ 15 fold increase) over its predecessor, Milagro is primarily attributed to the larger detector foot-print combined with higher elevation (2630 m to 4100 m). HAWC will be most sensitive to primary energies from 50 GeV to 100 TeV with angular resolution of ~ 0.1° at E > 1 TeV. One of the most distinguishing features of HAWC is its wide field of view (FOV) along with greater than 90% duty cycle, thus enabling HAWC to perform nearly continuous TeV sky survey in the visible sky. The ~ 2\sigma sr FOV will allow HAWC to monitor every source in its FOV for nearly 6 hours every day through out the year. This should be contrasted with the highly prolific ground-based air Cherenkov telescopes (ACT) such as VERITAS, which are limited by their small FOV and requirement for clear, moonless nights for successful operation (≤ 10% duty cycle). The wide FOV, high duty-cycle along with multi-TeV sensitivity makes HAWC ideally suited for AGN observations, in particular to bright and transient events such as a brilliant flare.

3 Sensitivity to AGN

Currently, there are over 40 known AGNs that have been observed to emit TeV radiation. Beginning with the detection of Mrk 421 at TeV energies in 1991 [8], the number of TeV AGNs detected has accelerated over the past decade due to the advances in stereoscopic ACT observations. Distances to these AGNs range from very close (M87, z = 0.044) to moderately distant (3C279, z = 0.54). More importantly, a number of these AGNs have been detected with unusually hard intrinsic power-law energy spectra \((dN/dE \sim E^{-\Gamma})\) after correcting for attenuation of gamma rays by the EBL. Consequently, these hard absorption corrected spectral indices are beginning to test current models for VHE emission from AGNs that involve standard shock acceleration and synchrotron-self-Compton (SSC) scenarios [9]. The variation in emitted flux is further amplified by instances of flaring AGNs where the flaring emission level has been observed to be as high as 15 times the quiescent flux, respectively. HAWC is situated at ~20° latitude. The flux is given in terms of the Crab units. We adopt “Crab Unit” to represent to the integral flux above 1 TeV from the Crab Nebula, the “standard candle” of TeV astronomy. Here, 1 Crab unit corresponds to \(2.11 \times 10^{-11} \text{cm}^{-2}\text{s}^{-1}\) from [11].

The HAWC instrument will be most sensitive over a declination range of ~ −20° to 50°. In order to characterize the sensitivity of HAWC to AGN, we selected a set of 16 TeV AGNs that will be visible in our FOV from the selection of all known AGNs. These AGNs were identified from the TeVCat catalogue \(^1\) and they primarily represent sources well-studied in the VHE gamma-ray regime by different ACT observatories. The observed energy spectra from a number of these AGNs have been shown to extend beyond 1 TeV. Furthermore, 5 out of the 16 selected AGN have been established as variable sources with flaring time-scales ranging from hours to days. Table 1 lists these 16

\(^1\) TeVCat Catalogue \(http://tevcat.uchicago.edu\)
AGN along with their known redshifts, observed fluxes and spectral indices, and the declinations. It should be noted that the flux constants reported in this table refer to quiescent fluxes only.

In this proceeding, we estimate the $5\sigma$ discovery time of HAWC for these 16 AGNs. In addition, we also estimate HAWC’s sensitivity to flaring AGNs by scaling up the quiescent flux levels by factors of 5 and 10, respectively while keeping the intrinsic spectral indices constants. AGN spectra are known to harden during flaring states in some cases [13]. However, we do not simulate the hardening of the intrinsic spectra in our analysis. The spectral hardening would only improve our estimates for the time required to discover a flaring source.

4 Simulation

We used the CORSIKA package [14] to simulate the cosmic ray dominated background in order to estimate the sensitivity of our instrument. In addition to protons (P), we simulated He, C, O, Ne, Mg, Si, and Fe nuclei with corresponding spectral fits derived from the ATIC-2 experiment [15]. The primary gamma rays were drawn from an intrinsic power-law spectrum of the form $E^{-\Gamma}$ with $\Gamma = 2$ and subsequently re-weighted to match the spectral indices of various observed AGNs. The simulation has been verified by the Milagro [17] analysis tools. In order to account for the attenuation of gamma rays over cosmological distance scale via pair-production with infrared EBL photons, we used the Gilmore EBL model [12] to derive the opacity as a function of energy and redshift, $\tau(E, z)$. Therefore, the EBL-attenuated VHE gamma-ray spectrum of any AGN is given by the relation,

$$f_{\text{observed}} = f_{\text{intrinsic}} \cdot \text{Exp}[-\tau(E, z)]$$

where $f_{\text{intrinsic}}$ and $f_{\text{observed}}$ correspond to the intrinsic and observed spectra, respectively. Afterwards, we used GEANT-4 based analysis tools to simulate the detector response to air showers induced by primary gamma rays and hadrons.

Presently, the HAWC trigger system is under active development. Our analysis assumes a single-level trigger system to reduce the rate of background events caused by cosmic ray showers and night sky background while retaining events consistent with gamma-ray showers. Based on a simple multiplicity trigger, we require a minimum of 50 PMTs to be hit in order to identify an air-shower event. This results in a slightly higher simulated trigger rate of 8 kHz compared to the baseline design specification of 5 kHz. However, this increased rate is justified by the need to raise our sensitivity to AGN since their measured energy spectra does not extend to higher energies. The location of the shower core on the detector plane is obtained by fitting a two-dimensional Gaussian to the observed distribution of charges across the PMTs. Hit timing information for individual PMTs at sub-nanosecond level precision are utilized to reconstruct the shower-axis for each air shower event. Additional information about the HAWC data analysis method can be found in [16].

Afterwards, we apply a gamma/hadron separation cut based on the compactness parameter to identify gamma-ray events in the simulated data. This parameter mainly discriminates hadronic background by identifying showers with a larger muonic component, a typical feature associated with hadron-induced air showers [17]. Finally, an angular cut of $\theta < 2.5^\circ$ is applied around the putative source in the sky to select gamma-ray events. We point out that the calculated sensitivity of HAWC to AGN is not only dependant on source characteristics such as its distance, spectral index, and intrinsic flux level but also depends on the analysis methods used. Therefore, future improvements in core and angular reconstruction algorithms combined with better background-rejection routines would enhance HAWC’s sensitivity to the detection of AGNs over varying source strengths and distances.

5 Results & Discussion

The sensitivity of HAWC to AGNs is measured by estimating the time required to detect any given source at the $5\sigma$ level. Figure 1 shows the $5\sigma$ discovery time of HAWC for a Mrk421-like source over varying declinations in the sky. The sensitivity is found to be strongly dependent on the source declination and peaks at $\sim 20^\circ$, which corresponds...
Table 1: 16 well-measured AGNs visible in HAWC’s FOV. Listed are the redshifts, declinations, and measured energy spectra for each source. Variable column indicates whether a source has been observed to be variable at VHE gamma-ray or not. References: [13], [6], [18], [19], [20], [6], [21], [22], [23], [24], [25]

<table>
<thead>
<tr>
<th>Source</th>
<th>Redshift (z)</th>
<th>Declination (°)</th>
<th>Measured Spectrum dF/dE (TeV⁻¹ cm⁻² s⁻¹)</th>
<th>Variable</th>
<th>Reference</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mrk421</td>
<td>0.031</td>
<td>38</td>
<td>(12.1 ± 0.5)10⁻¹²(E/1.0 TeV)⁻¹</td>
<td>Y</td>
<td>1</td>
</tr>
<tr>
<td>Mrk501</td>
<td>0.034</td>
<td>40</td>
<td>(8.4 ± 0.5)10⁻¹²(E/1.0 TeV)⁻¹</td>
<td>Y</td>
<td>1</td>
</tr>
<tr>
<td>1ES2344+514</td>
<td>0.044</td>
<td>51</td>
<td>(12.0 ± 0.2)10⁻¹¹(E/0.5 TeV)⁻¹</td>
<td>Y</td>
<td>1</td>
</tr>
<tr>
<td>1ES1959+650</td>
<td>0.047</td>
<td>65</td>
<td>(3.4 ± 0.5)10⁻¹²(E/1.0 TeV)⁻¹</td>
<td>Y</td>
<td>1</td>
</tr>
<tr>
<td>1H1426+428</td>
<td>0.129</td>
<td>43</td>
<td>(2.9 ± 1.1)10⁻¹¹(E/0.43 TeV)²±0.6</td>
<td>N</td>
<td>1</td>
</tr>
<tr>
<td>M87</td>
<td>0.004</td>
<td>12</td>
<td>(7.4 ± 1.3)10⁻¹³(E/1.0 TeV)²±0.17</td>
<td>Y</td>
<td>2</td>
</tr>
<tr>
<td>1ES1218+304</td>
<td>0.183</td>
<td>30</td>
<td>(7.5 ± 1.1)10⁻¹²(E/0.5 TeV)⁻¹</td>
<td>Y</td>
<td>3</td>
</tr>
<tr>
<td>Mrk180</td>
<td>0.045</td>
<td>70</td>
<td>(4.5 ± 1.8)10⁻¹¹(E/0.3 TeV)⁻¹</td>
<td>N</td>
<td>4</td>
</tr>
<tr>
<td>1ES0229+200</td>
<td>0.140</td>
<td>20</td>
<td>(2.34 ± 0.37)10⁻¹¹(E/3.0 TeV)⁻¹</td>
<td>N</td>
<td>1</td>
</tr>
<tr>
<td>1ES1011+496</td>
<td>0.212</td>
<td>50</td>
<td>(2.0 ± 0.1)10⁻¹⁰(E/0.2 TeV)⁻¹</td>
<td>N</td>
<td>1</td>
</tr>
<tr>
<td>PKS1424+240</td>
<td>0.240</td>
<td>24</td>
<td>(5.1 ± 0.9)10⁻¹¹(E/0.2 TeV)⁻¹</td>
<td>N</td>
<td>5</td>
</tr>
<tr>
<td>RGBJ0152+017</td>
<td>0.080</td>
<td>2</td>
<td>(5.1 ± 0.9)10⁻¹¹(E/0.2 TeV)⁻¹</td>
<td>N</td>
<td>6</td>
</tr>
<tr>
<td>1ES0806+524</td>
<td>0.138</td>
<td>52</td>
<td>(6.8 ± 1.7)10⁻¹²(E/0.4 TeV)⁻¹</td>
<td>Y</td>
<td>7</td>
</tr>
<tr>
<td>WComae</td>
<td>0.102</td>
<td>28</td>
<td>(2.0 ± 0.31)10⁻¹¹(E/0.4 TeV)⁻¹</td>
<td>Y</td>
<td>8</td>
</tr>
<tr>
<td>RGBJ0719+591</td>
<td>0.125</td>
<td>59</td>
<td>(8.54 ± 0.9)10⁻¹³(E/1.0 TeV)⁻¹</td>
<td>N</td>
<td>9</td>
</tr>
<tr>
<td>1ES0347-121</td>
<td>0.188</td>
<td>-12</td>
<td>(4.52 ± 0.85)10⁻¹³(E/1.0 TeV)⁻¹</td>
<td>N</td>
<td>10</td>
</tr>
</tbody>
</table>

Figure 2 shows the 5σ discovery time estimated for our set of 16 AGNs. Considering emission at the quiescent flux level, 3 of the nearest and brightest AGNs will be detected by HAWC within a year (triangles). HAWC’s sensitivity will mark a major improvement over Milagro with the latter claiming one successful detection of extragalactic source during its ten years of operation [17]. In order to determine HAWC’s sensitivity to flaring sources, the previous analysis was repeated after scaling the quiescent fluxes of the AGNs by a factor of 10. The results are shown with squares. The plot indicates that HAWC will be very sensitive to highly flaring sources over short duration as 3 of these simulated AGNs will be detectable within a day. We again emphasize that HAWC will provide unbiased monitoring of the TeV sky, thus observing every source in its FOV throughout the year. This unique capability will enable HAWC to observe powerful and rapid flares from both new and known AGNs. Observations by HAWC will also alert other VHE gamma-ray instruments to allow for deeper TeV probes of any new sources.

This work has been supported by the National Science Foundation, the U.S. Department of Energy, and Mexico Conacyt.

References

[16] Goodman, J., et al., (HAWC Coll.) In these proceedings