Monitoring the Variable Gamma-Ray Sky with HAWC

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Abstract. The High Altitude Water Cherenkov (HAWC) observatory monitors the gamma-ray sky at energies between 100 GeV and 100 TeV with a wide field of view of \(\sim 2\) steradians. A duty cycle of \(\sim 90\%\) allows HAWC to scan two thirds of the sky every day and has resulted in an unprecedented data set of unbiased and evenly sampled daily TeV light curves, collected over more than one year of operation since the completion of the array. These measurements highlight the flaring activity of the blazars Markarian 421 and Markarian 501 and allow us to discuss the frequency of high flux states and correlations with observations at other wavelengths. We will present a first look at how we are using the HAWC data to search for gamma-ray signals and variability from the directions of possible TeV gamma-ray sources and the locations of high-energy neutrinos observed by IceCube. For a selected list of objects, we perform a search for flares in real time during data taking in order to quickly alert other observatories when increased activity is detected. We include here the first results from these flare trigger efforts, focused on monitoring blazars.

INTRODUCTION

Gamma-ray emission at very high energies (VHE, \(> 100\) GeV) can be used to trace particle acceleration in both galactic and extra-galactic sources and provide insight into candidate objects for the production of charged cosmic rays or extra-solar neutrinos at the highest energies. Some of the most powerful astrophysical accelerators are Active Galactic Nuclei (AGN), and the subclass of blazars is known to exhibit changes in the VHE gamma-ray flux on time scales down to minutes, see for example [1, 2]. In this work we show that the High Altitude Water Cherenkov (HAWC) is sensitive to day-scale variations of TeV gamma-ray fluxes. In contrast to imaging air Cherenkov telescopes, the operation of HAWC is independent of the day-night cycle and other environmental conditions and data taking is only interrupted due to maintenance, leading to an instrument’s duty cycle of \(\sim 90\%\). This allows us to regularly monitor any source in the field of view of \(\sim 2\) steradians. We show the resulting unbiased light curves for selected objects and discuss how we have started to generate real time alerts for flaring. In a separate section we review recent results from how we have used HAWC to follow-up on external alerts by providing VHE observations for promising candidate location of multi-messenger signals.

THE HAWC OBSERVATORY

The HAWC Observatory is located on the slope of the Sierra Negra volcano (97.3°W, 19.0°N) in the state of Puebla, Mexico, at an altitude of 4,100 m above sea level. Completed in March 2015, HAWC is an array of 300 Water Cherenkov Detectors (WCDs) that is optimized for measuring extensive air showers induced by gamma rays with energies between approximately 100 GeV and 100 TeV. Each WCD is housed in a large steel tank, holding \(\sim 200,000\) liters of purified water in a light-proof bladder and instrumented with four photo-multiplier tubes (PMTs) at the bottom. Relativistic particles in an air shower passing through the array produce Cherenkov light in the water that is being measured as charges in the PMTs and recorded with sub-nanosecond precision. By fitting the core and plane of the shower front it is possible to reconstruct the size and incident direction of an air shower event. While most of the air showers recorded are produced by hadronic primaries, this background can be significantly reduced by measuring large charge deposits outside the core regions indicative of muons, which are not expected in gamma-ray showers. Corresponding data selection cuts are applied separately in 9 analysis bins that sort the events depending on...
the fraction of PMTs that recorded signals. More details about the reconstruction, data taking and hadron rejection are discussed in [3, 4].

DAILY LIGHT CURVE ANALYSIS

Method

HAWC can in principle record extensive air showers from all directions visible above the horizon. Due to the absorption of secondary particles in the atmosphere, the actual effective area for gamma rays is a function of the zenith angle of a primary particle and the sensitivity to events from outside a cone with an opening angle of $\sim 45^\circ$ around zenith is strongly suppressed. Given this definition of the field of view, any sky location with declination between $-26^\circ$ and $+64^\circ$ passes over HAWC once every sidereal day through the rotation of the Earth. Such a transit lasts approximately 6 hours for the sources discussed in detail in this contribution. The resulting signal expectation over a full transit for a given spectrum can then be compared with the observed event count, stored in a sky map with a pixel grid spacing of 0.11° for each analysis bin. This hypothesis testing and the optimization of free parameters in the source model is achieved via a maximum likelihood approach that combines the 9 analysis bins. More details are provided in the discussion of the first weekly light curve results from the partial HAWC detector in [5] and the likelihood analysis framework in [6]. As will be discussed in a forthcoming publication, this analysis method has a 35% uncertainty on the absolute value of gamma-ray flux values shown here, which only affects the overall scaling but not the time-dependent features of light curves discussed here. The statistics of the data for each individual transit are not sufficient to fit spectral features. Given the possibility of spectral changes during flare periods, we conservatively estimate the systematic uncertainty of individual fluxes to be 15%, based on simulations of the response to differences between the true and the assumed spectral shape.

We provide a first look at the flux light curves for the Crab Nebula, and Markarian (Mrk) 421, binned in sidereal days. The data included here were collected between November 26, 2014 and February 12, 2016. During the first few months of this period, the detector grew from 250 detectors (1000 PMTs) to the full size of 300 detectors (1200 PMTs), slightly improving the sensitivity in the process. A quality selection was applied to exclude data from the maps if they were taken during unstable conditions, for example related to construction. To ensure a uniform detector response, partially covered sidereal days are not included in the light curves if the integral of the expected signal is less than 75% of the total expectation for a transit. These location-dependent data selections result in slightly different exposure times for different sources.

Results

Crab Nebula

The upper panel of Fig. 1 shows the flux light curve of the Crab nebula, binned in intervals of one transit, in other words one sidereal day. The analysis was performed as described above, assuming a simple power law for the spectral shape,

$$\frac{dN}{dE} = F_i \cdot \left(\frac{E}{1 \text{ TeV}}\right)^{-2.63},$$

leaving only the differential normalization $F_i$ as a single free parameter in the fit of data for each sidereal day. The y-axis of the light curve shows the resulting photon (ph) flux after analytically integrating above 1 TeV. After quality selection, 383 transits from the period of 444 sidereal days under consideration were included.

We applied the same variability test as discussed in section 3.6 of [7] to this light curve, comparing the product of all per-transit likelihood values for the individual fit results with the product of those for a constant flux hypothesis (shown as red, dashed line). The data are compatible with being due to a constant source flux at 1.6 standard deviations, in agreement with previous analyses of the Crab VHE data, for example [8, 9]. We also investigated the 13-day period between December 28, 2015 and January 9, 2016, during which the Fermi-LAT collaboration reported an increased gamma-ray flux in the $> 100 \text{ MeV}$ energy band [10]. The HAWC data show no increase of the VHE flux. We calculate an upper limit for the flux during this 13-day interval of 1.01 times the average HAWC flux ($2.4 \cdot 10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1}$) at 95% confidence level.
FIGURE 1. Flux light curves for the Crab Nebula (top) and for Mrk 421 (bottom) with sidereal-day binning for transits between November 26, 2014 and February 12, 2016. The dashed red line in each plot is the best fit normalization when assuming a constant flux for the whole period.
The light curve for Markarian 421 in the lower panel of Fig. 1 was obtained by fitting the flux normalization for each transit under the assumption of a power law spectrum with exponential cut-off,

\[ \frac{dN}{dE} = F_i \cdot \left( \frac{E}{1 \text{ TeV}} \right)^{-2.3} \cdot \exp \left( -\frac{E}{5 \text{ TeV}} \right). \]

387 of 444 transits are included after quality cuts. The dashed, red line indicates the best fit to a constant flux for the integrated data of the whole period which is approximately 0.9 times the value measured for the flux of the Crab nebula, \(2.1 \times 10^{-11} \text{ ph cm}^{-2} \text{ s}^{-1}\). This flux level lies in between the lowest and highest yearly average fluxes reported in [11]. Applying the same variability analysis as described above, this light curve is ruled out as being consistent with a constant flux hypothesis with a p-value < \(10^{-10}\). In a simple classification of high states with respect to the average flux, we find that 10 transits exceed the displayed average flux by more than 3\(\sigma_i\), where \(\sigma_i\) represents the individual statistical uncertainty. A full discussion of all these light curves and the observed flaring states for the Markarian blazars will be the subject of a forthcoming publication.

**Online Monitoring of Gamma-Ray Sources**

The analysis described above for fitting daily flux values is performed for both Mrk 421 and Mrk 501 on the computers at the HAWC site immediately after each transit ends. It is based on the so-called *online* reconstruction, performed with only a few seconds time lag on all recorded events and a preliminary calibration and data quality selection. Since the start of this regular and mostly automated monitoring in January 2016, we have released two Astronomer’s Telegrams (ATel) to alert the community about increased flux states. In [12], we report a flaring state of Mrk 501, exceeding approximately 2 times the flux of the Crab nebula on April 6, 2016 and about half this value during the following transit. In a joint ATel with the FACT Collaboration and analyzers of X-ray data from *Swift* [13] we present complementary observations of increased flux from Mrk 421. The VHE flux increased over several days and reached a maximum on June 9, 2016 at 2 – 3 times the flux of the Crab Nebula, with a similar behavior in the X-ray band. The data from both of these periods are not yet included in the long term light curves in Fig. 1 because the corresponding data maps have not yet been reprocessed with the improved calibration and quality selection available after transfer to the off-site computers.

**FOLLOW-UP ON MULTI-MESSENGER ALERTS**

**Neutrinos**

We have monitored the direction of multiple neutrinos of likely astrophysical origin reported by IceCube. Our analysis is performed time integrated over all data existing at the time of the neutrino detection as well as in time windows of \(\pm 1\), \(\pm 2\), and \(\pm 5\) days centered at the time of the event. Presently there is no evidence for steady or transient gamma-ray emission from the locations of such neutrinos. These studies greatly benefit from the wide field of view and high uptime of HAWC, since a large number of neutrinos can be studied in temporal coincidence. Those monitored include the highest energy neutrino ever reported (more than 4.5 PeV) [14], and neutrinos reported real time by IceCube [15, 16]. The study of neutrinos reported in [17] and [18] is on-going.

**Gravitational Waves**

The wide field of view of the HAWC Observatory provides an opportunity to also search for gamma-ray counterparts to gravitational wave alerts from LIGO, if their rather large error region overlaps with the HAWC field of view. This was the case for the gravitational wave signal reported in [19] for 2015/12/26. We searched for a point-like burst emission in \(\pm 10\) seconds of HAWC data around the time of the LIGO trigger for the northern part of the localization contour. No location in the search area showed a significant excess, see [20]. We are also working on analyses for longer time scales of hours and days to be applied to this and future gravitational wave alerts.

**SUMMARY**

The HAWC gamma-ray observatory is monitoring two thirds of the sky with a duty cycle of \(~90\%\), providing flux measurements on various time scales for any location within the accessible declination range. We have shown our first
unbiased flux light curves binned in one transit intervals that show a steady flux for the Crab Nebula and day-scale variations for blazar Markarian 421. We apply this analysis in near real time to send out alerts for increased flux states for selected objects. We also follow-up on external alerts and have released results for analyzing candidate regions identified through neutrino signals from IceCube and gravitational wave alerts from LIGO. HAWC will continue these efforts and provide both long term variability information and immediate follow-up observations for the VHE sky.

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