On the TeV spectral energy distribution of HAWC’s sources

Filiberto Hueyotl-Zahuantitla\textsuperscript{a}, César Álvarez\textsuperscript{b}, Roberto Arceo\textsuperscript{b} and Karen Salomé Caballero\textsuperscript{b}

\textsuperscript{a}Cátedra CONACYT, CONACYT-México
\textsuperscript{b}Universidad Autónoma de Chiapas (FCFM-UNACH), Chiapas, México

E-mail: fhueyotl@conacyt.mx, crabpulsar@hotmail.com, roberto.arceo@unach.mx, karen.mora@unach.mx

on behalf of the HAWC Collaboration

We present a systematic study of the TeV gamma-ray spectrum for the sources in the 2HWC HAWC catalog. Three spectrum models are considered in the analysis: simple power law, power law with exponential cut-off and a log-parabola. A comparison of the test statistic of nested models was performed in order to look for the best description. We used gamma-ray sky maps of 17 and 25 months of HAWC data. From the analysis, only three sources of the catalog deviate from simple power law spectrum with high significance. The corresponding parameters are given in each case.
1. Introduction

The spectral energy distribution (SED) provides information on the emission mechanisms powering astrophysical objects, traditionally classified as either leptonic or hadronic. In the TeV range the emission is often interpreted as due to Inverse Compton scattering, i.e. leptonic, leading to simple power law approximations to first order $\sim E^{-\alpha}$, where $E$ is the energy of the photon and $\alpha$ is the spectral index. However, there is strong evidence of deviations from simple power law and thus more complicated fits has been suggested: power law with exponential cut-off, log-parabola, broken power laws, and others. Recent works suggest a log-parabola as the TeV spectrum model for the Crab Nebula, see for example [1, 2]. The TeV gamma-ray spectrum of the two blazars, Markarian 421 and Markarian 501 are modeled as power laws with exponential cut-off, see for instance [3, 4, 8]. Here we present a comparative study of spectral fits of the sources given in the second HAWC catalog beyond the simple power law reported in [5].

2. HAWC sample

The High Altitude Water Cherenkov Observatory (HAWC) is located in central Mexico at an elevation of 4100 meters a.s.l. HAWC consist of 300 water tanks with a footprint of 22,000 m$^2$. Each tank of 4.5 m high and 7.3 m diameter is instrumented with three 8-in PMTs arrayed around one central 10-in PMT at the bottom of the tank. The PMTs detect the Cherenkov light that relativistic particles emits as they cross the 200,000 L of water contained in each tank. HAWC is the most sensitive wide field-of-view TeV telescope, with an instantaneous field of view of 2 steradians and > 95% duty cycle, it continuously surveys and monitors the sky for gamma ray energies between 100 GeV to 100 TeV. In this work we consider the point sources listed in Table 2 of the 2HWC catalog [5]. From the list, two sources have been identified as extragalactic and are associated with blazars, seven may be pulsar wind nebulae (PWN), two supernova remnants (SNR), 14 have possible associations with PWN, SNR and molecular clouds. The remaining are unassociated.

3. Method

We used the so called Likelihood Fitting Framework (LiFF) [6] to compute a test statistic (TS) from HAWC maps. Two maps from HAWC data were used, for 17 and 25 months, both produced with a HEALPix grid of resolution of 1024. The TS is defined in term of the maximum likelihood ratio:

$$TS = 2\ln \frac{L_{\text{max}}(\text{source model})}{L(\text{null model})},$$

where $L_{\text{max}}(\text{source model})$ is the likelihood that a source is present and $L(\text{null model})$ is the null hypotheses that the observed events is due to background alone. The likelihood of a model $L(\text{model})$ is obtained by comparing the observed event counts with the expected counts, for all the pixels in the region of interest and for all energy bins. We used nine energy bins as in [5] and [8]. For the null model the expected counts are simply given by the background maps derived from data. For the source model the expected counts corresponds to the same background plus a signal contribution from the source derived from simulation. The physical model assume a point-like source and
three energy spectrum laws for each source: simple power law, power law with exponential decay and a log-parabola. These models are contained in the following formula:

\[
dN/dE = f_0 (E/E_0)^{-\alpha + \beta \log (E/E_0)} \cdot \exp (-E/E_c),
\]

where \(dN\) is the flux of gamma photons in the energy interval \(dE\), \(f_0\) is the normalization flux at the reference energy \(E_0 = 7\) TeV, the hardness of the spectrum is given by the spectral index \(\alpha\), \(\beta\) is a second index known as the curvature parameter and \(E_c\) is the cut-off energy. For \(\beta = 0\) and \(E_c \to \infty\) we recover the simple power law, when \(\beta = 0\) we recover the cut-off power law, and when \(E_c \to \infty\) we recover the log-parabola. The simple power law and the power law with exponential decay are nested, also the simple power law and the log-parabola. However, the power law with exponential cut-off and the log-parabola models are not nested. Therefore the last two models can not be compared each other by means of statistical test.

With LiFF the TS is maximized with respect to the parameters of the spectrum model. We leave the respective parameters free for each case. We use a threshold \(\Delta TS > 25\) between the nested models in order to see whether the observed spectrum deviates from the simple power law.

| Name           | Model | TS    | \(\Delta TS\) | \(f_0\) \([\text{TeV}^{-1} \text{cm}^{-2} \text{s}^{-1}]\) | \(\alpha\) | \(E_c, \beta\) |
|----------------|-------|-------|---------------|---------------------------------|------|----------------|
| 17 Months of HAWC data |       |       |               |                                 |      |                |
| 2HWC J0534+220  | SP    | 1120.6| 1.84E-13 ± 2.37E-15 | 2.59 ± 0.01                     |      |                |
|                | CP    | 11249.3| 2.98E-13 ± 1.77E-14 | 2.25 ± 0.04                     | 32.3 ± 4.9 |                |
|                | LP    | 11262.0| 2.40E-13 ± 6.19E-15 | 2.64 ± 0.02                     | 0.15 ± 0.016 |                |
| 2HWC J1104+381 | SP    | 1315.0| 7.09E-14 ± 2.86E-15 | 3.04 ± 0.03                     |      |                |
|                | CP    | 1385.8| 3.52E-13 ± 1.56E-13 | 2.27 ± 0.22                     | 5.7 ± 1.9 |                |
|                | LP    | 1389.7| 8.82E-14 ± 5.50E-15 | 3.61 ± 0.14                     | 0.35 ± 0.071 |                |
| 2HWC J1653+397 | SP    | 572.7 | 5.66E-14 ± 2.70E-15 | 2.86 ± 0.04                     |      |                |
|                | CP    | 623.6 | 3.84E-13 ± 2.62E-13 | 1.61 ± 0.48                     | 5.6 ± 2.5 |                |
|                | LP    | 623.7 | 1.01E-13 ± 1.01E-14 | 3.14 ± 0.13                     | 0.51 ± 0.151 |                |
| 25 Months of HAWC data |       |       |               |                                 |      |                |
| 2HWC J0534+220  | SP    | 17189.1| 1.88E-13 ± 2.0E-15 | 2.58 ± 0.01                     |      |                |
|                | CP    | 17409.1| 3.17E-13 ± 1.57E-14 | 2.23 ± 0.04                     | 29.4 ± 3.45 |                |
|                | LP    | 17423.5| 2.48E-13 ± 5.23E-15 | 2.64 ± 0.01                     | 0.155 ± 0.014 |                |
| 2HWC J1104+381 | SP    | 1523.8| 6.27E-14 ± 2.3E-15 | 3.03 ± 0.02                     |      |                |
|                | CP    | 1625.3| 4.32E-13 ± 1.75E-13 | 2.10 ± 0.20                     | 4.6 ± 1.19 |                |
|                | LP    | 1630.0| 7.95E-14 ± 4.80E-15 | 3.70 ± 0.15                     | 0.412 ± 0.077 |                |
| 2HWC J1653+397 | SP    | 474.0 | 4.12E-14 ± 2.1E-15 | 2.88 ± 0.04                     |      |                |
|                | CP    | 515.5 | 2.37E-13 ± 1.75E-13 | 1.75 ± 0.51                     | 6.3 ± 3.30 |                |
|                | LP    | 515.2 | 7.18E-14 ± 7.60E-15 | 3.13 ± 0.13                     | 0.472 ± 0.149 |                |

Table 1: TeV gamma-ray spectrum models and the corresponding parameters. In the first column, from the top to the bottom, the sources correspond to: Crab Nebula, Markarian 421 and Markarian 501. The parameters are described in the text. The uncertainties in the parameters are statistical only. Discussion on the systematic uncertainties are given in [1].
4. Results

We compared the TS between nested models, namely, simple power law (SP) versus power law with exponential cut-off (CP) and simple power law versus log-parabola (LP). Table 1 presents the sources of the catalog that fulfill the condition $\Delta TS > 25$, these sources are 2HWC J0534+220 (Crab Nebula), 2HWC J1104+381 (Markarian 421) and 2HWC J1653+397 (Markarian 501). The upper and the lower halves of the table are based on the 17 months and 25 months of data, respectively. The HAWC name of each source is given in column 1, column 2 gives the assumed spectrum model, TS is in column 3, $\Delta TS$ is given in column 4, column 5 shows the normalization flux $f_0$ at...
the reference energy $E_0 = 7$ TeV, the spectral index $\alpha$ appears in column 6, column 7 presents the cut-off energy $E_c$ or the curvature parameter $\beta$ depending on the spectrum model given in column 2. Note that $\Delta TS$ is slightly higher for SP versus LP than SP versus CP for the three sources in the case of 17 months of data. In the case of 25 months of HAWC data, $\Delta TS$ is slightly lower for SP versus LP than SP versus CP for Markarian 501. However we can not conclude which one of LP or CP is the most appropriate model for the spectrum because these are not nested models and therefore can not be compared directly via TS. The results presented here are consistent with those presented by [8] in the case of Markarians and by [1] for the Crab Nebula.

In Table 2 we present the sources with $\Delta TS<25$, according to this condition the spectrum of these sources are better described by a simple power law fit, in line with [5]. The parameters of the spectrum are given for each source. The map of 25 months was used in this case.

5. Conclusions

We studied the TeV gamma-ray spectra of the sources in the 2HWC catalog by applying different models to the spectra. We conclude that the TeV spectra for the Crab Nebula, Markarian 421 and Markarian 501 deviate from a simple power law. However we can not disentangle whether a power law with exponential cut-off or log-parabola is the most appropriate description for the TeV spectrum since they are not nested models and thus can not be compared via the TS. A detailed comparison between power law with exponential cut-off and log-parabola will be addressed in a forthcoming communication. The simple power law is a better description to most spectra of the HAWC catalog sources, this results is in line with the 2HWC catalog publication.

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