On the TeV spectral energy distribution of HAWC's sources

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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.

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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 α 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 México 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:

$$TS = 2\ln \frac{\mathsf{L}^{\text{max}}(\text{source model})}{\mathsf{L}(\text{null model})},\qquad(3.1)$$

where $\mathsf{L}^{\text{max}}(\text{source model})$ is the likelihood that a source is present and $\mathsf{L}(\text{null model})$ is the null hypotheses that the observed events is due to background alone. The likelihood of a model $\mathsf{L}(\text{model})$ 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:

$$dN/dE = f_0(E/E_0)^{-\alpha+\beta\log(E/E_0)} \cdot \exp(-E/E_c),\tag{3.2}$$

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 α, β 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 ΔTS > 25 between the nested models in order to see whether the observed spectrum deviates from the simple power law.

Name	Model	TS	ΔTS	f_0 [TeV^{-1} cm^{-2}s^{-1}]	α	E_c, β
			17 Months of HAWC data			
2HWC J0534+220	SP	11120.6		1.84E-13$\pm$ 2.37E-15	2.59 $\pm$ 0.01	
	CP	11249.3	128.7	2.98E-13$\pm$ 1.77E-14	2.25 $\pm$ 0.04	32.3 $\pm$ 4.9
	LP	11262.0	141.4	2.40E-13$\pm$ 6.19E-15	2.64 $\pm$ 0.02	0.15 $\pm$ 0.016
2HWC J1104+381	SP	1315.0		7.09E-14$\pm$ 2.86E-15	3.04 $\pm$ 0.03	
	CP	1385.8	70.8	3.52E-13$\pm$ 1.56E-13	2.27 $\pm$ 0.22	5.7 $\pm$ 1.9
	LP	1389.7	74.7	8.82E-14$\pm$ 5.50E-15	3.61 $\pm$ 0.14	0.35 $\pm$ 0.071
2HWC J1653+397	SP	572.7		5.66E-14$\pm$ 2.70E-15	2.86 $\pm$ 0.04	
	CP	623.6	50.9	3.84E-13$\pm$ 2.62E-13	1.61 $\pm$ 0.48	5.6 $\pm$ 2.5
	LP	623.7	60.0	1.01E-13$\pm$ 1.01E-14	3.14 $\pm$ 0.13	0.51 $\pm$ 0.151
			25 Months of HAWC data			
2HWC J0534+220	SP	17189.1		1.88E-13$\pm$ 2.0E-15	2.58 $\pm$ 0.01	
	CP	17409.1	220.0	3.17E-13$\pm$ 1.57E-14	2.23 $\pm$ 0.04	29.4 $\pm$ 3.45
	LP	17423.5	234.4	2.48E-13$\pm$ 5.23E-15	2.64 $\pm$ 0.01	0.155 $\pm$ 0.014
2HWC J1104+381	SP	1523.8		6.27E-14$\pm$ 2.3E-15	3.03 $\pm$ 0.02	
	CP	1625.3	101.6	4.32E-13$\pm$ 1.75E-13	2.10 $\pm$ 0.20	4.6 $\pm$ 1.19
	LP	1630.0	106.3	7.95E-14$\pm$ 4.80E-15	3.70 $\pm$ 0.15	0.412 $\pm$ 0.077
2HWC J1653+397	SP	474.0		4.12E-14$\pm$ 2.1E-15	2.88 $\pm$ 0.04	
	CP	515.5	41.5	2.37E-13$\pm$ 1.75E-13	1.75 $\pm$ 0.51	6.3 $\pm$ 3.30
	LP	515.2	41.2	7.18E-14$\pm$ 7.60E-15	3.13 $\pm$ 0.13	0.472 $\pm$ 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].

Name	TS	α	f_0 [TeV^{-1} cm^{-2}s^{-1}]	TeVCat
2HWC J0631+169	31.7	2.73± 0.14	6.13E-15± 1.15E-15	Geminga
2HWC J0635+180	31.9	2.57± 0.15	5.77E-15± 1.23E-15	Geminga
2HWC J1809-190	126.3	2.64± 0.09	8.34E-14± 1.22E-14	HESS J1809-193
2HWC J1814-173	230.9	2.59± 0.07	8.99E-14± 1.07E-14	HESS J1813-178
2HWC J1819-150	80.4	2.83± 0.10	5.14E-14± 6.63E-15	SNR G015.4+00.1
2HWC J1825-134	1227.2	2.57± 0.03	1.42E-13± 6.63E-15	HESS J1826-130
2HWC J1831-098	143.8	2.79± 0.08	4.09E-14± 3.87E-15	HESS J1831-098
2HWC J1837-065	918.5	2.87± 0.03	8.85E-14± 3.29E-15	HESS J1837-069
2HWC J1844-032	459.8	2.65± 0.05	4.64E-14± 2.59E-15	HESS J1844-030
2HWC J1847-018	222.4	2.85± 0.06	3.02E-14± 2.19E-15	HESS J1848-018
2HWC J1849+001	183.0	2.50± 0.08	2.06E-14± 2.33E-15	IGR J18490-0000
2HWC J1852+013	83.8	2.89± 0.10	1.57E-14± 1.86E-15	-
2HWC J1857+027	452.7	2.94± 0.04	3.44E-14± 2.01E-15	HESS J1857+026
2HWC J1902+048	48.8	3.16± 0.16	7.70E-15± 1.95E-15	-
2HWC J1907+084	69.0	3.24± 0.13	7.38E-15± 1.85E-15	-
2HWC J1908+063	646.6	2.58± 0.04	3.79E-14± 1.79E-15	MGRO J1908+06
2HWC J1912+099	120.6	3.01± 0.08	1.30E-14± 1.57E-15	HESS J1912+101
2HWC J1914+117	55.0	2.97± 0.12	8.40E-15± 1.42E-15	-
2HWC J1921+131	30.0	2.72± 0.16	6.29E-15± 1.22E-15	-
2HWC J1922+140	87.4	2.65± 0.10	1.04E-14± 1.27E-15	W 51
2HWC J1928+177	99.0	2.57± 0.10	1.02E-14± 1.32E-15	-
2HWC J1930+188	72.8	2.78± 0.10	9.60E-15± 1.20E-15	SNR G054.1+00.3
2HWC J1938+238	35.8	3.12± 0.15	5.40E-15± 1.41E-15	-
2HWC J1953+294	37.6	2.77± 0.13	7.57E-15± 1.29E-15	-
2HWC J1955+285	26.7	2.67± 0.19	6.06E-15± 1.32E-15	-
2HWC J2006+341	49.3	2.80± 0.12	9.74E-15± 1.46E-15	-
2HWC J2019+367	646.5	2.36± 0.05	3.27E-14± 2.46E-15	VER J2019+368
2HWC J2020+403	90.6	3.07± 0.09	1.65E-14± 2.26E-15	VER J2019+407
2HWC J2024+417	29.7	2.69± 0.18	1.01E-14± 2.17E-15	MGRO J2031+41
2HWC J2031+415	311.5	2.52± 0.06	3.03E-14± 2.67E-15	TeV J2032+4130

Table 2: 2HWC sources with ΔTS<25. The columns correspond to: HAWC source name, test statistic, spectral index, normalization flux at 7 TeV and the nearest TeVCat source name. The uncertainties are statistical only. The results were obtained with the map of 25 months.

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 ΔTS>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, ΔTS is given in column 4, column 5 shows the normalization flux f_0 at

the reference energy $E_0 = 7$ TeV, the spectral index α appears in column 6, column 7 presents the cut-off energy E_c or the curvature parameter β depending on the spectrum model given in column 2. Note that ΔTS 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, ΔTS 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 ΔTS<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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