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Monitoring radio galaxies at TeV energies with HAWC

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With an instantaneous field of view of 2 sr and a duty cycle $> 95\%$, the High Altitude Water Cherenkov (HAWC) Gamma-Ray Observatory is a perfect instrument for monitoring variable TeV sources. Because radio galaxies are a type of Active Galactic Nuclei (AGN) with their jets misaligned with respect to our line of sight, they may help us to probe the physics of very-high-energy (VHE) emission processes in these objects. Three out of four radio galaxies that have been detected at TeV energies by other facilities are located within the field of view of the HAWC Observatory: M87, NGC 1275, and 3C 264. A search for TeV gamma rays at their locations yields no statistically significant excess of counts. We present corresponding upper limits for each radio galaxy and light curves covering 3 years of data taken with HAWC.

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PoS(ICRC2019)622

1. Introduction

According to unification models, radio galaxies are a type of Active Galactic Nuclei (AGNs) presenting radio-loud emission and with its jet misaligned with the line of sight. Morphologically, they are classified according to their radio emission into two categories. FR-I with the bright radio emission dominating close to its center and FR-II with the radio emission peak further away at the lobes[1]. Although they were not expected to emit in TeV energies, recently four FR-I galaxies have been detected at these energies. Thus, an interesting debate concerning the very-high-energy (VHE) gamma-rays emission models has been opened. This emission is believed to be mainly originated in the jets and lobes. The spectral energy distribution (SED) of radio galaxies in this energetic band can be well-described by leptonic models, hadronic models or a combination of both. Leptonic models can explain gamma-ray emission up to GeV energy range by means of synchrotron self-Compton (SSC) emission [2, 3], while hadronic models describe emission at TeV energies as originated by photo-hadronic processes [4, 5].

The HAWC Observatory, with its instantaneous field of view of ~ 2 sr and a duty cycle $\gtrsim 95\%$, is well-suited for monitoring this kind of sources. In the present work we search for TeV emission from radio galaxies within the field of view of HAWC. Because no statistically significant excess of counts was collected, we report the upper limits on the VHE flux, as well as the light curves, for the radio galaxies M87, NGC 1275, and 3C 264 using 1017 days of data. The outline is as follows. In Section 2, we give a brief summary of the latest TeV observations for each radio galaxy as well as the explanation of the analysis, and in Section 3 we summarize our results.

2. Radio Galaxies Observations and Analysis

2.1 M87

M87 is a giant elliptical radio galaxy located in the Virgo cluster that harbors in its core a supermassive black hole (SMBH) with a mass of $(6.5 \pm 0.7) \times 10^9\,\mathrm{M}_\odot$ [6]. Its distance to Earth is 16.7 ± 0.2 Mpc with a redshift of $z = 0.0044$ [7], makes it the closest radio galaxy in the field of view of HAWC. A relativistic jet emerges from its core and extends from 1.5 to 2 kpc at an angle that has been estimated between $15° - 25°$ from the line of sight.

HEGRA first detected M87 above 730 GeV reporting $3.3\% \pm 0.8\%$ of the Crab Nebula flux. Since then, it has been monitored by different imaging atmospheric Cherenkov telescopes (IACTs), quiescent and active states have been observed during these campaigns. Because of its closeness to Earth this radio galaxy is of great interest, affording an excellent opportunity to study the mechanisms involved on the emission of VHE gamma-rays.

For a quiescent state M87 spectra have been fitted to a simple power law. In 2004 HESS reported the lowest flux ever registered with a spectral index of 2.62 ± 0.35 and a normalization of $(2.43 \pm 0.75) \times 10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$ at 1 TeV [8]. MAGIC monitored M87 between 2005 and 2007 and reported a spectral index of 2.21 ± 0.21 and a normalization of $(5.4 \pm 1.1) \times 10^{-12}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$ at 1 TeV [9]. In 2007 VERITAS monitored M87 and reported a spectral index of 2.31 ± 0.17 and a normalization of $(7.4 \pm 1.3) \times 10^{-13}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}\,\mathrm{TeV}^{-1}$ at

PoS(ICRC2019)622

1 TeV [10]. Between 2011 and 2012, M87 was monitored by VERITAS, monthly variation in the TeV flux was observed which may hint that the quiescent emission evolves over longer time scales in comparison with flare emission. VERITAS divided their data sets in two from the 2012 observations; the first one with a spectral index of 2.1 ± 0.3 and a normalization of $(6.3 \pm 1.6) \times 10^{-13}$ cm^{-2} s^{-1} TeV^{-1} at 1 TeV, and the second one with a spectral index of 2.6 ± 0.2 and a normalization of $(7.0 \pm 1.5) \times 10^{-13}$ cm^{-2} s^{-1} TeV^{-1} at 1 TeV [11].

M87 was in activity or flare states in 2005, 2008 and 2010. The spectra for these flares were fitted to simple-power laws. For the 2005 flare, HESS reported a spectral index of 2.22 ± 0.15 and a normalization of $(11.7 \pm 1.6) \times 10^{-13}$ cm^{-2} s^{-1} TeV^{-1} at 1 TeV [12]. For the 2008 flare MAGIC, reported a spectral index of 2.21 ± 0.18 and a normalization of $(48.1 \pm 8.2) \times 10^{-13}$ cm^{-2} s^{-1} TeV^{-1} at 1 TeV [13], while VERITAS reported a spectral index of 2.40 ± 0.21 and a normalization of $(15.9 \pm 2.9) \times 10^{-13}$ cm^{-2} s^{-1} TeV^{-1} at 1 TeV [14]. For the 2010 flare, VERITAS reported a spectral index of 2.19 ± 0.07 and a normalization of $(47.1 \pm 2.9) \times 10^{-13}$ cm^{-2} s^{-1} TeV^{-1} at 1 TeV [15].

2.2 NGC 1275

NGC 1275 is located in the center of the Perseus cluster with a redshift of $z = 0.017559$, at a distance of ~ 75.3 Mpc [16]. Its equatorial coordinates are $\alpha = 49.950°$ and $\delta = 41.512°$ (J2000). The mass of the SMBH in its core is $3 - 4 \times 10^8$ M$_\odot$ [17] and the parsec scale jet is oriented with an angle of $\sim 30° - 60°$ with respect to the line of sight. It was first detected by MAGIC above 100 GeV with a significance of 6.6 σ with nearly 100 h of data. Its flux between 70 and 500 GeV could be described by a simple power law with a spectral index of $4.1 \pm 0.7_{\text{stat}} \pm 0.3_{\text{sys}}$ and a normalization of $(3.1 \pm 1.0_{\text{stat}} \pm 0.7_{\text{sys}}) \times 10^{-10}$ TeV^{-1} cm^{-2} s^{-1} at 100 GeV[18].

Two flare activity periods have been reported: the first one in October 2016, was reported with 16% of the Crab Nebula flux and the second one in the night of December 31st, 2016, with ~ 1.5 of the Crab Nebula flux. The last flare correspond to the highest state ever reported for this source. The MAGIC Collaboration reported a spectrum fitted by a power law with an exponential cutoff with a spectral index of 2.11 ± 0.14, a normalization of $(1.61 \pm 0.23) \times 10^{-9}$ cm^{-2} s^{-1} TeV^{-1} at 300 GeV and a cutoff energy of 0.56 ± 0.11 TeV. A similar analysis was carried out including Fermi-LAT data, the spectrum was fitted with a power-law function with exponential cutoff, a spectral power index of 2.05 ± 0.03, a normalization of $(4.17 \pm 0.22) \times 10^{-9}$ cm^{-2} s^{-1} TeV^{-1} at 198.21 GeV and a cutoff energy of 492 ± 35 GeV [19].

2.3 3C 264

3C 264 is a FR-I radio galaxy located in the Leo cluster at a redshift of $z = 0.022$ corresponding to a distance of ~ 95 Mpc [20]. This makes it the most distant radio galaxy detected so far at VHE although the true nature of PKS 0625 35 is still under debate. Its equatorial coordinates are $\alpha = 176.271°$ and $\delta = 19.606°$ (J2000). It harbors a SMBH with a mass of $\sim 5 \times 10^8$ M$_\odot$ [21]. It has a relativistic jet that reaches kiloparsec scales, in which

PoS(ICRC2019)622

knots have been observed and those closest to the core present superluminal movement [22].

The only instrument that has observed this source at TeV energies is VERITAS, which observed it for a period of time of ~ 12 h between February and March 2018, making it the most recent galaxy radio to join the TeV emitters. The preliminary results showed an excess of 60 gamma-ray events on the background, with a significance of 5.4σ. The preliminary integral flux is $\sim 1\%$ of the Crab Nebula flux [23]. It has been argued that the VHE spectral index is ~ 2.3 and shows a low, weakly variable flux along with some month-scale variations [24].

2.4 Analysis and Results

We performed a search for TeV gamma-rays from the radio galaxies M87, NGC 1275 and 3C 264 using 1017 days of data via a maximum likelihood fit convolving spectral models applied to the data with the detector response of HAWC as described in [25]. No signal with enough statistical significance from these radio galaxies were detected, thus, 95% confidence level upper limits were calculated using a maximum likelihood method within HAWC analysis framework [26]. For the light curves we use the same procedure as the one used in [27]. We also applied a quality cut to the data for which the sources transit for at least a sidereal fraction of 0.75. In accordance to previous works [10, 24, 19], the spectral models used for the analysis are: i) for M87, a simple power law with spectral index $\Gamma = 2.31$, ii) for NGC 1275, a power law with exponential cutoff at 500 GeV and spectral index $\Gamma = 3$ and iii) for 3C 264, a simple power law with spectral index $\Gamma = 2.3$.

We summarize on Table 1 the resulting VHE upper limits on the flux normalization for the radio galaxies M87, NGC 1275 and 3C 264. The VHE upper limits were computed using 1017 days of data taken with the HAWC Observatory. Given that these radio galaxies are potential candidates for accelerating cosmic rays, and then for producing VHE photons by hadronic interactions, an estimate of the characteristics of the emitting region, magnetic fields and the amount of cosmic rays in the jet could be given.

Table 1: Upper limits calculated for the radio galaxies within the field of view of HAWC. For all radio galaxies the attenuation in the flux due to interaction with the extragalactic background light (EBL) was considered. For M87 the first value of the upper limit considers no EBL attenuation.

Radio Galaxy	Energy Range [TeV]	Spectral Index	Upper Limit [$10^{-13}\,\mathrm{TeV}^{-1}\,\mathrm{cm}^{-2}\,\mathrm{s}^{-1}$]
M87	3 - 100	2.31	1.76
M87 (EBL)	3 - 100	2.31	3.51
NGC 1275 (EBL)	1 - 4	3	167.8
3C 264 (EBL)	2 - 40	2.3	6.88

Energy range were chosen as the one that provides a 90% of the sensitivity for a given spectral shape and declination of the source. The upper limit for M87 is consistent with past observations of the source in a quiescent state. For NGC 1275 the upper limit is

PoS(ICRC2019)622

comparable with the flux of the 2017 flare. The upper limit for 3C 264 will be compared with the data taken by VERITAS as soon as their results get published.

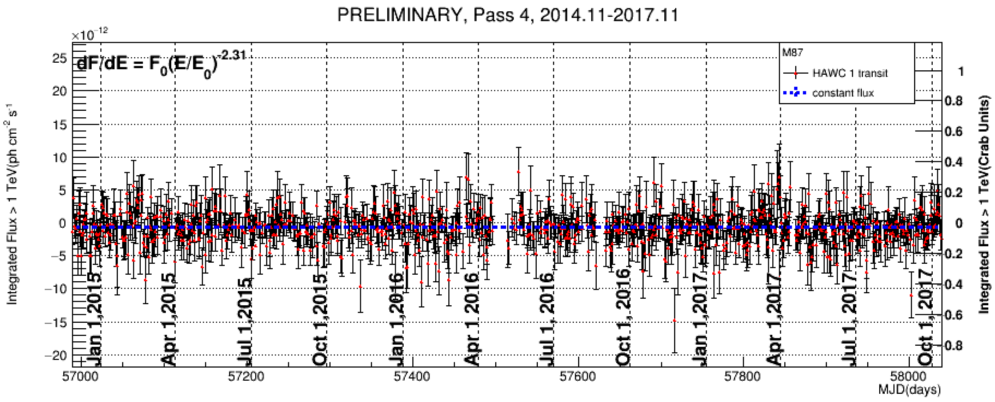

Figure 1: Light curve for 1017 days of HAWC data for M87.

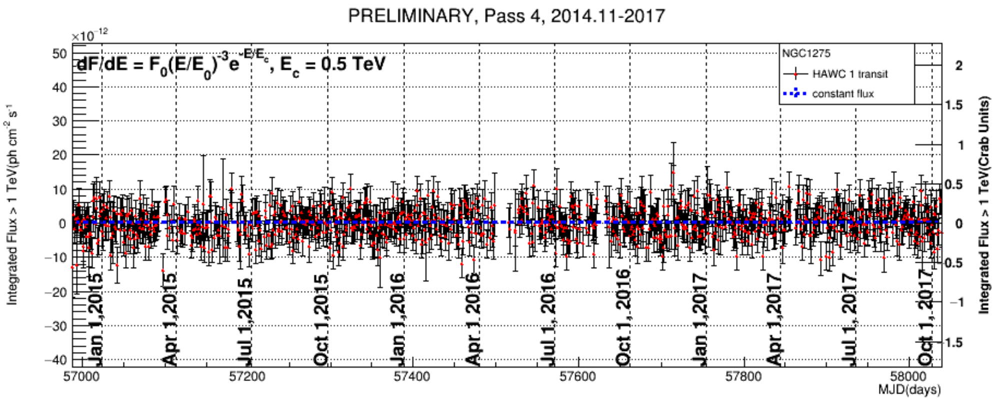

Figure 2: Light curve for 1017 days of HAWC data for NGC 1275.

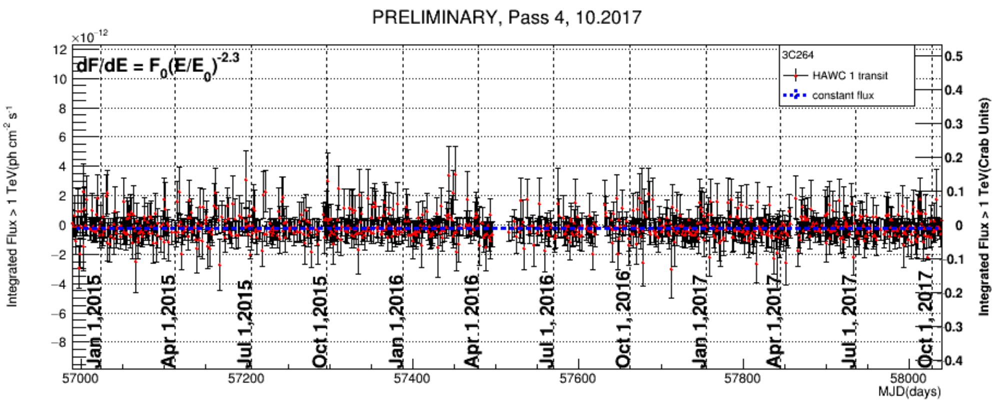

Figure 3: Light curve for 1017 days of HAWC data for 3C 264.

PoS(ICRC2019)622

All of the light curves have mean flux values consistent with zero. There are no signatures of evident flare events, however, a Bayesian analysis will be done to dismiss the possibility of any hidden activity in the light curves.

3. Conclusions

The upper limits calculated in the GeV - TeV energy range would help to constrain the physics of these radio galaxies (e.g., the emission processes, the size of the emitting region, magnetic fields, the amount of cosmic rays, etc). The light curves derived in this work will be updated using the ZEBRA framework as done in [28]. Weekly and monthly light curves will be done to search for variability of the sources in these time scales.

HAWC gamma-ray observatory will continue monitoring the radio galaxies in its field of view with the goal of detecting VHE photons in the following years.

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PoS(ICRC2019)622