Observations of blazars 1ES 1426+428, 1ES 1218+304 and 3C 454.3 by HAGAR telescope

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We have observed three blazers, viz., 1ES 1426+428, 1ES 1218+304 and 3C 454.3 using the High Altitude Gamma Ray (HAGAR) telescope array. The HAGAR array is a wavefront sampling array of 7 telescopes, set-up at Hanle, at 4270 amsl, in Ladakh region of the Himalayas (Northern India). These three sources 1ES 1426+428, 1ES 1218+304 and 3C 454.3 are observed for 28, 56 and 10 hrs respectively. Our observation span is about 6 year period from 2009 to 2015. From the preliminary data analysis of above mentioned sources we do not find any evidence for a statistically significant γ-ray signal. The results of these analysis will be discussed in this paper.

1. Introduction

High Altitude GAmma Ray (HAGAR) telescope system is an array of 7 telescopes which is based on the nonimaging atmospheric Cherenkov technique. It is designed to detect very high energy γ-rays from various astronomical sources. In the nonimaging atmospheric Cherenkov technique, the arrival time of Cherenkov shower front at various locations in the Cherenkov light pool is measured, from which the direction of shower axis is estimated to enable rejection of off-axis cosmic ray showers [14]. HAGAR set-up at Hanle (longitude: $78^o\ 57'\ 51''$ E, latitude: $32^o\ 46'\ 46''$, altitude: 4270 m) is the first array of atmospheric Cherenkov telescopes established at a so high altitude. Because of the high altitude, even with a modest mirror area of 31 m^2, this experiment achieves a comparatively low energy threshold of 208 GeV. Since September 2008 regular source observations have been going on with the complete set up of seven telescopes. In this article we present details of HAGAR data analysis done to obtain the γ-ray flux from three blazers, viz., 1ES 1426+428, 1ES 1218+304 and 3C 454.3.

2. The HAGAR experiment details

Out of the seven telescopes of the HAGAR array, six are deployed at the vertices of a hexagon and the seventh one is placed at the center of the hexagon (see Fig. 1) [2]. Each telescope consists of seven front coated mirrors of parabolic shape with $\frac{f}{d}$ equal to 1 and each of diameter 0.9 m. The mirrors are fabricated from 10 mm thick float glass sheets. All the seven mirrors of each telescope are mounted para-axially on a single platform while the telescopes themselves are mounted alt-azimuthally. A fast Photonis UV sensitive PMT XP 2268B is placed at the focus of each mirror. The diameter of PMT photo cathode defines the field of view to be 3^o at FWHM. Coaxial cables of length 85 m and of types LMR-ultraflex-400 (of length 30 m) and RG 213 (of length 55 m) are used to bring pulses from the photo-tubes to control room situated below the central telescope. The telescope movement is maneuvered by a control software written on Linux platform. High voltages fed to photo tubes are controlled and monitored using C.A.E.N controller (model SY1527). PMT pulses are given to CAMAC based

Figure 1. Schematic layout of HAGAR array (left) and one of the telescope of the array (right).

interrupt driven system in control room which acquires and records the data. For trigger generation, the 7 pulses of PMTs of a given telescope are linearly added to form telescope pulse, called royal sum pulse. A coincidence of any 4 telescope pulses above a preset threshold out of 7 royal sum pulses with in a resolving time of 150 to 300 ns generates a trigger pulse [3]. RS discriminator biases are adjusted to keep the RS rates within 25 to 35 kHz to maintain a chance coincidence rate within a few percent of the trigger rate. Data recorded on event interrupt includes relative arrival time of a shower front recorded by the TDCs accurate to 0.25 ns. 12 bit QDCs are used to record the Cherenkov photon density at each telescope, given the total charge in PMT pulses. An absolute arrival time of an event accurate to μs is given by a Real Time Clock (RTC) module synchronized with GPS. Various other information, such as the triggered telescopes in an event, are also recorded.

3. Signal extraction procedure

The HAGAR data analysis is based on the arrival angle estimation of the incident atmospheric shower w.r.t. the source direction. This angle called space angle i.e the angle between the direction of arrival of the shower and the direction of the source, is obtained for each event by measuring relative arrival times of the showers at each telescope. An accurate pointing of telescopes as well as precise time calibration of the optoelectronic chain is then required [2]. The later part is achieved first by computing TDC differences between pairs of telescopes from fix angle runs. Fix angle runs are used to compute the theoretical time-offsets, using information on the pointing direction, coordinates of telescopes, and on the transit time of each channel through the electronic chain. The TDC differences between pairs of telescopes from fix angle runs yield the calculation of T_0*'s* (read as *tzeros*). T_0's are the relative time offsets for all telescopes to be used in the analysis to ensure a valid estimation of the relative timing differences in the arrival of the Cherenkov signal on the telescopes. Plane front approximation is then used to fit the arriving spherical Cherenkov wavefront in order to compute the space angle. For each event, the value of the χ^2 of the fit and other fit parameters are taken, and the number of telescopes with valid TDC information, i.e. participating in the trigger, is written. Thus four types of events, based on the Number of Triggered Telescopes (NTT), viz. events with NTT = 4, NTT = 5, NTT = 6 and NTT = 7 are defined. Atmospheric conditions change during observation time, reflected by variations on the trigger rate readings. This add systematics in our analysis. In order to remove isotropic emission due to cosmic rays, source observation region (ON) is compared with OFF-source region at same local coordinates on the sky, but at a different time (before or after tracking the source region for about 30 to 50 min). Normalisation of background events of both the ON and OFF source data sets is done by comparing number of events at large space angles, where no γ-ray signal is expected. This yield a ratio, called normalisation constant, which allows to calculate the ON-OFF excess below one specific cut on the space angle distribution [3].

4. Data selection criteria

In order to reduce systematics as much as possible data selection is done using some parameters which characterize good quality data. First, only those runs are selected for which trigger rate is stable. Runs with high value of the trigger rate are data that were taken under different conditions and hence are kept aside for future analysis. Then, the stability of the trigger rate of each run is quantified using one variable, called R_{stab}, defined as the RMS of the rate on the square root of its mean. For perfect Poissonnian fluctuations, this variable is expected to be equal to 1. Difference of R_{stab} ($R_{stab(ON)} - R_{stab(OFF)}$) of a given ON-OFF pair, gives relative rate stability of that run pair. A Gaussian fit to distribution of $R_{stab(ON)} - R_{stab(OFF)}$ and events within 3σ (standard deviation) limit define the range of R_{stab} cut for selection of pairs. Pair selection is then done imposing constraints on several other parameters. The relative difference of the coincidence window rate between ON and OFF source runs is imposed to be less than 10%, otherwise the pair is rejected. This parameter is related to the night sky background rate. Difference between the mean trigger rates of an ON and an OFF run is restricted to less than 2 Hz. Also, to prevent additional systematics during space angle computing, where some events are rejected, we impose difference between mean trigger rates to be less than 1 Hz after this analysis processing. During the pair processing, ratio of events for each telescope are computed and constrained to be between 0.8 and 1.2. Events with $\chi^2 \geq$ (mean + 1σ) are rejected, where χ^2 is the parameter of plane front fit. Further events with space angle greater than 7^o are rejected, as these are mostly due to bad fits [3]. Additional cuts viz., position error (Pos_{err}) cut of reproduced source position from TDC events relative to source position in sky is also applied. Position error is calculated separately for RA and DEC directions. A Gaussian fit to distribution of relative Pos_{err} in between ON-OFF pairs and events within 3σ (standard deviation) limit define the range of position error cut for selection of pairs [5]. At the last step of the selection, value of the normalization constant between ON and OFF events is computed and is constrained to be between 0.85 and 1.15.

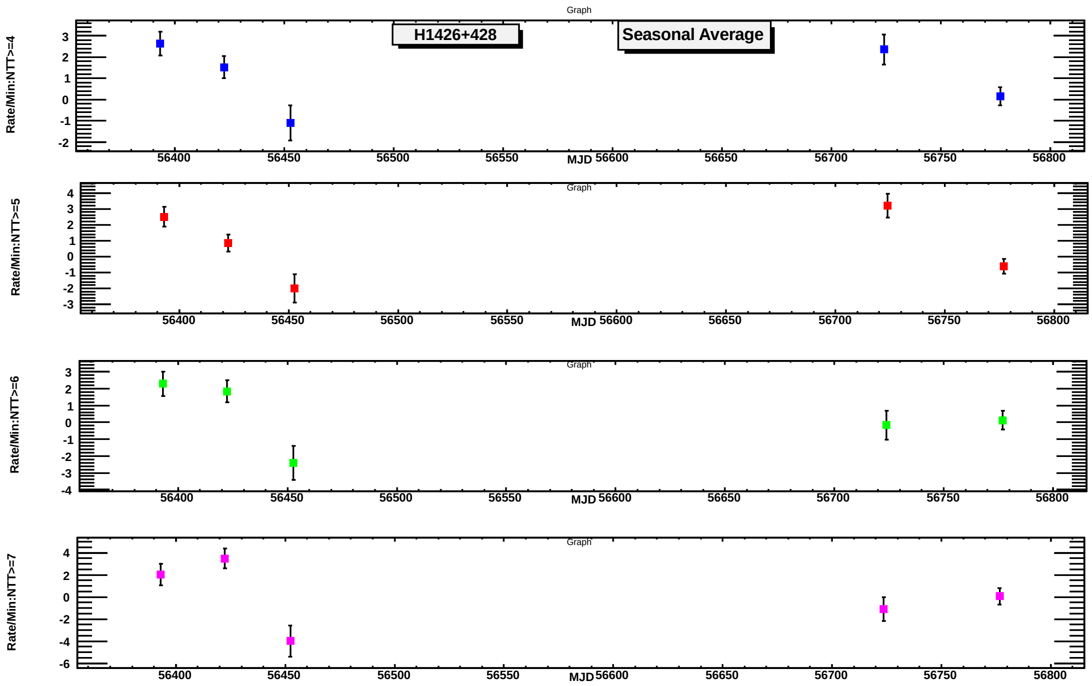

Figure 2. Light curve of 1ES 1426+428 averaged over each observation season.

5. Observed sources

3C454.3 is a powerful flat-spectrum radio quasar located at a redshift z = 0.859. Its RA is 22:53:57.7 and DEC is 16:08:54. It is one of the brightest gamma ray sources in the sky. In 2005 it underwent a very active phase in optical and X-ray bands, triggering intensive observations in the radio, optical and X-ray (Swift, Chandra, INTEGRAL) bands [6, 7, 8].

1ES 1228+304 is a HBL object. It has a redshift of z = 0.182 and it is one of the more distant VHE blazars detected to date. Its RA is 12:21:26.3 and DEC is 30:11:29. It was first detected at VHE by MAGIC [9] and confirmed by VERITAS [10].

1ES 1426+428 (z = 0.129) is classified as a BL Lac object. Its RA is 14:28:32.6 and DEC is 42:40:21. H 1426 + 428 is classified as an *extreme*. The source was first detected at TeV energies by the Whipple collaboration [11] and later confirmed using other ground-based imaging atmospheric Cherenkov telescopes [12].

6. Results

The HAGAR has observed these three sources 1ES 1426+428, 1ES 1218+304 and 3C 454.3 for 28, 56 and 10 hours respectively over an observation span of about 6 year period from September, 2009 to May, 2015. After imposing different analysis cuts, out of 39, 79 and 16 total run pairs, we had 23, 16 and 50 good ON-OFF pairs for the 1ES 1426+428, 1ES 1218+304 and 3C 454.3 that corresponds to 16.4, 9.8 and 35.9 hours of data respectively. The light curve of the three sources 1ES 1426+428, 1ES 1218+304 and 3C 454.3, for different telescope trigger conditions are shown in the Fig. 2, Fig. 3 and Fig. 4 respectively. Rate excess from the pair analysis is now

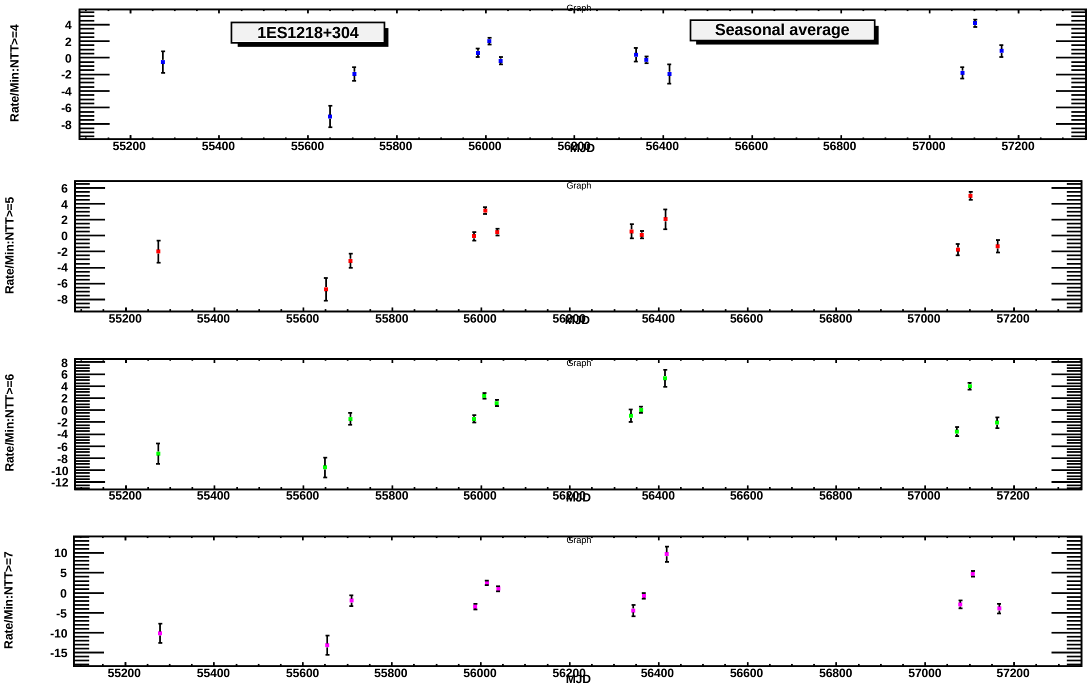

Figure 3. Light curve of 1ES 1218+304 averaged over each observation season.

represented for each selected pair as a number of counts per minute, expected to contain a significant fraction of γ-rays. The estimated γ-ray rates from these three sources for different triggering criteria are given in Table 1, Table 2 and Table 3 respectively.

Considering the facts that the sources 1ES 1426+428, 1ES 1218+304 and 3C 454.3 are situated farther in distance and the sensitivity of HAGAR, very long duration observations are required to detect significant excess from these three sources. Therefore we have estimated flux upperlimit for these three sources from our observations. Thus we have obtained 3σ upperlimit on VHE γ-ray flux as 2.43x10^{-6} photons $m^{-2}s^{-1}$, 6.57x10^{-6} photons $m^{-2}s^{-1}$ and 1.63x10^{-6} photons $m^{-2}s^{-1}$ at the energy threshold of about 182 GeV for NTT $\geq$ 4-fold for these sources respectively.

Table 1. Results of the 1ES 1426+428 for NTT $\geq$ 4-fold, 5-fold, 6-fold and 7-fold.

NTT	Rate/min.	RMS/min.	σ	T(hours)	Runs	σ/T
NTT $\geq$ 4	- 6.67	1.44	- 4.64	7.91	12	- 1.65
NTT $\geq$ 5	- 3.18	1.18	- 2.70	7.91	12	- 0.96
NTT $\geq$ 6	- 2.19	0.95	- 2.31	7.91	12	- 0.82
NTT$\geq$7	- 0.70	0.70	- 1.00	7.91	12	- 0.36

7. Summary

In summary, we have presented data analysis from HAGAR observations of the three blazers 1ES 1426+428, 1ES 1218+304 and 3C 454.3. We had a total of 28, 56 and 10 hrs of data for these three sources respectively, over an observation span of about 6 year period from 2009 to 2015. We have not detected a signal from either of these

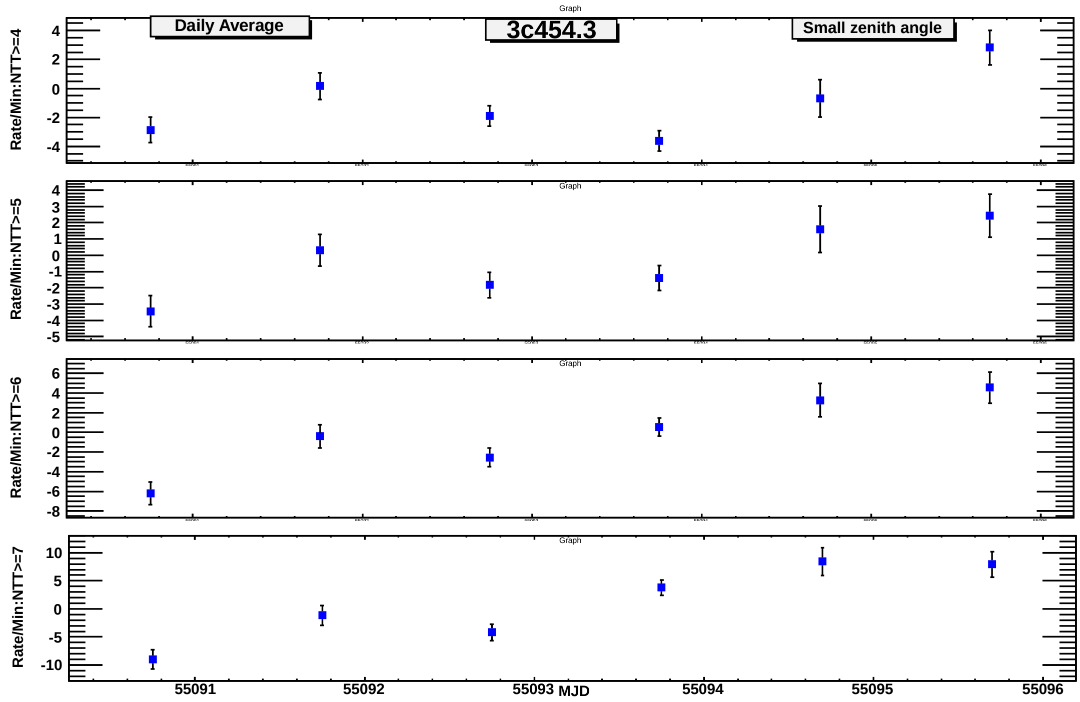

Figure 4. Light curve of 3C 454.3 averaged over a day (zenith $< 30^o$).

Table 2. Results of the 1ES 1218+304 for NTT $\geq$ 4-fold, 5-fold, 6-fold and 7-fold.

NTT	Rate/min.	RMS/min.	σ	T(hours)	Runs	σ/T
NTT $\geq$ 4	2.02	0.68	2.96	35.99	50	0.49
NTT $\geq$ 5	2.22	0.54	4.10	35.99	50	0.68
NTT $\geq$ 6	0.21	0.41	0.52	35.99	50	0.09
NTT $\geq$ 7	-0.48	0.27	-1.83	35.99	50	-0.30

Table 3. Results of the 1ES 3c454.3 for NTT$\geq$ 4-fold, 5-fold, 6-fold and 7-fold (zenith $< 30^o$).

NTT	Rate/min.	RMS/min.	σ	T(hours)	Runs	σ/T
NTT $\geq$ 4	- 6.67	1.44	- 4.64	7.91	12	- 1.65
NTT $\geq$ 5	- 3.18	1.18	- 2.70	7.91	12	- 0.96
NTT $\geq$ 6	- 2.19	0.95	- 2.31	7.91	12	- 0.82
NTT $\geq$ 7	- 0.70	0.70	- 1.00	7.91	12	- 0.36

sources and have set upper limits on their γ-ray flux levels. The source 3c454.3 is a quasar with a very high redshift (z = 0.859). The flux of very high energy γ-rays from this source is likely to be affected by absorption due to extragalactic background radiation during their propagation in the inter galactic medium and get attenuated. As a result this source is not detected by the any of the VHE experiments so far. Further, since HAGAR sensitivity is very less compared to other ground based VHE γ-ray telescopes, so for a significant detection of 1ES 1426+428 and 1ES 1218+304 number of hours of observation must be increased.

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