GAMMA-RAY SOURCE OBSERVATIONS WITH THE HAGAR TELESCOPE SYSTEM AT HANLE IN THE HIMALAYAS

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Abstract. We have observed Crab nebula using the recently commissioned wavefront sampling high altitude (4270 m) array, HAGAR, at Hanle in the Ladakh region of the Himalayas. Regular source observations have begun with the complete setup of 7 telescopes since Sept. 2008. HAGAR is the first array of atmospheric Cherenkov telescopes established at a so high altitude and was designed to reach a relatively low threshold with quite a low mirror area ($31\ m^2$). Estimation of the sensitivity of the experiment is undergoing using several hours of data from the direction of Crab nebula, the standard candle source of TeV gamma-ray astronomy. Data were acquired using the On-source/Off-source mode and by comparing these sky regions the strength of the gamma-ray signal could be estimated. Gamma-ray events arrive close to telescope axis direction while the cosmic-ray background events arrive from the whole field of view. We discuss our analysis procedures for the estimate of arrival direction, estimate of gamma-ray flux from Crab nebula and the sensitivity of the HAGAR system etc in this paper. Also preliminary results on blazars 1es2344+514 and Mkn421 will be presented.

1 The HAGAR experiment

Located at 4270 m a.s.l., the HAGAR experiment (Latitude: 32°46'46" N, Longitude: 78°57'1"E) uses the Atmospheric Cherenkov Technique (A.C.T.). When a gamma-ray photon enters the Earth atmosphere, it causes a shower of relativistic particles. These particles initiate a spherical wavefront of blue-UV Cherenkov light which originates mostly from the shower maximum region (at about 10 km a.s.l. at 100 GeV). This wavefront has a width of few nanosecondes and forms on the ground a pool of light with a diameter of several tens of metres. Sampling the Cherenkov light using fast PMTs and recording precise relative arrival time between the detectors are the key for the detection of gamma rays at GeV energies, using wavefront sampling detectors.

Technical characteristics of the experiment are: 7 telescope array based on Wavefront Sampling Technique; 7 para-axially mounted parabolic mirrors of diameter 0.9 m in each telescope; f/D ∼ 1; fast Photonis UV sensitive PMT XP 2268B at the focus of each mirror and with a field of view of 3°17′; data recorded for each event: relative arrival time of shower front at each mirror accurate to 0.25 ns using TDCs; total charge at each mirror recorded using 12 bit QDCs (ADCs); absolute event arrival time accurate to μs; 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 (Chitnis et al. 2009a).

At GeV energies, gamma-ray signal is strongly dominated by cosmic rays which also produce Cherenkov light. In order to remove all isotropic emission, source observation is done by pair, *i.e.*, by comparing the source region with a off-source region at same local coordinates on the sky.

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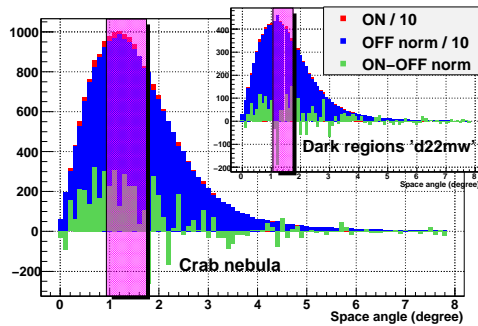
Fig. 1. Distribution of space angle of ON, OFF and ON-OFF events from the selected pairs on Crab nebula (in enclosed panel for the dark regions). For readability, ON and OFF distributions were respectively rescaled by a factor 10.

2   Signal extraction procedure

The HAGAR data analysis actually derived from the method used in the PACT experiment in Pachmarhi (Bose 2007). It is based on the arrival angle estimation of the incident atmospheric shower w.r.t. the source direction. This so-called space angle[1] is obtained for each event by measuring relative arrival times of the showers at each telescope. Precise time calibration of the optoelectronic chain is then required, as well as pointing accuracy (Chitnis et al. 2009a). Space angle is then computed by fitting the arriving spherical Cherenkov wavefront, using plane front approximation. For each event, the value of the χ^2 of the fit and other fit parameters are given, and the number of telescopes with valid TDC information, *i.e.* participating in the trigger, is written. Thus are defined 4 types of events, each type with a different number of degrees of freedom involved in our fitting procedure.

Atmospheric conditions change during observation time, reflected by variations on the trigger rate readings. This add systematics in our analysis. Normalization 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 signal is expected. This yield a ratio, called normalization constant, which allows to calculate the ON-OFF excess below one specific cut on the space angle distribution.

An important step in the validation of the analysis method is to analyse data pairs from fake sources (tracking dark regions), located at a similar declination as the observed gamma-ray source. Data were taken on a dark region located at the same declination as Crab nebula ($\simeq 22°$), and at the Milky Way border such as this standard source. Also, this dark region was associated in pair with other dark regions, shifted from the latter in right ascension, either towards the Galactic equator, or off the Milky Way. Because of source position constraint, the most recent pairs were formed from runs taken out off the Milky Way, but still at $\delta = 22°$. A statistical significance close to zero is then expected from this OFF-OFF analysis, if we are not dominated by systematic effects.

3   Data selection and preliminary results on dark regions and Crab nebula

Crab nebula is known as the standard candle of the gamma-ray astronomy. To get signal from this source is the priority of every new gamma-ray detector, in order to calibrate the instrument and optimize hadronic rejection. Now, we present preliminary selection of data as well as preliminary results so far obtained from observations carried out between September to December 2008 (Crab Nebula) and in April-May 2009 (dark regions).

Data selection is done using some parameters which characterize good quality data, in order to reduce systematics as much as possible. By run selection we reject acquisitions—or parts of them—where trigger rate is non stable and whose defaults in timing information are identified. Runs with high value of the trigger rate are laid aside for future analysis, as they were taken under different conditions. 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. Run rejection is done for $R_{stab} \geq 1.25$.

Pair selection is then done by constraining several parameters. One of our selection parameter is related to the differences on the mean night sky backgroung rates. It was used for the Crab data, and for some of the dark regions. An other criterion is on the mean trigger rate values. Difference is imposed to be less than

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[1]the angle between the direction of arrival of the shower and the direction of the source

Table 1. Result summary of the analysis of the selected pairs on the dark regions

Event type	No. selected pairs (initially 20)	duration (hour)	N_{ON}	N_{OFF}	excess	rate [2] (count(s) min^{-1})	significance (no. of σ)
All tel.	9	3.9	46643	47294	642.81 ± 302.52	3.18 ± 1.20	2.12
4 tel.	5	2.1	11732	12051	-62.78 ± 152.74	-0.55 ± 1.20	-0.46
5 tel.	7	3.1	12286	12635	-324.99 ± 157.80	-1.74 ± 0.85	-2.06
6 tel.	8	3.4	10123	10228	234.83 ± 140.45	1.14 ± 0.68	1.67
7 tel.	8	3.4	12502	12380	802.75 ± 153.59	3.91 ± 0.75	5.23

Table 2. Result summary of the analysis of the selected pairs on Crab nebula

Event type	No. selected pairs (initially 43)	duration (hour)	N_{ON}	N_{OFF}	excess	rate [2] (count(s) min^{-1})	significance (no. of σ)
All tel.	13	9.1	99000	100430	2604.47 ± 437.93	4.12 ± 0.70	5.95
4 tel.	9	6.5	31855	31587	1460.44 ± 247.22	5.91 ± 0.63	5.91
5 tel.	12	8.6	28486	29152	455.83 ± 235.66	1.93 ± 0.46	1.91
6 tel.	10	7.5	18517	18832	-237.96 ± 192.92	-1.93 ± 0.43	-1.23
7 tel.	12	8.5	20142	20859	926.16 ± 194.16	1.81 ± 0.38	4.76

2 Hz. These previous criteria are designed to control dramatic changes in atmospheric condition and acquisition within a pair. 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 + 1 σ) are rejected, where χ^2 is the parameter of plane front fit. Further we reject events with space angle greater than 7°, as these are mostly due to bad fits. Space angle distribution is plotted for each pair and each event type. For a given space angle distribution, we call ψ_{85}, the edge containing 85 % of the remaining events. Then, constraint on the shape parameters of the space angle is applied: differences on the value of the ψ_{85} cuts, peak position, and FWHM are all three to be within 0°.15. 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. Due to this analysis procedure, some of our pairs are not fully selected or fully rejected, and only 1, 2 or 3 event types of some runs are selected.

After application of selection criteria and analysis cuts as defined above, dark region analysis can be performed from 9 selected pairs, and Crab signal can be estimated from 13 selected pairs. Normalization constant between ON and OFF event numbers is calculated considering the shape of the space angle distribution and between ψ_{85}(OFF) (typically found to lie between 1° to 1.75°) and 7°. The subtraction of the total number of normalized OFF events with total of ON events is perform below ψ_{85}(OFF), and shows an excess, as visible in figure 1, and reported in tables 1 and 2.

Rate excess from the pair analysis is now represented for each selected pair as a number of counts per minute, expected to contain a significant fraction of gamma rays, respectively for dark region and Crab nebula analysis (figure 2(a) and 2(b)). The global result of the analysis of 3.9 hours on dark regions shows a result compatible with zero, with a total significance of 2.12 σ. This indicates that systematic effects due to sky and time differences within one pair are not dominant in our analysis. However, a significance equal to 5.23 σ for events involving the 7 telescopes, requires more investigation. Also, additional data are to be added to this analysis.

From Crab nebula analysis, we report a rate of 4.12 ± 0.70 counts min^{-1}, corresponding to a significance of 5.95 σ, out of 9.1 hours of data. The expected values computed from simulation is 9.6 gamma rays per minute, and 5 σ for ~8 hours for this source, but without event rejection from analysis procedure. By rough extrapolation of simulations (Chitnis et al. 2009a), energy threshold of these analysis is expected to be around 200-220 GeV, for a collection area (effective surface) around 5×10^4 m^2. This yield an integral flux of $\sim 8.2 \times 10^{-11} cm^{-2} s^{-1}$ from Crab nebula. Our result is consistent with the flux already calculated from other experiments (Fig. 2(c)).

4   Study of other sources and further improvements

In parallel with the development of our analysis on Crab nebula data, we performed preliminary analysis of the blazars 1es2344+514 and Markarian 421. The blazar 1es2344+514 was observed during Sept-Nov 2008. Out of 4.4 hrs of selected data, an upper limit was computed above a threshold expected to be $\sim$ 250 GeV (Shukla et

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[2]Total mean rate is computed by applying a weight to each pair, corresponding of the number of event types selected
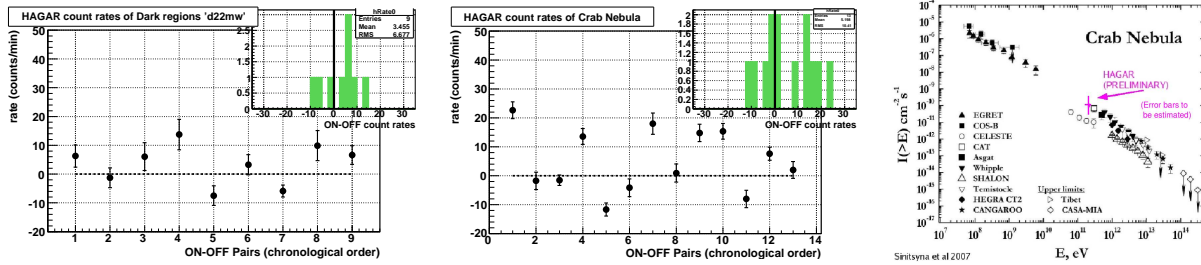
Fig. 2. Count rates of the selected pairs on the dark regions (left panel) and on Crab nebula (middle panel), in chronological order. Enclosed panels show the distributions of these counts. Right panel: integral spectrum of Crab nebula, as given by many experiments (Sinitsyna at al 2007). Preliminary flux estimation from HAGAR is added.

al 2009). Markarian 421 was observed during March-May 2009. No significant signal was found from the 6.6 hrs of selected data (Chitnis et al. 2009b). A preliminary study of pulsed emission from Crab and Geminga pulsars also led to upper limits on the fluxes (Acharya et al. 2009).

Improvement of the analysis procedure is currently going on. New modules are installed in the data acquisition system for additional informations. Till now, information from QDCs was not used, but first tests are conducted to implement discriminating variables based on the distribution of density of photons on the mirrors and telescopes. Also, spherical or parabolic fit of the Cherenkov wavefront is to be implemented, in order to reduce systematic error on the space angle estimation, and to take advantage of the angular resolution of HAGAR. Furthermore, newly installed Acqiris 1 Ghz flash ADC modules (model DC271A, using an 8-bit digitizer) are expected to improve many steps of our analysis, reduce systematics, and improve sensitivity of the experiment (Chitnis et al. 2009a). For example, software padding procedure used to balance night sky background between ON and OFF runs may replace the method of the normalization constant, as the latter is applied event by event and channel by channel.

5   Conclusions and Perspectives

Observation of the Crab nebula was carried out from September to December 2008 with the HAGAR telescope array at Hanle. Out of the 30 h of available data, a sample of 9.1 hours was selected. A preliminary analysis allowed us to report a $5.95\,\sigma$ detection of $4.1 \pm 0.7\,\gamma\,min^{-1}$ above 200 GeV. Analysis of systematic uncertainties are under going. Further improvements in the pair selection, as well as development of hadronic rejection methods based on simulations and newly installed flash ADCs, are expected to improve this preliminary results, which are however consistent with previous measurements by other experiments operating at similar energies. This preliminary result gives encouraging perscetive for on-going observation on blazars and other gamma-ray sources.

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