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STATUS OF THE HIMALAYAN GAMMA-RAY OBSERVATORY (HIGRO) AND OBSERVATON WITH HAGAR AT VERY HIGH ENERGIES

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Abstract. High Altitude GAmma Ray (HAGAR) telescope array, which is the first stage of HImalayan Gamma Ray Observatory (HIGRO), has been successfully installed at Hanle in Himalayas and has been collecting science data since September, 2008. In last three years, we have observed several sources including Galactic objects like Crab Nebula, Geminga, LSI+61 303 and some of the Fermi detected pulsars as well as extragalactic objects including Mkn 421, Mkn 501, 1ES2344+514, 3C454.3 etc. Analysis of data on all these sources is underway. Preliminary results include detection of Crab Nebula and Mkn 421 during its flare in February, 2010. Upper limits are given for several pulsars. In the second phase of HIGRO, Major Atmospheric Cherenkov Experiment (MACE), a 21 m-imaging telescope, will be installed at Hanle, next to HAGAR.

Keywords: gamma rays: atmospheric Cherenkov technique, methods: data analysis, telescopes: HAGAR

1 Introduction

Located at 4270 m amsl in the Ladakh region of the Himalayas, in Northern India (Latitude: 32°46'45" N, Longitude: 78°58'36" E), the HImalayan Gamma Ray Observatory (HIGRO) is the highest altitude ground-based gamma-ray observatory using the atmospheric Cherenkov technique. Phase 1 of HIGRO is the HAGAR experiment, operating with the full array since 2008. HAGAR is a sampling array of 7 telescopes, each one built with 7 para-axially mounted 0.9 m-diameter mirrors, giving a total reflective area of $\sim 31\ m^2$. Relative arrival time of Cherenkov shower front at each mirror is recording using TDCs and Flash ADCs, in order to obtain a timing precision as good as 1 ns, to sample the Cherenkov flash. Technical details as well as analysis procedure are given in companion paper (Britto et al. 2011), refered as *Paper I* hereafter.

In order to remove isotropic emission due to cosmic rays, source observation region (ON) is compared with OFF-source region at same local coordinates. The analysis of data is based on the arrival angle estimation of the incident atmospheric shower w.r.t. the source direction. This angle—called space angle—is obtained for each event by measuring relative arrival times of the shower at each telescope. Signal is extracted after rejecting large space angle events, and following the process of normalisation of ON/OFF background events (at large space angle), to balance night sky background differences between both data samples (Paper I). As the process of computing the normalisation constant 'C' is difficult due to the lack of statistics in the normalisation region, C is computed through two methods, as explained in Paper I. This gives the C1 and C2 values of C respectively.

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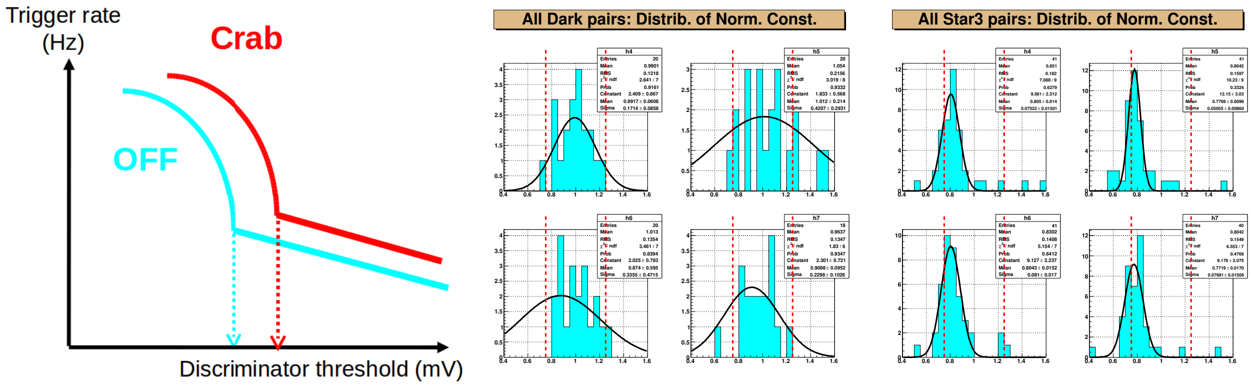

Fig. 1. (a) Representation of the Crab ON/OFF trigger rate versus hardware energy threshold. (b) Distribution of normalisation constants "C2" for "dark regions". (c) Distribution of normalisation constants "C1" for "star3" runs. From left to right and top to bottom of (b) and (c) respectively, are normalisation constants for NTT=4, 5, 6 and 7. The dashed red vertical lines delimitate the accepted range of C for dark region pairs (Paper I).

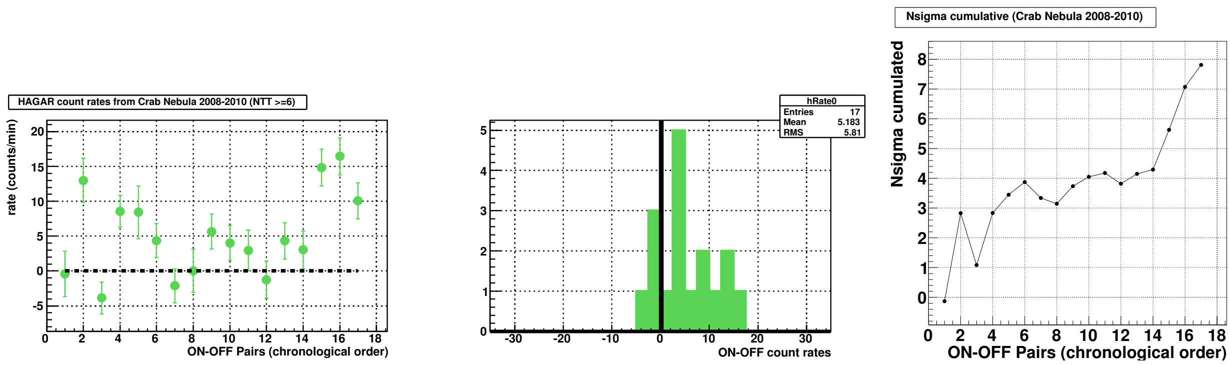

Fig. 2. Pair by pair count rates, computed using C1, for the selected data set of Crab Nebula 2008-2011.

2 A bright star in the field of view of Crab Nebula

The Crab Nebula is located at 67.5' from a star of magnitude 3. This star is within the FOV of the PMT during observations of Crab Nebula. As we keep PMT rates at 5 kHz for both ON and OFF runs, hardware energy threshold of Crab runs is higher than for off-source runs, as illustrated in Fig. 1(a). We need to verify if our analysis method could be biased by the presence of this bright star. So we performed acquisitions of so-called "star3" pairs, where we keep this bright star (or a star of similar magnitude and colour) in the field of view (FOV) of HAGAR, but with the Crab Nebula outside FOV. Due to these ON/OFF differences in trigger rates, we had to redefine the pair selection related to the ON/OFF ratio of events per telescope and the normalisation constant values. The mean values of normalisation constant are around 1 for "dark regions" (Fig. 1b), but systematically below 1 for "star 3" pairs (Fig. 1c).

The ranges for the normalisation constant were constrained to be within 0.65-0.95, as the mean value is around 0.8 (Fig. 1c). Results based on a minimum of 4 triggered telescopes (NTT $\geq$ 4) gives an artefact of signal. By keeping NTT ≥ 6, we increase the energy threshold and significantly reject low energy events. Out of the initial 47 pairs, we have selected 11 pairs, corresponding to 7.2 hours of data. No excess is seen (significance less than 2.0 σ, which is compatible with zero (Tab. 1). This indicates that systematic effects induced by a much brighter FOV during observations are to be considered in our data/analysis, and can be balanced by an appropriate event selection.

3 Analysis of the data from Crab Nebula

Since Sep. 2008, more than 120 hours of data have been collected from Crab Nebula. Using an event selection procedure, similar to the one of "star 3" data analysis, we perform the analysis of 10.4 hours of Crab Nebula data from the period 2008-2011.

Data sets	C	no. of pairs sel./ini.	duration	Count rate	N_σ	$N_\sigma/\sqrt{h}$
Dark	1	15(-)/26	6.5 h	-	0.8	-
	2	14(-)/26	6.4 h	-	-0.4	-
Star3	1	11/47	7.2 h	-	1.4	-
	2	11/47	7.2 h	-	2.0	-
Crab	1	17/153	10.4 h	5.1 ± 0.7	7.8	2.4
	2	20/153	12.6 h	5.7 ± 0.6	9.5	2.7

Tab. 1. Summary of results obtained from the 3 data sets used to report our results on Crab Nebula. Dark region results are described in Paper I. (-) indicates that two pairs share a common "OFF 1" run respectively in two occurrences. NTT $\geq$ 4 for 'dark' pairs; NTT $\geq$ 6 for "star3" and "Crab" pairs.

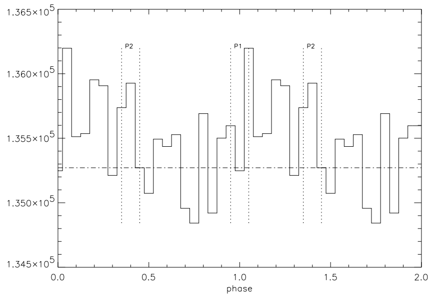

Fig. 3. Phase histogram for Crab pulsar.

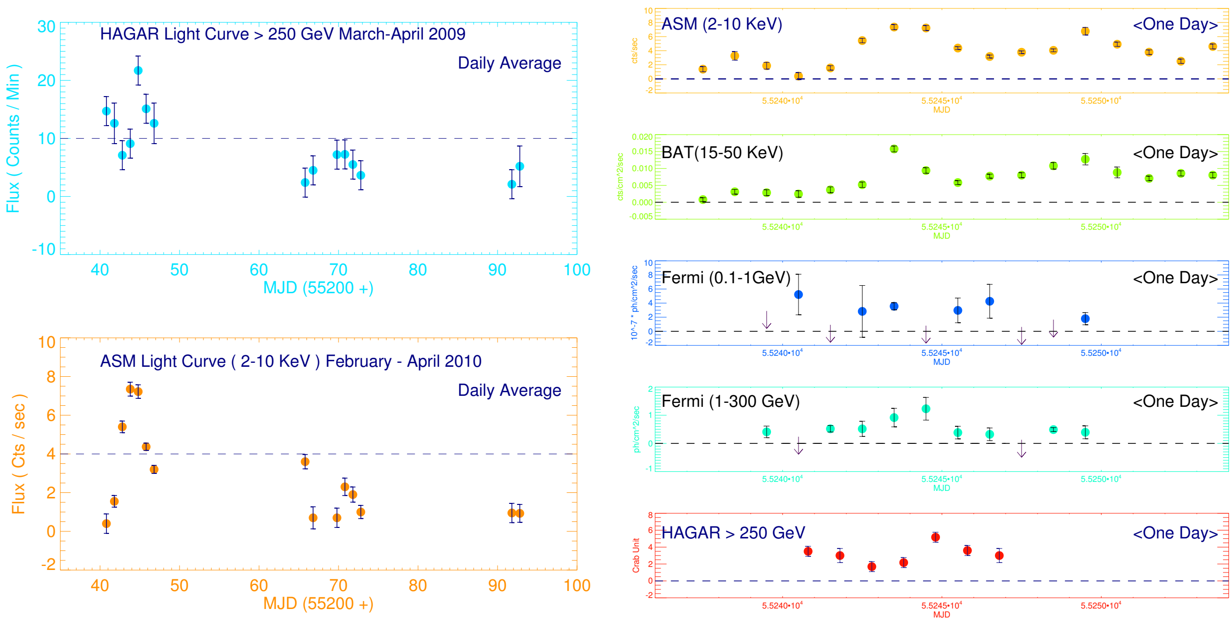

Fig. 4. *Left:* Daily average light curve of Mrk421 during Feb.-Apr. 2010. *Right:* Daily average light curve of Mrk421 during Feb. 2010.

An excess at $7.8\,\sigma$ $(2.4\,\sigma/\sqrt{h})$ is reported, corresponding to 5.1 ± 0.7 *counts min*$^{-1}$, while computing the excess using C1. An excess of $9.5\,\sigma$ $(2.7\ \sigma/\sqrt{h})$, corresponding to $5.7 \pm 0.6\,\mathrm{counts\,min}^{-1}$, is obtained based on 12.6 hours of data and using the normalisation constant C2 (Fig. 2 and Tab. 1). However, these values seem overestimated while comparing with our simulations, which predict $1.3\,\mathrm{gamma}/\sqrt{h}$ and $2.6\,\mathrm{counts\,min}^{-1}$ for vertical showers for a 1 Crab flux (Saha et al. 2011).

4 Study of pulsars

Search for pulsed emission at the known period has been carried out for several pulsars (Singh et al. 2011). Phase histogram for Crab pulsar is shown folded over rotation period (33 ms) for two cycles in Fig. 3. The

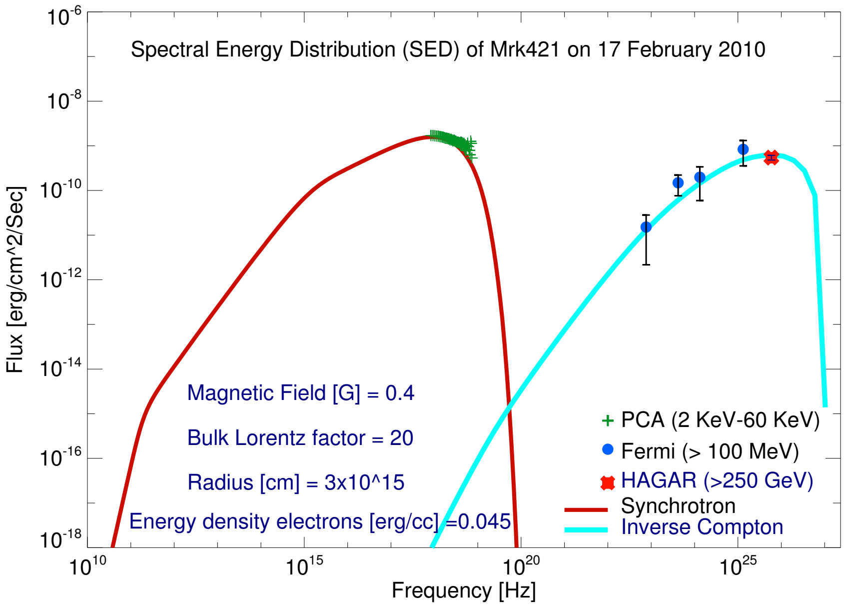

Fig. 5. Spectral Energy Distribution of Mrk421 of 17 February, 2010.

monthly timing ephemeris of the Crab pulsar were extracted from Jodrel Bank crabtime data base*. From HAGAR data, no evidence for pulsed emission was seen at energies above 200 GeV. Time averaged $3\,\sigma$ upper limits on pulsed component of gamma ray flux are estimated. For Crab pulsar, the estimated upper limit is $1.5 \times 10^{-11}\, ph\, cm^{-2}\, s^{-1}$. The upper limit for Gemimga pulsar is $3.6 \times 10^{-11}\, ph\, cm^{-2}\, s^{-1}$. Three Fermi detected pulsars, viz. J0357+32, J0633+0632 and J2055+2539 are being observed with HAGAR. These pulsars have high confidence pulsed emission, rotational energy loss rate and flat emission spectrum. Preliminary analysis indicate that there is no evidence of pulsed emission from any of these sources in our data at energies above 200 GeV.

5 Analysis of the data from Markarian 421 during its high activity state

HBL BL Lac AGN Markarian 421 (Mkn 421, z=0.031) has been observed during its high activity state, in Feb.-Apr. 2010 (Shukla et al. 2011). Data analysis was performed on data with a zenith angle less than 6 deg. The analysis method is similar to the one described in Paper I, but as the source is far from the Galactic plane, sky is darker and so selection cuts are less tight. We report an excess of 13.4 ± 1.05 *count min*$^{-1}$ at 12.7 σ based on 479 minutes of data during February 2010.

We show on Fig. 4 (left) daily light curve of Mkn 421 during the high state of the X-ray and gamma ray from February to April 2010. It's clearly seen that source was in brightest state in the month of February in both Gamma rays and X-rays. Activity of the source has reduced in the months of March and April but it was still brighter than its quiescent level flux. On Fig. 4 (right) is shown quasi-simultaneous light curves of Mrk 421, during Feb. 2010, as obtained in X-ray and gamma ray bands, using archived data from other observatories together with the present data. The light curves are plotted with one day binning (daily average) in the above figure. One zone homogeneous SSC model (Krawczynski et al. 2004) is fitted to the X-ray and gamma data to obtain the SED (Fig. 5). This model assumes a spherical blob of radius R and uniform magnetic field B, moving with respect to the observer with the Lorentz Factor delta which is filled with a homogeneous non-thermal electron population. Best fit SED is obtained for the parameters given in Fig. 5.

*http://www.jb.man.ac.uk/pulsar/crab.html

6 Major Atmospheric Cherenkov Experiment

The Major Atmospheric Cherenkov Expriment (MACE) is a 21 m-imaging Cherenkov telescope which is expected to be installed at Hanle by 2012, next to the HAGAR array (Koul et al. 2005, 2011). It will have the following characteristics: a total reflective area of $\sim$330 m^2 from 356 mirror panels; f/1.2 m; FOV of $4° \times 4°$, a 1088 pixel camera. The energy threshold is expected to be below 30 GeV. The sensitivity of MACE is expected to be comparable to the MAGIC one. Simultaneous observations with HAGAR are expected, in such a way that the same event can be detected by both the experiments. Foundations for the first imaging telescope and building of the control room of MACE at Hanle are well advanced. Installation of MACE is now going on in Hyderabad (South India), but with a limited number of mirror and PMTs. This will allow a phase of calibration and observations of Crab Nebula for a few months before the instrument is shifted to Hanle. We also expect at least a second similar imaging element to be installed next to the first element by 2014 or 2015, to perform stereoscopic observations (MACE II project).

7 Conclusions

The analysis of data from regions containing a bright blue star shows us that we can perform the analysis of gamma-ray point sources while balancing cosmic ray triggers and acquisition threshold differences. The preliminary results obtained from Crab Nebula give encouraging perspective for the study of gamma-ray point sources with the HAGAR telescope array. We report detection of Mkn 421 during its high activity state, and give upper limit on several pulsars. Furthermore, improvement of the method and development of new analysis softwares are still under going. The differences between Monte Carlo simulations and data regarding the strength of the signal (rate of gamma rays per minute) need to be probed further.

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