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Observation of pulsars with HAGAR Cherenkov Telescope

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Abstract: We have been operating a 7 element atmospheric Cherenkov telescope array called HAGAR at very high altitudes (about 4300 m above mean sea level) in the Ladakh region of Himalayan Mountain. The HAGAR is an array of non-imaging wavefront sampling telescopes, with 7 glass (90cm dia) parabolic mirrors mounted on each telescope and each mirror is viewed by a fast UV sensitive PMT at its focus. The relative timing of arrival and the total charge of the signals are recorded. The regular observations were carried out since October 2008 using this set up. We have observed Crab, Geminga and few other Gamma-ray pulsars reported by Fermi-LAT collaboration and corresponding background regions. The results of the analysis for Crab pulsar will be discussed.

Keywords: Crab pulsar, Cherenkov Telescope, VHE gamma rays

1 Introduction

The Crab Pulsar, PSR J0534+2200 is located at the center of supernova remanant (SNR) that occurred in 1054 A.D. It is one of the most energetic known pulsar (spin down power $\dot{E} = 4.6 \times 10^{38} erg\ s^{-1}$), located at a distance of (2.0 ± 0.2) kpc has characteristic age of 1240 years, which is close to observational value. First high energy gamma ray emission from Crab pulsar was observed by SAS-2 (1972-1973) satellite borne detector [?] and subsequently followed by COS-B (1975-1982) mission [?], EGRET telescope (1991-2001) on board CGRO [?] and Fermi-LAT (2008) telescope [?]. In the ground based detection, MAGIC imaging telescopes detected pulsed signal at energies greater than 60 GeV [?] and VERITAS imaging telescopes at energies greater than 100 GeV [?], upto 400 GeV.

A test for the standard pulsar models, such as the polar cap (PC), outer gap (OG), and slot gap (SG) models depend upon the precise measurement of the energy spectrum and spectral cut off of pulsed emission. In the PC model, emission takes place within a few neutron star (NS) radii above a PC surface [?, ?]. If PC model is responsible for the high energy emission then high-energy γ-rays above few GeV should be absorbed by the strong magnetic field [?] of the pulsar, which results in a very sharp cutoff in the energy spectrum. VERITAS telescope measured energy spectrum of pulsed gamma ray emission between 200 GeV and 400 GeV. Pulsed emission at this energy is only possible if the emission region is at least 10 stellar radii from the stars surface [?].

The detection of gamma-ray emission above 100 GeV provides strong constraints on the gamma-ray radiation mechanisms. The emission region near PC and curvature radiation contradicts the detected pulsed emission above 100 GeV. The other favoured emission mechanism is Inverse Compton scattering which motivate search of pulsed emission in GeV-TeV energy.

2 HAGAR

The High Altitude GAmma Ray Observatory consists of an array of seven atmospheric Cherenkov telescopes located at the centre and corners of a hexagon inscribed in a circle of 50 meter radius as shown in Fig. ??. Each telescope consists of seven parabolic glass mirrors of 10 mm thickness and 0.9 m diameter having f/d=1. These mirrors are front coated and average reflectivity in the visible range is 75 %. Each mirror has a UV-blue sensitive XP2268B Photo-multiplier tube (PMT), mounted at its focal point behind 3.0 deg angular mask. The total reflector area is about 31 m^2. These telescopes which are based on Alt-Azimuth mounting are controlled remotely through Linux based system using 17-bit rotatory encoders, stepper motors, Microcontroller-based Motion control interface units (MCIU) etc. The control system allows to achieve a steady state pointing accuracy of 10 arcsec with maximum slew rate of 30 deg per minute for each axis and continuous monitoring of the telescope positions. Guide telescopes are used to arrive at a pointing model for each telescope. The co-planarity of all 7 mirrors of a given telescope with its axis is achieved by a series of bright star scans. The over-all accuracy in pointing of the mirrors is about 12 arc minutes [?]. The High Voltages to PMTs are controlled and monitored through CAEN universal multi-channel power supply system. The analog PMT signals are transmitted to the central control room located at the centre of the array (below Tel #7) through coaxial cables. A CAMAC based data acquisition system has been used for signal processing. An eight channel Flash ADC (Acqiris make) system has also been used to digitize 7-telescope data. Using Monte Carlo simulation studies, threshold energy (peak energy) of gamma rays incident vertically is calculated to be about 210 GeV [?]. The sensitivity of the telescope system from source like Crab nebula is $\frac{1.2\sigma}{\sqrt{(T)}}$ where T is observation time in hours and σ is statistical signicance.

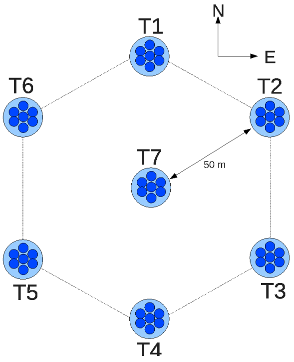

Fig. 1: Schematic diagram of HAGAR telescope array

3 Observations

HAGAR is an array of seven (non-imaging) atmospheric Cherenkov telescopes. The relative time of arrival and photon density (total charge) of incident Cherenkov shower front are recorded. Observations are taken in ON-OFF mode (source followed by its background or vice-versa). All telescopes are aligned at the same celestial position and track the object over the same zenith angle range corresponding ON-OFF pair. A typical duration of a source or background run is 40 minutes. Short duration runs minimize the effect of change in the sky condition during observation. We have observed several pulsars including Crab, Geminga and some of the pulsars detected by Fermi, namely PSR J0357+3206, PSR J0633+0632, PSR J1846+0919 and PSR J2055+2539. In the case of Crab pulsar observations, the run duration varies from 40 minutes to 90 minutes and cover hour angle range from -30 to +30 degree. Crab source observations are taken between October to February months every year. Observation log after preliminary checks on data quality are given in Table-1.

Year	Crab ON (hrs)	Crab OFF (hrs)
2008	38.0	28.3
2009	18.6	22.0
2010	18.0	12.8
2011	31.4	24.0
2012	32.7	20.8
Total	**138.7**	**107.9**

Table 1: Observation Log of Crab source

4 Data Analysis

The entire data collected by HAGAR for Crab source has been used to search for pulsed emission. After preliminary data checks for good sky condition, stable event rates *etc*, total duration of pulsar data available is 139 hours (ON) and 108 hours (OFF) respectively. In the analysis, the recorded arrival times of atmospheric Cherenkov wavefront and events are processed with in-house developed standard analysis codes. Event rate of each run data is checked for the presence of any spurious events. Average event rate is 10 Hz from the direction of Crab pulsar and shown in Fig. **??**. The arrival direction of primary is calculated by fitting Cherenkov shower-front with the plane surface. The space angle (ψ), as defined as the angle between telescope pointing and reconstructed shower direction, is obtained for each event. A selection cut is exercised on space angle to reject off-axis events. Fig. **??** shows the typical space angle distribution obtained for 40 minutes observations of Crab pulsar. The four distributions correspond to the number of triggered telescopes in an event which varies from 4 to 7 telescopes.

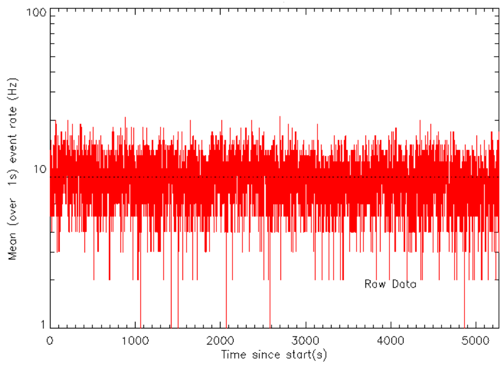

Fig. 2: Event rate from the direction of Crab source

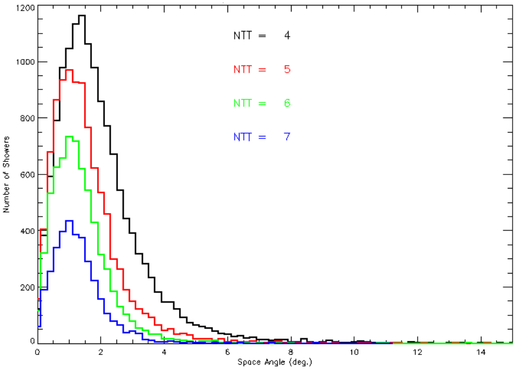

Fig. 3: Space angle distribution. The four distributions correspond to the number of triggered telescopes (NTT) in an event which varies from 4 to 7 telescopes.

4.1 Search of Periodic Signal

The arrival times of the Cherenkov events which trigger the telescope were recorded using oven controlled crystal oscillator clock synchronized with a Global Positioning System (GPS) clock which provide a precision of 1 μs. For the timing analysis, all the arrival times (t_{obs}) are transformed to the the solar system barycenter (SSB, t_{ssb}) using the JPL DE200 planetary ephemeris and the standard TEMPO[1] codes [**?**]. The corrected barycentric times t_{ssb}) were folded at the rotation period (33 ms) of Crab pulsar relative to reference epoch T_0 to get the absolute phase ϕ. The absolute phase is calculated using the TEMPO code for every half an hour. A Taylor expansion is used to calculate the phase of events through interpolation for events with arrival times in between, as given below :

$$\phi(T) = \phi(T_0) + f_0(T - T_{0)} + \frac{1}{2}\dot{f}(T - T_0)^2 + \frac{1}{6}\ddot{f}(T - T_0)^3 + ..$$

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[1] developed by the Princeton group

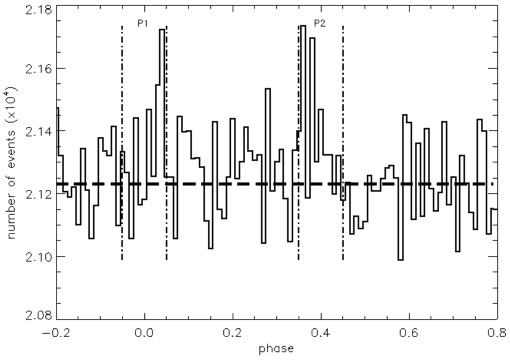

Fig. 4: Phasogram of Crab pulsar folded at radio frequency

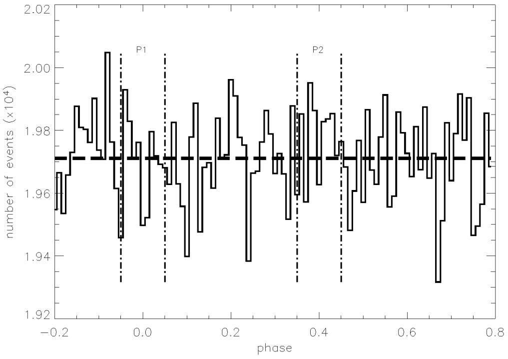

Fig. 5: Phasogram of Off-source folded at Crab radio frequency

The monthly radio timing ephemeris of the Crab pulsar were extracted from Jodrel Bank crabtime data base [**?**]. The phasogram obtained by folding the events recorded from the direction of the Crab pulsar and background (off-source) regions are shown in Fig. **??** and Fig. **??** respectively. Search for the pulsed emission is first carried out on short duration data sets (40 minutes) and then added episodically. The light curve (phasogram) of events shown in Figs. **??**,**??** is for space angle ($\psi \leq 1.5$) degree.

5 Results and Conclusion

Pulsed signal in VHE band were calculated at phases corresponding to the EGRET and Fermi-Lat detections. According to EGRET detection phasogram is divided into 4-regions P1(0.95-0.05), P2(0.35-0.45), bridge(0.05-0.035) and background(0.45-0.95) [**?**]. Phase interval P1 and P2 constitute the pulsed signal counts (N$_{on}$). Events in the background region constitute non-pulsed signal counts (N$_{off}$) and cosmic ray background. The background events are normalized by multiplying it by a factor R corresponding to the ratio of the phase ranges spanned by the pulse and non-pulse region. The expression for statistical significance (σ) of the excess signal [**?**] is defined as

$$\sigma = \frac{N_{on} - R * N_{off}}{\sqrt{N_{on} + R^2 * N_{off}}}$$

Runs taken at low zenith angles are used in this analysis. This selection keeps energy threshold of detection low. Events were further grouped based on number of triggered telescopes. This selection of events gives signal at other trigger energy threshold. The preliminary analysis of HAGAR data shows 3.6σ pulsed signal at @ 0.33±0.09 γ per minute. The energy threshold corresponding to the average zenith angle (15 deg.) of observations is 234 GeV [**?**] for an energy spectrum of Crab nebula. The effective area for $\gamma-$rays is 3.4×10^4 m^2. Since VERITAS results indicate a steeper energy spectrum for the pulsed emission, collection area and energy threshold have to be revised.

Telescope	$\gamma - ray$ rate/minute	σ
NTT$\geq$ 4	0.3333±0.0928	3.59
NTT$\geq$ 5	0.1494±0.0769	1.94
NTT$\geq$ 6	0.0815±0.0698	1.34
NTT = 7	0.0182±0.0427	0.43

Table 2: Pulsed signal derived at different energy threshold

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