

Monitoring of Blazars from 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 been observing Mrk 421, Mrk 501 and few other blazars and the corresponding background regions regularly in the ON-OFF mode. Recently, we have attempted to study the evolution of the spectral energy distribution (SED) observed from Mrk 421 during the intense flare in February 2010. Here we present our data and results on Mrk 501 blazar and other AGN objects.

Keywords: Atmospheric Cherenkov technique, VHE gamma ray astronomy, AGN, Blazars

1 Introduction

High Altitude GAMMA RAY (HAGAR) telescope array, an array of seven small telescopes, is operational in Himalayas for more than four years. This telescope array is located in Ladakh, which is cold desert of Himalayas, at an altitude of 4300 m. With this array based on wavefront sampling technique, main emphasis has been on observations of Blazars and gamma ray pulsars. Blazars are a particular class of AGNs with their jets directed towards us and these are prime targets for atmospheric Cherenkov telescopes located in Northern hemisphere. Multi-waveband spectral energy distributions of Blazars show double peaked structure. Majority of Blazars detected at TeV energies are high-energy peaked Blazars with their SEDs showing lower energy peaks at UV-X-ray energies and higher energy peaks in gamma ray band. Lower energy peak is generally attributed to synchrotron emission from electrons in the jet. Whereas origin of higher energy peak is not well-established. There are models attributing second peak to Comptonisation of lower energy photons by same population of electrons (Synchrotron Self-Compton i.e. SSC) model, Comptonisation of photons originating outside the jet (External Compton i.e. EC), Synchrotron emission from hadrons, hadronic cascades etc. We have extensively observed the Blazars, Mrk 421, Mrk 501, 1ES2344+514 and also have some coverage for Blazars, 1ES1218+304, 1ES1959+650, BL Lac, 3C454.3, S5 0716+714 etc. In this paper, we report results from some of the observations of Mrk 421 and Mrk 501 followed by study of their multi-waveband SED.

2 HAGAR instrument details

HAGAR is an array of seven telescopes with six telescopes located at the corners of hexagon and one telescope in centre (Fig. 1). Spacing between telescopes is 50 m. Each

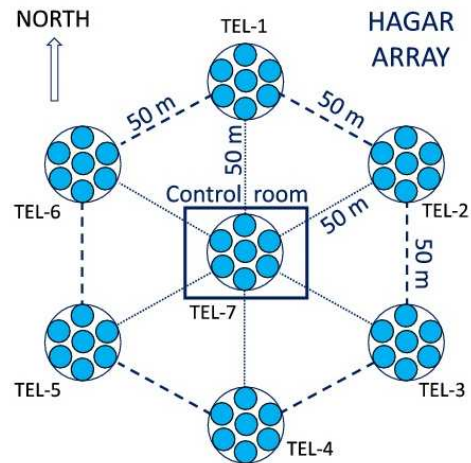


Fig. 1: HAGAR schematic diagram

telescope consists of seven para-axially mounted parabolic mirrors of diameter 0.9 m each and with $f/D \sim 1$. At the focus of each mirror UV sensitive phototube (X-P2268B, Photonis make) is mounted. Field of view is 3° FWHM. Pulses from all phototubes are brought to the control room located below central telescope through low attenuation coaxial cables. Each telescope has alt-azimuth mount. Details of tracking system are given by Gothe et al. [1]. High voltages given to phototubes are controlled using CAEN controller. In control room, analog addition of phototube pulses is performed to generate seven telescope pulses. Trigger is generated using these seven pulses and data recording initiated on coincidence of at least 4 telescope pulses out of 7 in narrow coincidence window of 60 ns. Data acquisition system is based on CAMAC and data recorded for each event includes arrival time of Cherenkov

shower front at each mirror/telescope accurate to 0.25 ns given by TDCs, total charge in each telescope given by 12 bit QDCs and absolute arrival time of event accurate to μs given by Real Time Clock (RTC) module synchronised to GPS. Further details are given by Chitnis et al. [2].

Energy threshold of HAGAR, as given by the peak of the differential rate curve, is estimated to be about 210 GeV, for vertically incident showers. Collection area of HAGAR is $3.2 \times 10^4 \text{ m}^2$. Raw sensitivity of HAGAR, without any gamma-hadron segregation cuts, is estimated to be $1.2\sigma/\sqrt{\text{hour}}$, for Crab like sources near zenith. Further details about HAGAR performance parameters are given by Saha et al. [3].

Installation of HAGAR at Hanle in Ladakh was completed and observations of astronomical sources commenced in September, 2008. During last four and half years, about 2500 hours of data has been recorded.

3 Analysis of HAGAR data on Mrk 501

Observations with HAGAR are carried out typically in ON-OFF pairs. Source region is tracked for about 40 minutes followed by tracking of background region for another 40 minutes. Background region is chosen such that similar angular region of the sky is scanned during ON and OFF pair. For each recorded event, arrival direction of shower axis is determined fitting a plane front to arrival time of Cherenkov shower front at various telescopes. Normal to the fitted front gives direction of shower axis. For each event, space angle i.e. angle between shower axis direction and pointing direction of the telescope is calculated and distributions of space angles are generated for ON and OFF runs. These distributions are then compared and excess of events is attributed to the gamma ray signal. Details of this analysis procedure are given by Shukla et al. [4].

We have been observing Mrk 501, which is the second Blazar to be detected in VHE gamma ray band, since 2009. We have collected 89 hours of data on this Blazar during 2009-2012. Here we report on multiwaveband study of Mrk 501 during 2011. HAGAR observations of this source were performed in three observation seasons during March-June 2011 and about 14 hours of good quality data were analysed following the procedure given above. In present analysis we have only considered the events with at least 5 telescopes participating in trigger. Corresponding energy threshold is 250 GeV. Space angle distribution from one typical ON-OFF pair for the events with all 7 telescopes participating in trigger is shown in Fig. 2 and results are given in Table 1. Mean γ -ray rates given in the Table correspond to events with at least 5 telescopes triggering. Amongst the three observation seasons, highest flux at the level of about 1.5 Crab units was seen in April-May 2011.

Observation season	Total duration (minutes)	Mean γ ray rate (minute^{-1})	Significance σ
March-April 2011	280	3.53 ± 1.43	2.47
April-May 2011	349	6.62 ± 1.30	5.07
May-June 2011	213	4.55 ± 1.73	2.6

Table 1: HAGAR observations of Mrk 501 in year 2011

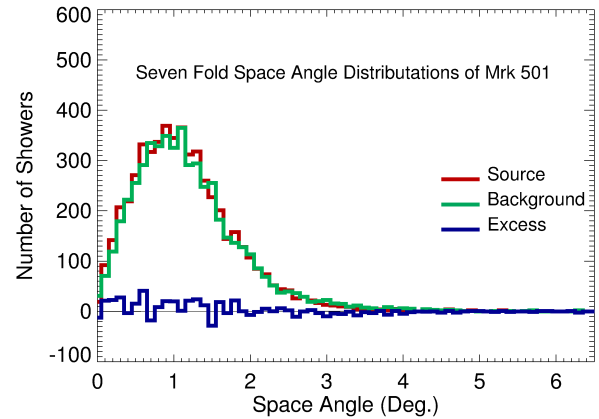


Fig. 2: Space angle distribution for ON-OFF pair 1865-1864 for events with all seven telescopes triggering

4 Multi-waveband SED of Mrk 501

In order to get multi-waveband spectral energy distribution (SED) of Mrk 501, we analysed or used already analysed data from various missions including lower energy gamma ray data from LAT onboard Fermi satellite, hard X-ray data from BAT onboard Swift, soft X-ray data from XRT onboard Swift and PCA and ASM onboard RXTE, UV data from UVOT onboard Swift, optical V band data from SPOL and radio data at 15 GHz from OVRO. Multi-waveband light curve spanning the period from about end of March 2011 to middle of June 2011 is shown in Fig. 3.

Multi-waveband SED is generated for each of the three observation seasons of HAGAR in 2011. SED for May 2011 is showed in Fig. 4. SEDs are fitted with one zone Synchrotron Self-Compton (SSC) model developed by Krawczynski et al. [5]. This model assumes a spherical blob of plasma of comoving radius R , traveling with a bulk Lorentz factor Γ towards the observer. The emission volume is filled with an isotropic population of electrons and a randomly oriented uniform magnetic field B . The energy spectrum of the injected electrons in the jet frame is described by a broken power-law with low energy (E_{min} to E_b) and high energy (E_b to E_{max}) with indices p_1 and p_2 . The emitted radiation is Doppler-boosted by the Doppler factor

$$\delta = [\Gamma(1 - \beta \cos(\theta))]^{-1} \quad (1)$$

where β is the bulk velocity of the plasma in units of the speed of light and θ is the angle between jet axis and the line of sight in the observer frame. The VHE γ -ray spectrum is corrected for absorption by the extragalactic background light [6]. The radius of the emission zone is constrained by the variability time scale. Since X-ray and γ -ray flux of Mrk 501 has shown variability on time scale of the order of one day, we have chosen $t_{var} \sim 2$ days. The comoving radius of the emission zone is defined as

$$R \sim c\delta t_{var}/(1+z) \quad (2)$$

We attempted to model SEDs of Mrk 501, covering radio to TeV bands and corresponding to three seasons of HAGAR observations in 2011, in the framework of standard one zone model. Satisfactory fits were obtained for

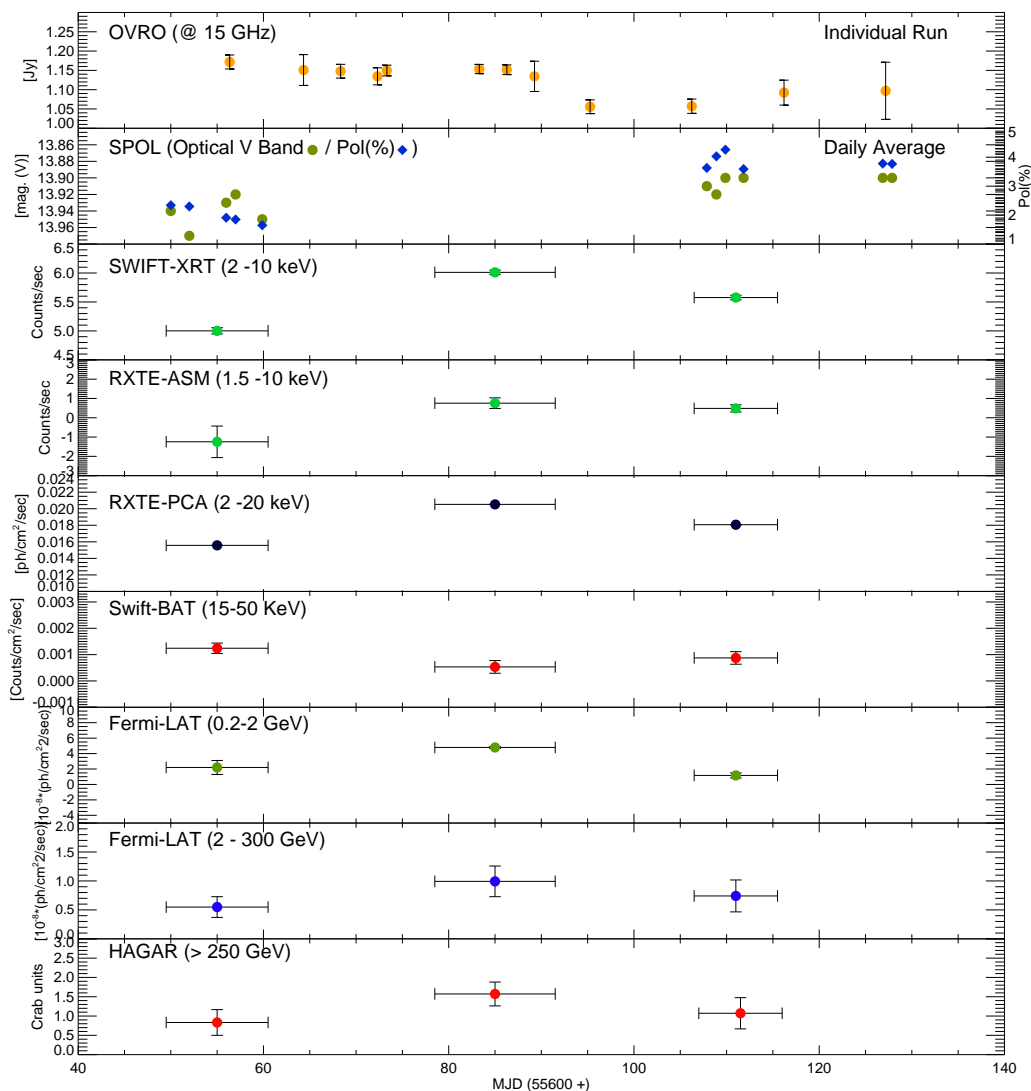


Fig. 3: Multi-wavelength light curve of Mrk 501 during March-June 2011

SEDs corresponding to March-April and May-June seasons. Fit was not satisfactory for April-May season and it was essential to use two zones. Physical parameters for these fits are given in Table 2 and SED for April-May 2011 is given in Fig. 4. Single zone seems to provide good fit for quiescent state whereas flare state as seen in April-May 2011 has additional component.

5 HAGAR observations of Mrk 421

We have been regularly observing Mrk 421, the first Blazar detected at TeV energies, with HAGAR since 2009. We have collected about 166 hours of data for this source during several observation seasons during 2009-2012. With HAGAR, we successfully detected flare from Mrk 421 during February 2010 [4]. Here we report on detection of recent flare in March-April 2013. Following the procedure outlined in section 2, we analysed data collected using HAGAR in March and April observation seasons. Results are given in Table 3. Source brightened from the level of one Crab unit to about 3 Crab units from March to April obser-

vation season. Multiwavelength light curve covering soft X-ray data from MAXI, hard X-ray data from BAT onboard Swift, lower energy γ -ray data from LAT onboard Fermi and VHE γ -ray data for energies above 250 GeV from HAGAR, is shown in Fig. 5. Work on multi-wavelength SED is underway.

Observation season	Total duration (minutes)	Mean γ ray rate (minute^{-1})	Significance σ
March 2013	198	2.26 ± 1.88	1.20
April 2013	300	10.34 ± 1.46	7.09

Table 3: HAGAR observations of Mrk 421 in year 2013

6 Conclusions

HAGAR telescope array is operational for more than four years and several objects including Blazars, Fermi detected

Epoch	Magnetic field (G)	Doppler factor (δ)	$\log E_{min}$ [eV]	$\log E_{max}$ [eV]	$\log E_{break}$ [eV]	p1	p2	U_e [10^{-3}] (erg/cc)	η [u'_e/u'_B]
March-April 2011	0.022	11.2	9.5	12.15	10.6	2.0	3.0	1.35	70.10
April-May 2011 (I) (Red)	0.058	10.9	9.5	12.00	11.1	3.3	3.8	27	202
(II)(Blue)	0.014	11.36	10.2	12.20	10.7	2.3	2.8	1.6	205
May-June 2011	0.020	11.2	10.1	12.25	10.80	2.2	3.1	1.2	75.39

Table 2: SED parameters for Mrk 501

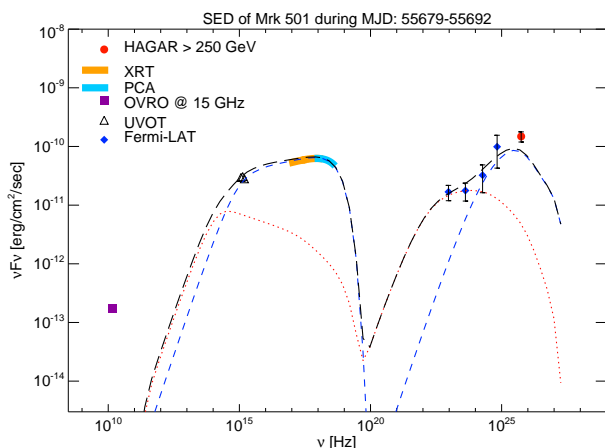


Fig. 4: Multi-waveband SED of Mrk 501 in April-May 2011 fitted with two zone SSC model

γ -ray pulsars, supernova remnants have been monitored regularly. Earlier we had detected flare from Mrk 421 successfully in February, 2010. Here we have reported preliminary results from observation of flare from same source in March-April 2013. We have also conducted long duration observations of Mrk 501 and results on data recorded in year 2011 have been reported here. We have fitted multi-waveband SED of this source and fitted it with one zone SSC model. This fit was not adequate to describe SED from April-May 2011 season. This data is modeled with two-zone model. We have also observed some more Blazars including 1ES2344+514, 1ES1218+304, BL Lac, 3C454.3, 1ES1426+428, 1ES1959+650, 3C454.3 et. Analysis of this data is underway.

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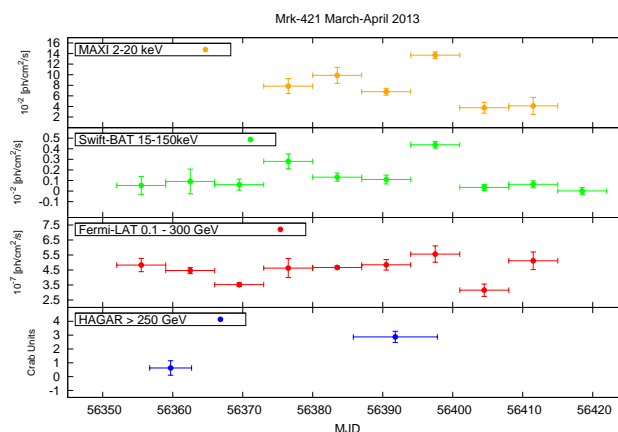


Fig. 5: X-ray and γ -ray light curve of Mrk 421 during 2013

References

- [1] K. S. Gothe et al., *Experimental Astronomy*, vol. 35, p. 489, 2013
- [2] V. R. Chitnis et al., *32nd ICRC*, vol. 9, p. 165, 2011
- [3] L. Saha et al., *Astroparticle Physics*, vol. 42, p. 33, 2013
- [4] A. Shukla et al., *A&A*, vol. 541, id.A140, 2012
- [5] H. Krawczynski et al., *ApJ*, vol. 601, p. 151, 2004
- [6] A. Franceschini et al., *A&A*, vol. 487, p. 837, 2008