A Multiwavelength study of TeV blazars

A Thesis

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by
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To my dearest cousin, Pounomi
(1993 - 2015)
- One of the most creative and interesting persons
  I have ever met.
DECLARATION

This thesis is a presentation of my original research work. Wherever contributions of others are involved, every effort is made to indicate this clearly, with due reference to the literature, and acknowledgement of collaborative research and discussions.

The work was done under the guidance of Dr. Varsha R Chitnis, at the Tata Institute of Fundamental Research, Mumbai.

Atreyee Sinha

In my capacity as supervisor of the candidate’s thesis, I certify that the above statements are true to the best of my knowledge.

Dr. Varsha R Chitnis

Date:
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“No man is an island entire of itself; every man is a piece of the continent, a part of the main.

John Donne
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0.1 INTRODUCTION

An active galactic nucleus (AGN) is a compact region (∼ light days) at the centre of a galaxy that outshines the total emission from the remaining of the host galaxy. Such excess emission has been observed across the entire electromagnetic spectrum, from radio to γ-rays, and is believed to be powered by accretion onto super-massive black holes (Salpeter 1964, Lynden-Bell 1969). Depending upon the ratio of the radio (5 GHz) to optical (B band) flux, AGNs are further classified as radio-loud and radio quiet. Around 10-15% of the AGNs are radio-loud (Urry & Padovani 1995), and observationally exhibit prominent bipolar radio jets reaching up to Mpc scales.

Blazars count among the most violent sources of high energy emission in the known universe. They are characterized by highly variable nonthermal emission across the entire electromagnetic spectrum, strong radio and optical polarization, and apparent superluminal motion. According to the classification scheme of Urry & Padovani (1995), the likely explanation of such observations is that they are a subclass of radio-loud AGNs where the relativistic jet is oriented close to the line of sight. Based on the rest frame equivalent width of their emission lines in optical/UV spectra, blazars have been further classified in two subgroups: BL Lacertae objects (BL Lacs) with very weak/no emission lines and Flat Spectrum Radio Quasars (FSRQ) with strong broad-line emission.

The broadband spectral energy distribution (SED) of blazars is characterized by two peaks, one in the IR - X-ray regime, and the second one in the γ-ray regime. According to the location of the first peak, BL Lacs are further classified into low-energy peaked BL Lacs (LBL), intermediate peaked BL Lacs (IBL) and high-energy peaked BL Lacs (HBL) (Padovani & Giommi, 1995). Both leptonic and hadronic models have been used to explain the broadband SED with varying degrees of success. The origin of the low-energy component is well established to be caused by synchrotron emission from relativistic electrons gyrating in the magnetic field of the jet. However, the physical mechanisms responsible for the high-energy emission are still under debate. It can be produced either through inverse Compton (IC) scattering of low-frequency photons by the same electrons responsible for the synchrotron emission (leptonic models), or through hadronic processes initiated by relativistic protons, neutral and charged pion decays, or muon cascades (hadronic models). The seed photons for IC in leptonic models can be either the synchrotron photons themselves (synchrotron self-Compton, SSC) or from external
sources such as the broad line region (BLR), the accretion disc, and the cosmic microwave background (external Compton, EC). A comprehensive review of these mechanisms may be found in Böttcher (2007).

The advent of the Atmospheric Cherenkov Telescopes (ACT) opened a new window into blazar research. The first significant detection of extragalactic TeV photons was from the blazar Mkn 421 by the Whipple collaboration in 1992 (Punch et al., 1992). Since then, over 55 blazars (Wakely & Horan, 2016) have been detected in the very high energy (VHE) regime, and form the dominant source of high energy radiation in the extragalactic sky.

When a VHE gamma-ray enters into the Earth’s atmosphere, it interacts with atmospheric nuclei and produces an electron-positron pair, which in turn dissipates its energy producing secondary gamma rays through bremsstrahlung processes. The secondary gamma rays further produce electron-positron pairs. This process of pair production and bremsstrahlung continues, resulting in a shower of electrons, positrons and secondary gamma rays, which is called an Extensive Air Shower (EAS). When the charged particles move down in the atmosphere with velocities greater than the velocity of the light in that medium, they produce Cherenkov light, which falls in Ultra Violet and blue (UV-blue) region of the electromagnetic spectrum. The Cherenkov light illuminates a large circular area with a diameter in the range of 200 m - 250 m on the ground for a vertically incident shower. This light can be captured with optical sensors, and by reconstructing the shower axis in space and tracing it back onto the sky, celestial origin of the gamma rays can be determined. The energy of the primary $\gamma$-ray can be estimated from the intensity of the Cherenkov light pool.

The High Altitude GAmma Ray (HAGAR) (Chitnis et al., 2011) array is a hexagonal array of seven ACTs which uses the wavefront sampling technique to detect celestial gamma rays. It is located at the Indian Astronomical Observatory site (32° 46' 46" N, 78° 58' 35" E), in Hanle, Ladakh in the Himalayan mountain ranges at an altitude of 4270m. The Cherenkov photon density of a shower increases with altitude, and thus, a lower energy threshold is achieved by operating the telescope at such high altitudes. Each of the seven telescopes has seven para-axially mounted front coated parabolic glass mirrors of diameter 0.9 m, with a UV-sensitive photo-multiplier tube (PMT) at the focus of individual mirrors. The Cherenkov photons arriving at each telescope are detected by these PMTs. The relative arrival time of the Cherenkov shower front at each telescope is recorded for each event using a 12 bit Phillips Time to Digital Converter (TDC), which is then used to reconstruct the initial shower direction by the triangulation method. The energy threshold for the HAGAR array for vertically incident $\gamma$-ray showers is 208 GeV, with a sensitivity of detecting a Crab nebula like source in 17hr for a 5 $\sigma$ significance. Detailed descriptions of HAGAR instrumentation and simulations can be found in Shukla et al. (2012) and Saha et al. (2013).

Studies at TeV energies are complicated due to the fact that VHE photons emitted from blazars are absorbed en-route by forming electron-positron pairs on interaction
with the photons of the extra-galactic background light (EBL), thereby causing the observed spectrum to differ significantly from the intrinsic one. The EBL is an isotropic diffuse radiation field extending from Ultraviolet (UV) to Infrared (IR) wavelength ($\lambda = 0.1 - 1000\mu m$). It is the relic radiation containing information about the structure formation epoch of the universe and hence, is an important cosmological quantity (Dwek & Krennrich, 2013; De Angelis et al., 2013). Direct measurement of EBL is very difficult due to strong foreground contamination by the Galactic and zodiacal light, and depends on the choice of the zodiacal light models (Kelsall et al., 1998; Wright, 1998). However, different upper and lower limits on EBL, based on various observations and deep galaxy number counts, have been put forth (Hauser et al., 1998; Madau & Pozzetti, 2000; Domínguez et al., 2011; Helgason & Kashlinsky, 2012). Theoretical prediction of the EBL SED can be obtained by evolving stellar populations and galaxies under various cosmological initial conditions (Primack et al., 2005; Franceschini et al., 2008; Gilmore et al., 2009; Finke et al., 2010; Kneiske & Dole, 2010). However, such models involve a large number of parameters and the estimated EBL spectrum depends upon the underlying assumptions (Hauser & Dwek, 2001; de Angelis et al., 2009; Dwek & Krennrich, 2013).

0.2 Motivation and Aims

Blazars are the ideal objects for studying the physics of the ubiquitous but poorly understood astrophysical jets. The jet formation, collimation and acceleration are still only vaguely understood. The observed rapid variability suggests that the emission region is compact and located close to the nucleus (Dondi & Ghisellini, 1995), which lies below the resolution limit of modern facilities. Thus, even the sites of production of radiation at different energies are also not well known.

In such a scenario, multi-wavelength temporal and spectral studies offer powerful diagnostics to study the underlying blazar environment. Moreover, indirect estimation of the EBL intensity can be obtained by studying its imprint on the VHE spectrum of blazars. Various constraints have been imposed on the EBL intensity under different assumptions of the intrinsic blazar spectrum (Madau & Phinney, 1996; Coppi & Aharonian, 1999; Stanev & Franceschini, 1998; Aharonian et al., 2006b; Mazin & Raue, 2007; Guy et al., 2000; Orr et al., 2011). However, these estimates depend heavily on the assumption of the intrinsic VHE spectrum, which itself is not well known.

In this work, we have tried to obtain a model independent estimate of the EBL from a statistical study of TeV blazars. We have also tried to understand the intrinsic particle spectrum in the jets through a thorough temporal and spatial study of HAGAR observed blazars in the ambit of leptonic models.
The HAGAR Telescope has been regularly observing bright blazars since its inception in 2008. Data obtained over the past few years were analysed and integral flux (or 3-$\sigma$ flux upper limits) computed. Monthly averaged calibration runs were used to calculate the fixed time offsets of the telescopes, which were then used for reconstruction of arrival direction of the shower front. The source counts were computed according to the procedure outlined in Shukla et al. (2012), with appropriate data selection cuts imposed. Only events with signals in at least 5 telescopes were retained to minimize the systematic errors, for which the energy threshold was estimated to be $\sim 250\text{GeV}$.

In addition, data from the Fermi-LAT, NuSTAR, Swift X-ray and UV telescopes were analyzed according to the standard procedures suggested by the respective instrument teams. X-ray observations by the Monitor of All-sky X-ray Image (MAXI) telescope, optical observations by SPOL CCD Imaging/Spectropolarimeter at Steward Observatory, Arizona and radio data from the Owens Valley Radio Observatory (OVRO), California were also used to construct the SEDs and light-curves.

We quantified the variability at different wavelengths using the fractional variability amplitude parameter $F_{\text{var}}$, defined in Vaughan et al. (2003; Chitnis et al., 2009). To study the time lags between the various unevenly sampled energy bands, we used the z-transformed discrete cross correlation function, freely available as a FORTRAN 90 routine, with the details of the method described in Alexander (1997).

Signatures of lognormality were investigated for by fitting the histograms of the observed fluxes at different wavelengths with a Gaussian and a Lognormal function. To test the rms-flux relationship, following Giebels & Degrange (2009); Chevalier et al. (2015), the scatter plot of the excess variance vs the mean flux was fit by a constant and a linear function.

The SEDs were modelled with a one zone leptonic model, incorporating synchrotron and SSC processes. In this model, the broadband emission is assumed to originate from a single spherical zone of radius $R$ filled with a tangled magnetic field $B$. A non-thermal population of electrons is assumed to lose its energy through synchrotron and self Compton (SSC) processes. As a result of the relativistic motion of the jet, the radiation is boosted along our line of sight by a Doppler factor $\delta$. The numerical codes developed in Sahayanathan & Godambe (2012) and Saha & Bhattacharjee (2015) were incorporated in the XSPEC spectral fitting software to perform a $\chi^2$ minimization (Sahayanathan et al., 2016).

The EBL density was estimated by looking at its imprint on the VHE spectrum of HBLs. We computed the Spearman’s rank correlation between the spectral index at different wavelengths vs the redshift. It was found that very high energy (VHE) gamma ray spectral index of high energy peaked blazars correlates strongly with its corresponding redshift whereas no such correlation is observed in the X-ray or the GeV bands. Attributing this
correlation to a result of photon-photon absorption of TeV photons with the extragalactic background light (EBL), the allowed flux range for the EBL was constrained.

0.4 RESULTS

We concentrated on studying the most abundant blazar subclass in the TeV sky, the HBLs. The HBLs constitute more than 80% of TeV detected blazars, and usually do not require an EC mechanism to explain the observed $\gamma$-ray spectrum.

0.4.1 Longterm study of Mkn 421

In [Sinha et al. (2016b)], we studied the long term temporal and spectral variability in the radiation from the nearby HBL Mkn 421 during 2009-2015. One of the closest ($z = 0.031$) and the best-studied TeV blazars, Mkn 421 is also one of the brightest BL Lac objects seen in the UV and X-ray bands. In this paper we presented the results of the long term monitoring of this source by the HAGAR telescope array for the past 7 years, since 2009. We used data at the radio, optical, X-ray and gamma ray energies to characterize lognormality in the intrinsic flux variations across the multi-wavelength spectrum. Correlation studies between different wavelengths were also performed. Spectral energy distribution during different flux states of the source were constructed simultaneous with HAGAR observations, and fit with leptonic SSC models. The main aim of this paper was not to investigate the fast temporal and spectral variabilities, but to study the smooth variations over weekly and monthly timescales, which may throw light on the underlying jet environment.

The multi-wavelength lightcurve of Mkn 421 from all available instruments during 2009-2015 was studied in details. The flux was found to be highly variable across all time scales. The variability was energy dependent, and maximum in the X-ray and VHE bands. A strong correlation was found between the Fermi-LAT (gamma) and radio bands, and between Fermi-LAT and optical, but none between Fermi-LAT and X-ray.

Lognormality in the flux distribution, and a strong flux-rms correlation was seen. Lognormality was clearly detected for the survey instruments, Fermi-LAT, Swift-BAT and MAXI, but the correlations decreased for the other instruments. This is likely due to the fact that the observations from the pointing instruments were biased towards the flaring states. This is the third blazar, following BL Lac and PKS 2155+304 to show this behaviour.

Twenty one SEDs were extracted over the past 7 years, during epochs contemporaneous with HAGAR observation periods. During these epochs, the total bolometric luminosity varied almost by a factor of 10. All the states could be successfully fitted by our SSC model, and variations in the flux states attributed mainly to changes in the particle distribution. A strong correlation was seen between the break energy $\gamma_b$ of the particle
spectrum and the total bolometric luminosity. During all the epochs, the energy density in the jet was matter dominated, with the model parameters a factor of 10 away from equipartition.

0.4.2 Study of Mkn 421 during giant X-ray flare

The largest X-ray flare of Mkn 421 over the past decade was seen during April 2013 (MJD 56392 – 56403). In Sinha et al. (2015), we undertook a multi-wavelength study of this flare, with emphasis on the X-ray data to understand the underlying particle energy distribution. The flux varied rapidly in the X-ray band, with a minimum doubling timescale of $1.69 \pm 0.13$ hr. There were no corresponding flares in UV and gamma-ray bands. The variability in UV and gamma rays was relatively modest with $\sim 8\%$ and $\sim 16\%$, respectively, and no significant correlation was found with the X-ray light curve.

We modeled the underlying particle energy spectrum with a single population of electrons emitting synchrotron radiation, and statistically fitted the simultaneous time-resolved data from *Swift*-XRT and *NuSTAR*. The observed X-ray spectrum showed a clear curvature that could be fit by a log parabolic spectral form. This was best explained as originating from a log parabolic electron spectrum. However, a broken power law or a power law with an exponentially falling electron distribution could not be ruled out either.

Moreover, the excellent broadband spectrum from $0.3 – 79$ keV allowed us to make predictions of the UV flux. We found that this prediction was compatible with the observed flux during the low state in X-rays. However, during the X-ray flares, depending on the adopted model, the predicted flux was a factor of $2 – 50$ lower than the observed one. A plausible interpretation of this inconsistency between X-ray and UV fluxes could be made by associating the UV emission from the putative accretion disk. However, such thermal emission from the disc has never been an important contribution in the UV bands for Mkn 421 Abdo et al. (2011a), and the UV spectral detail was not sufficient to support this interpretation. Alternatively, the underlying particle distribution might be more complex than those we studied. Nevertheless, such a particle distribution demands a concave spectrum, which is not possible with our present understanding of particle acceleration (Sahayanathan, 2008). Hence, we attributed this unusual X-ray - UV behaviour of the source to a two-population electron distribution.

0.4.3 Multi-epoch multi-wavelength study of 1ES 1011+496

1ES 1011+496 is a HBL located at a redshift of $z = 0.212$. It was discovered as a VHE emitter by the MAGIC collaboration in 2007, following an optical outburst in March 2007 (Albert et al., 2007b). At its epoch of discovery, it was the most distant TeV source. Albert et al. (Albert et al., 2007b) had constructed the SED with simultaneous optical
R-band data, and other historical data (Costamante & Ghisellini, 2002) and modelled it with a single zone radiating via SSC processes. However, the model parameters could not be constrained due to the sparse sampling and the non-simultaneity of the data.

In February 2014, 1ES 1011+496 was reported to be in its highest flux state till date as seen by Fermi-LAT (Corbet & Shrader, 2014), and Swift-XRT (Kapanadze, 2014). During this time, the VERITAS collaboration also detected a strong VHE flare from this source, at an integral flux level of ~ 20% to 75% of the Crab flux, which is almost a factor of 10 higher than its baseline flux (Cerruti, 2015b). This source was observed by the High Altitude GAmma Ray (HAGAR) Telescope array during the February-March 2014 season. In Sinha et al. (2016a), we studied the simultaneous SED of this source as seen by Swift, Fermi-LAT and HAGAR during this epoch. To understand the broadband spectral behaviour, we also constructed SEDs using quasi-simultaneous data of two previous epochs.

It was observed that the broadband SED could be successfully reproduced by synchrotron and synchrotron self Compton emission models. However, the observed curvature in the photon spectrum at X-ray energies could not be explained by an underlying broken power law (BPL) electron spectrum, but demanded a gradual curvature in the particle spectrum, eg: a smooth broken power law or a cutoff power law. The different flux states could be reproduced by mainly changing the particle indices and the break energy; whereas, the variations in other parameters like the Doppler factor and the magnetic field were minimal. While the total bolometric luminosity, $L$, changed by more than a factor of 3, the variations in $B$ and $\delta$ were less than 10%.

To investigate the origin of a curved particle distribution, the time dependent kinetic equation (Kardashev, 1962) was solved under appropriate assumptions using the Green’s function technique (Atoyan & Aharonian, 1999). It was found that an energy dependent escape rate of particles from the emission region gives rise to a smooth curvature in the particle spectrum. Specifically, particles escaping at a rate proportional to $E^{0.7}$ give rise to a particle spectrum consistent with the one described by the power law with an exponentially decreasing tail.

0.4.4 EBL estimation from VHE observations

Before the year 2000, the number of blazars detected at VHE energies were few (~ 4), primarily due to low sensitivity of first generation atmospheric Cherenkov telescopes (Costamante & Ghisellini, 2002). However, with the advent of new generation high sensitivity telescopes, namely VERITAS, MAGIC and HESS, the number of blazars detected at this energy are more than 55. Hence the present period allows one to perform a statistical study of VHE blazars to estimate the EBL, independent of various emission models.
In [Sinha et al. (2014)], we utilized a novel method to estimate the EBL spectrum at IR energies from the observed VHE spectrum of HBLs. First, we showed that the observed VHE spectral index of HBLs correlates well with its corresponding redshift. Since such correlations are absent in other wavebands, we attributed this correlation to a result of EBL absorption of the intrinsic spectrum. Spurious correlations occurring due to Malmquist bias were ruled out by studying the correlations between luminosity and index.

The observed VHE spectrum of the sources in our sample could be well approximated by a power-law, and if the de-absorbed spectrum was also assumed to be a power law, then we showed that the spectral shape of EBL had to be of the form $\epsilon n(\epsilon) \sim k \log(\frac{\epsilon}{\epsilon_p})$. The range of values for the parameters defining the EBL spectrum, $k$ and $\epsilon_p$, was estimated such that the correlation of the intrinsic VHE spectrum with redshift was nullified. The estimated EBL depended only on the observed correlation and the assumption of a power law source spectrum. Specifically, it did not depend on the spectral modeling or radiative mechanism of the sources, nor on any theoretical shape of the EBL spectrum obtained through cosmological calculations. The estimated EBL spectrum was consistent with the upper and lower limits imposed by different observations, and agreed closely with the theoretical estimates obtained through cosmological evolution models.

0.5 CONCLUSION

We have tried to set up a general framework for exploring the physical processes and underlying mechanisms using both spectral (SEDs) and temporal analyses as well as modeling based on theoretical understanding of physical processes. We studied both long term variations and bright flares of two HBLs, Mkn 421 and 1ES 1011+496, and found similar variability in the Optical-GeV bands, and the X-ray-VHE bands. This indicates a similar origin for the Optical and Fermi-LAT bands, and for the X-ray-VHE bands. In the framework of the SSC model, this is attributed to the lower energy electrons contributing to the Optical-GeV bands (synchrotron and SSC respectively), and the higher energy ones to the X-ray-VHE bands. The detection of lognormality hints at a strong disk-jet coupling in blazar jets, where lognormal fluctuations in the accreting rate give rise to an injection rate with similar properties.

The underlying electron distribution was clearly preferred to have a smooth curvature for 1ES 1011+496. While a similar trend was seen for Mkn 421, the sharp broken power law could not be ruled out either. However, the second index $p_2$ was much steeper than what would be expected from synchrotron cooling, thus ruling out the broken power law spectrum as originating from a cooling break. Plausible origin of intrinsic curvature in the underlying spectrum was investigated, and could be attributed to energy dependent escape time scales in the emission region.
The variations in flux states were found to be mainly due to a change in the underlying particle spectrum, rather than in the underlying jet parameters. While the time-resolved UV-X-ray spectra of Mkn 421 during the April 2013 flare could not be explained by synchrotron emission from a single region, the time averaged broadband spectrum during the same time could be well fit by our model. This motivates a need for better time resolved broadband spectra.

A close agreement was seen between our estimated EBL intensity, and the theoretical estimates obtained through cosmological evolution models. VHE photons from distant blazars should thus be expected to suffer significant absorption leading to an observed flux below the detection limit of our telescopes. Thus, the detection of VHE photons from distant sources continues to be an open problem, and may possibly be related to VHE emission through secondary processes resulting from the development of electromagnetic and hadronic cascades in the intergalactic medium (Essey & Kusenko, 2010) or more exotic scenarios associated with creation of axion like particles (de Angelis et al., 2009).

With the launch of ASTROSAT (Singh et al., 2014b) in September 2015, we now have unprecedented access to simultaneous, high resolution, time resolved spectral and temporal data from optical to hard X-rays energies. The upcoming Major Atmospheric Cherenkov Experiment (MACE; Koul et al. (2011)) at Hanle, Ladakh, scheduled to see first light in early 2017, is expected to provide us with excellent time resolved spectrum at VHE energies. Data from these instruments will let us probe into blazar jets at very small time scales, thus uncovering the physics behind blazar flares. Future high sensitivity telescopes like the Cherenkov Telescope Array (CTA; Acharya et al. (2013)) will enlarge the dynamical flux range and explore the high-redshift universe at VHEs, thus putting tighter constraints on the EBL. A large number of blazars are expected to be available for statistical analysis for various classes of objects. The more exciting possibility is that these instruments might uncover unexpected phenomena that may challenge current theoretical concepts, and trigger to deepen our understanding of the extragalactic sky.
List of Publications

1. Refereed journals
   - “Estimation of the Extragalactic Background Light using TeV observations of BL Lac objects”,
   - “Underlying particle spectrum of Mkn 421 during the huge X-ray flare in April 2013”,
   - “Longterm monitoring of Mkn421 with the HAGAR telescope system”,
   - “On the spectral curvature of 1ES1011+496 : Effect of spatial particle diffusion”,
   - “Broadband spectral fitting of blazars using XSPEC”,
     S. Sahayanathan, R. Misra & A. Sinha, to be submitted

2. Conference proceedings
   - “Monitoring of Blazars from HAGAR Cherenkov telescope”,
     B. S. Acharya, A. Shukla, A. Sinha, et. al for the HAGAR collaboration, ICRC, 2013, id:1010
   - “Very high energy gamma ray astronomy using HAGAR Telescope System”,
     V.R. Chitnis, A. Shukla, A. Sinha, et. al for the HAGAR collaboration, CICAHEP, 2015, 1, 16

3. Publications not a part of this thesis
   - “A time dependent approach to model the X-ray and γ-ray lightcurves of Mrk 421 observed during the flare in 2010”,
Contents

2.1 The Telescope Array: Design and Instrumentation 29
2.2 Data Acquisition system (DAQ) 31
2.3 Observations 33
2.4 Simulations 36
  2.4.1 Performance parameters 37
2.5 Data Reduction and Analysis 38
  2.5.1 Space Angle Estimation 38
  2.5.2 Data Selection 41
  2.5.3 Signal Extraction 42
2.6 Results 42

3 Multiwavelength Instrumentation and Data Analysis 45
  3.1 Fermi-LAT 45
  3.2 NuSTAR 47
  3.3 Swift 48
    3.3.1 Swift-BAT 49
    3.3.2 Swift-XRT 49
    3.3.3 Swift-UVOT 51
  3.4 MAXI 52
  3.5 CCD-SPOL 53
  3.6 OVRO 53

4 Mkn 421: Longterm spectral and temporal study 55
  4.1 Brief review of past results 55
  4.2 Data Analysis 58
    4.2.1 HAGAR 58
    4.2.2 Other multiwavelength data 59
  4.3 Multiwavelength temporal study 60
    4.3.1 Variability and correlations 61
    4.3.2 Detection of lognormality 65
  4.4 Spectral modelling 65
  4.5 Results and discussions 73
    4.5.1 Spectral variability 73
    4.5.2 Location of the emission zone 74
    4.5.3 Implications of lognormality 75
  4.6 Conclusions 76

5 Mkn 421: Underlying particle spectrum during giant flare 77
  5.1 Behaviour during previous flares 77
  5.2 Multiwavelength observations and data analysis 78
  5.3 Multiwavelength temporal study 80
List of Tables

Table 2.1 Observations of extragalactic sources with HAGAR 43
Table 3.1 Swift-UVOT filter characteristics 52
Table 4.1 HAGAR observation details for different epochs 59
Table 4.2 X-ray and GeV spectral parameters during various epochs 60
Table 4.3 Fractional variability $F_{var}$ at different wavebands 63
Table 4.4 Detection of lognormality 68
Table 4.5 Fit parameters for the different SED states 73
Table 5.1 Details of NuSTAR pointings 79
Table 5.2 Details of Swift pointings 79
Table 5.3 $F_{rms}$ at different frequencies during X-ray flare 82
Table 5.4 Reduced $\chi^2$ values for the photon spectrum 85
Table 5.5 Fit parameters of the log parabolic photon spectrum 86
Table 5.6 Reduced $\chi^2$ for the various particle distributions 89
Table 5.7 Sample parameters of the best fit model for the photon and particle spectrum 89
Table 5.8 The best fit parameters for the LP particle distribution 89
Table 6.1 Spectral details of different epochs 95
Table 6.2 Models parameters for different particle spectra 103
Table 7.1 List of HBLs detected at VHE 116

List of Figures

Figure 1.1 Basic structure of AGN 3
Figure 1.2 AGN classification scheme 3
Figure 1.3 Multiwavelength image of Cygnus A 5
Figure 1.4 Unified AGN model 6
Figure 1.5 Typical double hump SED of blazars 8
Figure 1.6 The blazar sequence 8
Figure 1.7 Polarisation in dielectric medium 11
Figure 1.8 Toy model of EAS 12
<table>
<thead>
<tr>
<th>Figure</th>
<th>Description</th>
<th>Page</th>
</tr>
</thead>
<tbody>
<tr>
<td>1.9</td>
<td>Schematic differences between photon and hadron showers</td>
<td>12</td>
</tr>
<tr>
<td>1.10</td>
<td>Lateral distribution of photon and hadron showers</td>
<td>13</td>
</tr>
<tr>
<td>1.11</td>
<td>The VHE sky</td>
<td>14</td>
</tr>
<tr>
<td>1.12</td>
<td>Synchrotron spectrum</td>
<td>17</td>
</tr>
<tr>
<td>1.13</td>
<td>Synchrotron self absorption spectrum</td>
<td>18</td>
</tr>
<tr>
<td>1.14</td>
<td>Inverse Compton cross-section</td>
<td>20</td>
</tr>
<tr>
<td>1.15</td>
<td>Bremsstrahlung spectrum</td>
<td>21</td>
</tr>
<tr>
<td>1.16</td>
<td>Leptonic and hadronic SED models</td>
<td>25</td>
</tr>
<tr>
<td>1.1</td>
<td>The HAGAR Telescope Array</td>
<td>30</td>
</tr>
<tr>
<td>2.1</td>
<td>Schematic layout of the HAGAR Array</td>
<td>30</td>
</tr>
<tr>
<td>2.2</td>
<td>Bright Star Scan</td>
<td>32</td>
</tr>
<tr>
<td>2.3</td>
<td>Pointing offset for HAGAR mirrors</td>
<td>32</td>
</tr>
<tr>
<td>2.4</td>
<td>Rate-threshold plot</td>
<td>34</td>
</tr>
<tr>
<td>2.5</td>
<td>HAGAR Telescope Electronics</td>
<td>34</td>
</tr>
<tr>
<td>2.6</td>
<td>HAGAR Trigger Set-up</td>
<td>35</td>
</tr>
<tr>
<td>2.7</td>
<td>HAGAR observation duration</td>
<td>36</td>
</tr>
<tr>
<td>2.8</td>
<td>HAGAR differential rate plots</td>
<td>38</td>
</tr>
<tr>
<td>2.9</td>
<td>HAGAR significance plot</td>
<td>39</td>
</tr>
<tr>
<td>2.10</td>
<td>Arrival time reconstruction</td>
<td>41</td>
</tr>
<tr>
<td>2.11</td>
<td>Space angle distribution</td>
<td>43</td>
</tr>
<tr>
<td>3.1</td>
<td>Schematic of the LAT telescope</td>
<td>46</td>
</tr>
<tr>
<td>3.2</td>
<td><em>Fermi</em>-LAT counts map of Mkn421</td>
<td>46</td>
</tr>
<tr>
<td>3.3</td>
<td>Schematic of the NuSTAR telescope</td>
<td>47</td>
</tr>
<tr>
<td>3.4</td>
<td><em>NuSTAR</em> image of Mkn421</td>
<td>48</td>
</tr>
<tr>
<td>3.5</td>
<td>Schematic of the Swift telescope</td>
<td>49</td>
</tr>
<tr>
<td>3.6</td>
<td><em>Swift</em>-XRT operating mode images</td>
<td>50</td>
</tr>
<tr>
<td>3.7</td>
<td>Pileup estimation in <em>Swift</em>-XRT</td>
<td>51</td>
</tr>
<tr>
<td>3.8</td>
<td>Pileup exclusion in <em>Swift</em>-XRT</td>
<td>51</td>
</tr>
<tr>
<td>3.9</td>
<td><em>Swift</em>-UVOT image of BL Lac</td>
<td>52</td>
</tr>
<tr>
<td>4.1</td>
<td>Historical VHE lightcurve of Mkn 421</td>
<td>56</td>
</tr>
<tr>
<td>4.2</td>
<td>Radio image of Mkn 421</td>
<td>57</td>
</tr>
<tr>
<td>4.3</td>
<td>Optical image of Mkn 421</td>
<td>57</td>
</tr>
<tr>
<td>4.4</td>
<td>HAGAR lightcurve for Mkn 421</td>
<td>58</td>
</tr>
<tr>
<td>4.5</td>
<td>Multiwavelength light curve of Mkn421 from 2009-2015</td>
<td>62</td>
</tr>
<tr>
<td>4.6</td>
<td>Fractional variability $F_{var}$ at different wavebands</td>
<td>63</td>
</tr>
<tr>
<td>4.7</td>
<td>Hardness ratio in the X-ray and GeV bands</td>
<td>63</td>
</tr>
<tr>
<td>4.8</td>
<td>z-DCF between the various wavebands</td>
<td>64</td>
</tr>
<tr>
<td>4.9</td>
<td>Histogram of flux distribution</td>
<td>66</td>
</tr>
<tr>
<td>4.10</td>
<td>Flux-rms scatter plots</td>
<td>67</td>
</tr>
<tr>
<td>4.11</td>
<td>Mkn 421 R-band flux distribution</td>
<td>68</td>
</tr>
<tr>
<td>4.12</td>
<td>SED during different states fit with SSC model</td>
<td>72</td>
</tr>
</tbody>
</table>
List of Figures

- Figure 4.13 Cross plot of the fit parameters for the one-zone SSC 74
- Figure 4.14 Origin of lag between radio and γ-ray flares 74
- Figure 4.15 Observation bias in pointing instruments 75
- Figure 5.1 Flux brightening during April 2013 80
- Figure 5.2 Multiwavelength light curve during April 2013 flare 81
- Figure 5.3 Computed z-DCF with NuSTAR data 83
- Figure 5.4 Hardness ratio during April 2013 flare 83
- Figure 5.5 Time bins for which spectral fitting 84
- Figure 5.6 Cross plot of parameters for the logparabolic photon and particle spectrum 86
- Figure 5.7 Cross plot of the two indices of the broken power-law particle spectrum 88
- Figure 5.8 Observed X-ray and UV spectrum during two states. 90
- Figure 5.9 Fitted spectrum and residuals for the three spectral models 91
- Figure 6.1 Redshift measurement of 1ES 1011+496 94
- Figure 6.2 Published TeV spectrum and SED of 1ES 1011+496 95
- Figure 6.3 Longterm Fermi-LAT spectrum and extracted SEDs 98
- Figure 6.4 Multiwavelength lightcurve of 1ES 1011+496 99
- Figure 6.5 Detection of lognormality in 1ES 1011+49 100
- Figure 6.6 SEDs modelled with CPL and SBPL 102
- Figure 6.7 Comparison of different particle spectra 103
- Figure 6.8 Difference between the Thomson condition and KN condition 105
- Figure 6.9 Effect of energy dependence of the escape time scale on final spectrum 106
- Figure 6.10 Particle spectra obtained for ξ = −0.7 106
- Figure 7.1 Background radiation in the universe 110
- Figure 7.2 Observational limits on the EBL intensity 111
- Figure 7.3 Variation in different EBL models 112
- Figure 7.4 Schematic illustration of the γ−γ pair production 113
- Figure 7.5 The cross section for the γ−γ interaction 113
- Figure 7.6 Limits on the EBL as determined from γ−ray observations of blazars 114
- Figure 7.7 Distribution of the observed VHE spectral index with redshift 118
- Figure 7.8 Distribution of the observed X-ray spectral index with redshift 118
- Figure 7.9 Distribution of the observed Fermi-LAT spectral index with redshift and luminosity 119
- Figure 7.10 Distribution of the observed VHE spectral index with luminosity 119
- Figure 7.11 EBL spectrum estimated in this work 122
- Figure 7.12 Parameter space for k and ε_p 123
List of Figures

| Figure 7.13 | Validity of the estimated EBL within radiative transfer models | 126 |
| Figure 7.14 | The Gamma Ray Horizon | 127 |
| Figure 7.15 | Exponential turnover in the absorption corrected VHE spectra of distant sources. | 128 |
| Figure 8.1 | AstroSat simulations of HBLs | 134 |
| Figure 8.2 | Status of the MACE telescope | 135 |
| Figure 8.3 | Sensitivity plot for CTA | 136 |
| Figure A.1 | Comparison between analytical and numerical solutions for SSC and EC | 143 |
| Figure A.2 | XSPEC module fit to SED of 3C 279 | 145 |
“It doesn’t matter how beautiful your theory is, it doesn’t matter how smart you are. If it doesn’t agree with experiments, it’s wrong.”

Richard P. Feynman

1

Introduction: Blazars in the high energy Universe

Out of the billions of galaxies in our Universe, a small fraction (∼ 5%) has a very active nucleus - a small region (∼ light days) at the center of the galaxy, which outshines the total emission from the remaining of the host galaxy. These galaxies have total luminosity exceeding $10^{44}$ ergs/s, and are termed as active galactic nuclei (AGN). In contrast to the energy spectrum from normal galaxies (a blackbody), AGNs have a broad energy spectrum extending from radio to beyond X-ray energies. Around 10-15% of the AGNs are radio-loud, and observationally exhibit prominent bipolar radio jets reaching up to Mpc scales. According to the unified AGN model of Urry & Padovani (1995), blazars are radio-loud AGNs with one of the jets aligned at a close angle to our line of sight. Blazars are the most prominent objects seen at very high energies (VHE; > 100 GeV). In this chapter, we review our present understanding of blazars and address some of the open questions in the field, with emphasis on VHE emission and detection techniques.

1.1 AGN Classification and Morphology

By the end of the 1950s, synchrotron emission was well established to be the dominant process for the radio emission from extragalactic radio sources. Burbidge (1959) used this to show that the minimum energy content of AGNs is extremely large ∼ $10^{60}$ ergs, and attributed this large energy to a chain of supernovae explosions occurring in a tightly packed set of stars at the nuclear region of the galaxy. Hoyle & Fowler (1963a,b) showed in their pioneering papers that such close packed stars can as well form a single super massive object, and that the energy of the radio sources was of gravitational origin derived from the slow contraction of a super massive object under its own strong gravitational
1. Introduction: Blazars in the high energy Universe

Field. This idea was further developed by many authors (e.g., Salpeter (1964); Shakura & Sunyaev (1973); Lynden-Bell (1969)), and we now believe that AGNs host a supermassive black hole \((\sim 10^6 - 10^9 M_{\odot})\) at their center, and as matter is attracted by the black hole gravity, it is compressed, heated, and then it radiates.

The development of our understanding of AGNs, observations and theory, is a fascinating read, and can be found in the books by Schmidt (1990) and Krolik (1999). Here, we only outline the basic structure of AGNs (Figure 1.1) as we currently understand (Ghisellini, 2013):

- **A supermassive blackhole** at the center, which acts as the central engine.

- **An accretion disk**, formed by matter spiralling into the central black hole. This is understood to be the major source of power in the jet.

- **An X-ray corona**, sandwiching the accretion disk. It is supposed to be a hot layer, or an ensemble of clumpy regions particularly active in the inner parts of the disk.

- **An obscuring torus** located at several parsec from the black hole, intercepting some fraction of the radiation produced by the disk and re-emitting it in the infrared.

- **Broad Line Regions (BLR)**, regions of many small and dense \((n(H) \sim 10^{10} \text{ cm}^{-3})\) clouds at a distance of \(\sim 1\) pc from the black hole moving rapidly \((\sim 3000 \text{ km/s})\). They intercept \(\sim 10\%\) of the ionizing radiation of the disk, and re-emit it in the form of lines, which are broadened due to Doppler shifts.

- **Narrow Line Regions (NLR)**, which are regions of less dense clouds \((\sim 10^3 \text{ cm}^{-3})\) moving less rapidly \((n(H) \sim 300 \text{ km/s})\) as compared to BLR.

- **Relativistic, bipolar radio jets** characterized by a non-thermal broadband emission.

1.1.1 The AGN Zoo and the unified model

AGNs emit spectacularly over the entire accessible electromagnetic spectrum and thus have been one of the main sources in any new window of the electromagnetic spectrum resulting from the technological advances in instrumentation. This has led to many different and independent classification schemes (Figure 1.2) in different energy bands e.g optical morphology, radio morphology, variability, luminosity etc. (Tadhunter, 2008); making the AGN classification complex and often confusing.

- Based on *radio emission*, AGNs are broadly classified into two groups, namely, radio-loud and radio-quiet. Sources with the ratio of emission at the 5 GHz to
1.1. AGN classification and morphology

Figure 1.1.: Basic morphology of AGNs (according to the classification scheme of Urry & Padovani (1995).

Figure 1.2.: The AGN zoo showing the different classes of AGNs.
1. Introduction: Blazars in the high energy Universe

emission in the optical B-band greater than 10 have been termed as radio-loud, others radio-quiet. Though the first quasars that were discovered were radio-loud, we now know that these radio-loud AGNs constitute roughly 10% of all AGNs, with the majority being radio-quiet. Observationally, radio-loud AGNs are distinctly characterized by highly relativistic bipolar radio jets reaching up to Mpc scales, and are generally more powerful than their radio-quiet counterparts.

Radio-quiet AGNs include Seyferts, galaxies which show a bright star-like nucleus with very high surface brightness and strong, high-ionization lines in their optical-UV spectra. They are further subdivided into Seyfert 1 or Seyfert 2 according to whether their optical spectra show both broad and narrow emission lines or only narrow emission lines. These are mainly spiral galaxies and are radio-quiet. However, a particular subclass known as Narrow Line Seyfert Galaxies is now known to be radio-loud and shows a rapid and large variation across the entire accessible electromagnetic spectrum similar to blazars. Quasars, characterized by a blue bump due to excess UV emission, may be both radio-loud and radio-quiet. Radio Galaxies (radio-loud AGNs) show a bright star-like nucleus in optical but a non-stellar continuum and an extended structure in radio emission exhibiting core-jet morphology. The relativistic bipolar jets are often symmetrical on either side of the active nucleus. They are further subdivided into Broad Line Radio Galaxies and Narrow Line Radio Galaxies depending on whether their optical spectra show both broad and narrow emission lines or only narrow emission lines, which are further subdivided morphologically according to their appearance in radio images as Fanaroff Riley I (FR I) and Fanaroff Riley II (FR II) (Fanaroff & Riley, 1974). FR I have jets that become fainter and fainter as one moves away from the central engine. Due to this feature they are also known as edge-darkened sources. On the other hand, FR II are edge-brightened sources where jets become fainter towards the central engine. Figure 1.3 shows a composite radio, optical and X-ray image of the powerful radio galaxy Cygnus A, showing the edge brightened radio jets, the X-ray corona and the host galaxy.

- Based on Optical/UV Spectroscopy, AGNs are subdivided on the basis of strength and nature of their observed optical-UV emission lines. Those exhibiting strong, broad, as well as narrow emission-lines have been classified as Type-1 AGN while sources with only narrow emission lines are known as Type-2 AGNs.

The AGN unification model, first proposed by Antonucci (1984) and later developed by several authors (see Netzer (2015) and references therein) assumes that the physics of all the AGNs are same and the observed differences between different classes are only due to their relative orientation with respect to the line of sight (Figure 1.4). It is mainly based on three fundamental pillars: orientation, covering factor and luminosity. The main elements responsible for different realizations are the axis-symmetric dust clouds known as the torus and the bipolar relativistic jets in case of radio-loud sources. The
1.1. AGN classification and morphology

Figure 1.3.: Multiwavelength image of the powerful radio galaxy Cygnus A taken from the NASA archives. Radio emission (red) extends to either side along the same axis for nearly 300,000 light-years powered by jets of relativistic particles emanating from the galaxy’s central supermassive black hole. Hot spots likely mark the ends of the jets impacting surrounding cool, dense material. That it is an extended source of X-rays is seen by the data (in blue) from the orbiting Chandra Observatory. Confined to yellow hues, optical wavelength data of the galaxy from Hubble and the surrounding field in the Digital Sky Survey complete a remarkable multiwavelength view.
1. Introduction: Blazars in the high energy Universe

unification within radio-quiet counterparts requires only the torus while the radio-loud counterparts requires both the torus and the bipolar jets. The integration of radio-loud and radio-quiet under one family “AGNs” requires both the anisotropic components and Doppler boosting. Thus in radio-quiet AGNs, Seyfert 1 is the one where the view of the central engine is not blocked by the torus while the converse is true in case of Seyfert 2.

![Unified AGN Model](image)

**Figure 1.4.:** An artist impression of the unified AGN model taken from Beckmann & Shrader (2012b). The core of the diagram shows all the possible components that constitute an AGN (not to scale). The outer part depicts the manifestation of AGN depending on our viewing angle to the source.

1.1.2 **Blazars**

Blazars count among the most violent sources of high energy emission in the known universe, observationally characterized by:

- A highly variable nonthermal emission across the entire electromagnetic spectrum
- A typical double hump broadband spectral energy distribution (SED), with one in the IR - X-ray regime, and the second one in the $\gamma$-ray regime
- Variability at all time scales, from hours to years
- Strong radio and optical polarization
- Apparent superluminal motion in high resolution radio maps

According to the classification scheme of Urry & Padovani (1995), the likely explanation of such observations is that they are a subclass of radio-loud AGNs where the relativistic jet is oriented close to the line of sight. The observed properties are believed to be a
manifestation of relativistic aberration associated with relativistic bulk motion of plasma at small angles to our line of sight, resulting in Doppler boosting of flux, frequency, and temporal characteristics. The relativistic bulk motion is duly attested by the ubiquity of superluminal motion, one-sided morphologies, $\gamma$-ray transparency and intra-day variability in the radio wavebands.

Based on the rest frame equivalent width of their emission lines in optical/UV spectra, blazars have been further classified in two subgroups: BL Lacertae objects (BL Lacs) with very weak/no emission lines and Flat Spectrum Radio Quasars (FSRQ) with strong broad-line emission. In terms of radiative output, BL Lacs belong to the low luminosity class of blazars and are thought to be FR I sources in the AGN unification scheme ([Urry & Padovani, 1995; Tadhunter, 2008]), while FSRQs are more powerful and are believed to be the FR II counterparts.

The broad-bimodal SED (Figure 1.5) is one of the unique characteristics of blazars. Except for few cases, the broadband SED is fully non-thermal with two broad components peaking between well defined energy ranges. According to the location of the first peak ($\nu_p$), BL Lacs are further classified into low-energy peaked BL Lacs (LBL; $\nu_p < 10^{14}$ Hz), intermediate peaked BL Lacs (IBL; $10^{14} < \nu_p < 10^{15}$ Hz) and high-energy peaked BL Lacs (HBL; $\nu_p > 10^{15}$ Hz) ([Padovani & Giommi, 1995]). The two humps also exhibit a tight anti-correlation between the source bolometric luminosity and location of the peak of the low energy hump in the average SED of blazars (Figure 1.6). In addition to this, anti-correlation has also been found between the low-energy-hump peak with the luminosity of the low-energy-hump as well as with the $\gamma$-ray dominance. These correlations were termed as evidence for a “blazar sequence” ([Fossati et al., 1998]) - an apparent continuous spectral trend from luminous, low-energy-peaked, $\gamma$-ray dominant sources with prominent broad emission lines to a less luminous high-energy-peaked sources with very weak or no emission lines. Since its proposal, the blazar sequence has been observationally and phenomenologically studied in depth by various authors, with roughly similar conclusions [eg: Giommi et al. (2012); Ghisellini et al. (2009); Ghisellini & Tavecchio (2008); Nieppola et al. (2006); Antón & Browne (2005); Ghisellini (2016)].

The first significant detection of extragalactic TeV photons from the blazar Mkn 421 by the Whipple collaboration in 1992 ([Punch et al., 1992]) using the Atmospheric Cherenkov Technique has given us new clues, and unfolded new mysteries behind the workings of these objects. Detection at TeV energies is particularly challenging because

1. The flux of photons falls off steeply at these energies, $\frac{dN}{d\nu} \sim \nu^{-\alpha}$, where $\alpha \sim 3$. This implies very poor statistics, and large integration time of telescopes with large effective areas are required.

2. TeV photons from distant galaxies interact with the optical/UV photons of the extragalactic background light (EBL) and suffer attenuation (thus further steepening the index) and spectral distortion.
1. Introduction: Blazars in the high energy Universe

Figure 1.5.: The typical double hump SED of blazars (Mkn 421) as seen in the best sampled SED till date (Abdo et al., 2011a).

Figure 1.6.: The blazar sequence of Fossati et al. (1998). A strong anti-correlation exists between the location of the first peak and the source luminosity (from black to blue: FSRQ → LBL → IBL → HBL).
3. The Atmosphere is opaque to $\gamma$-rays, and these photons have to be indirectly detected through the induced air showers. Reconstructing the initial energy and direction of the primary $\gamma$-ray requires the use of extensive Monte Carlo simulations and novel techniques which we describe in the next section.

### 1.2 THE ATMOSPHERIC CHERENKOV TECHNIQUE

In 1952, a new window was opened on our universe when Galbraith and Jelly detected brief flashes of light in the night-sky using an ex-war time parabolic signalling mirror clamped with a small photomultiplier tube at the focus on a free running oscilloscope at the Extensive Air Shower (EAS) array experiment at UK Atomic Energy Research Establishment in Oxfordshire \cite{GalbraithJelley1953}. Over several nights, they confirmed a correlation between signals from the array and the detected short duration ($\sim 100$ ns) pulses. This confirmed Blackett’s suggestion that cosmic rays, and hence also gamma rays, contribute to the light intensity of the night sky via the Cherenkov radiation produced by the air showers that they induce in the atmosphere. However, it took a long and frustrating wait of more than 25 years before the first detection of a TeV source - the Crab Nebula at 5$\sigma$ by the Whipple Telescope \cite{Weekes1989}. An engrossing history of the development of this field can be found in the review article by Hillas \cite{Hillas2013}.

#### 1.2.1 Cherenkov radiation

Cherenkov radiation is an electromagnetic radiation emitted when a charged particle (such as an electron) passes through a dielectric medium at a speed greater than the phase velocity of light in that medium. Cherenkov radiation was first observed by Marie Curie in the year 1910 as a bluish glow from bottles containing radioactive radium salts dissolved in liquids. However, she attributed this to some kind of luminescence, and it took a series of experiments by Cherenkov and Vavilov between the years 1934 to 1937 to understand the nature of this radiation.

When a charged particle of mass $m_0$ is moving in a dielectric medium, the electric field of the particle distorts the atoms in the vicinity of its track, resulting in induced dipole moments of the atoms. When the particle moves to another point, the elongated atoms along the initial point, say $P$, return to their original configuration, which is accompanied by the emission of an electric pulse. For slow moving particles ($v < c_m$, where $c_m$ is the phase velocity of light in the medium), the polarization is more or less symmetrical w.r.t particle position, as shown in panel (a) of Figure 1.7, resulting in no net electric field at long distances due to destructive interference and thus, no radiation. However, for particles with $v > c_m$, the polarization is no longer symmetrical along the planes in the trajectory of the particle (panel (b) of Figure 1.7). Thus, a cone of dipoles develops behind the charged particle, creating a distinct dipole field.
1. Introduction: Blazars in the high energy Universe

collapses, it results in wavelets emanating from all portions of the track, which are in phase, and interfere constructively to produce Cherenkov radiation. Radiation is emitted perpendicular to the surface of this cone. The Cherenkov radiation is emitted at an angle \( \theta \) that depends on the refractive index of the medium \( n \) and the relative velocity \( \beta \) and is beamed in the forward direction, such that,

\[
\cos \theta = \frac{1}{\beta n}
\]  

(1)

As can be seen, this implies a threshold velocity of particles corresponding to \( \beta_{\text{min}} = \frac{1}{n} \) when \( \cos \theta = 1 \), such that no radiation takes place below this. The corresponding threshold energy of the particle is then given by \( E_{\text{min}} = \frac{m_0 c^2}{\sqrt{1-\beta^2}} \).

For the case of Cherenkov radiation from EAS, we must take into account the change in refractive index \( n \) due to atmospheric height \( h \),

\[
n(h) = \delta(h) + 1
\]  

(2)

where, \( \delta \) depends on the density of air, and hence, the altitude, given by \( \delta(h) = \delta_0 \exp(-h/h_0) \), where the scale height \( h_0 \) is 7.1 km and \( \delta_0 = 2.9 \times 10^{-4} \). In the atmosphere at ground level at N.T.P, \( n \approx 1.00029 \) and \( \theta_{c,\text{max}} = 1.3^\circ \). The bulk of the Cherenkov radiation is emitted in ultra-violet and visible blue part of the electromagnetic spectrum. Energy thresholds for Cherenkov emission from electron, muon and proton in the atmosphere are 21 MeV, 4 GeV and 39 GeV, respectively. The Cherenkov photons from the air shower induced by a gamma-ray or a cosmic ray are distributed over a large area and form a circular pool of light of about \( \sim 200 - 250 \) m diameter. The size of this light pool is determined by the altitude of the emission, the Cherenkov emission angle at that altitude and the altitude of observation. The Cherenkov light reaches the ground in a narrow time window, typically of about 5 ns width.

1.2.2 Extensive Air Showers

When a high energy photon (or cosmic ray) enters the Earth’s atmosphere, it interacts with the atmospheric nuclei to initiate electromagnetic (and hadronic) showers, known as EAS.

- **Gamma-ray initiated showers**

  When a gamma-ray photon of energy \( E_0 \) enters into the Earth’s atmosphere, it interacts with nuclei, and initiates an electromagnetic shower of charged particles and photons. In this interaction, an electron-positron (\( e^+ / e^- \)) pair is produced, each with an average energy of \( E_0 / 2 \), which moves further down in the atmosphere, radiating through bremsstrahlung process. The photons so produced further produce \( (e^+ / e^-) \) pairs. This process continues into the atmosphere, creating a cascade of particles. A simple toy model (Figure 1.8) developed by [Heitler (1937)] illustrates...
1.2. The Atmospheric Cherenkov Technique

![Figure 1.7.](image)

Figure 1.7.: Polarization state of the medium when the velocity of the charged particle is (a) less than the phase velocity of light in that medium \( (v < c_m) \) and (b) greater than the phase velocity of light in that medium \( (v > c_m) \).

many interesting features: Assuming that in each electro-magnetic interaction two particles are produced, after \( n = (X / \lambda \), where \( X \) is the first interaction point, and \( \lambda \) the mean radiation length due to bremsstrahlung) radiation lengths there will be \( 2^n \) particles. The shape of the EAS is quite symmetric since the interaction length due to pair production is \( X^\gamma = 7/9X \). The width of the shower along the horizontal direction maximizes when energy losses due to ionization become dominant over bremsstrahlung losses. This happens at a critical energy \( E_C \) (\( = 81 \) MeV in the air for \( e^+/e^- \)), and the maximum horizontal spread \( (X_{\text{max}}) \) is obtained at

\[
X_{\text{max}} = \lambda \frac{\ln(E_0/E_C)}{\ln(2)}
\]

For air, \( \lambda = 37.2 \text{ gm/cm}^2 \). In addition to this, there is a lateral spread of the shower due to multiple Coulomb scattering, which is important at lower energies of electrons as multiple Coulomb scattering varies as \( 1/E^2 \). Also small deflections of charged particles due to the Earth’s magnetic field need to be considered.

- **Cosmic-ray initiated showers**
  When a cosmic ray (proton or heavier nuclei) interacts with atmospheric nuclei to produce mesons and baryons. These particles move down in the atmosphere and further interact with air molecules and produce the particles similar to those produced in the first interaction. Neutral pions decay into gamma rays \( (\pi^0 \rightarrow \gamma\gamma) \) which then produce electromagnetic showers as described above. Nuclear cascades are produced through various baryonic interactions, and the charged pions and kaons produce a shower of muons, electrons and neutrinos. Showers generated by cosmic ray electrons create showers similar to produced by gamma rays, and create irreducible background for Atmospheric Cherenkov Telescopes (ACT). However,
1. Introduction: Blazars in the high energy Universe

since the flux of cosmic ray electrons is low and falls rapidly with energy, the electron background is not very significant above 100 GeV.

**Figure 1.8.** Toy model of Heitler (1937) to explain EAS in atmosphere.

Figure 1.9 shows a schematic diagram of photon (electromagnetic only) and cosmic-ray (electromagnetic, muonic and hadronic) induced cascades. Hadronic showers, consisting of many sub-shower profiles, show more fluctuations in their timing profile as compared to photon showers, and while the lateral shower profile of photon showers show a typical hump (Figure 1.10) due to artificial focussing of Cherenkov light, the same is wiped out in hadronic showers due to the fluctuations.

**Figure 1.9.** Schematic differences between photon (left) and hadron (right) induced showers, taken from Mankuzhiyil (2010).
1.2. The Atmospheric Cherenkov Technique

Figure 1.10.: Lateral distribution of Cherenkov photons on ground for $\gamma$ and hadronic showers as obtained from simulations (Fegan, 1997).

1.2.3 Detection techniques

The Cherenkov emission produced by EAS is coherent and it can be detected by an array of optical detectors on the ground by using ACT against the night sky background (NSB) and ambient light. Gamma-ray astronomy at the highest energies, (at $\sim$ above 100 GeV), is performed through this technique.

1.2.3.1 Wavefront sampling Technique

The Cherenkov photons from EAS create a light cone on the ground, which are collected by optical reflectors with a PMT at the focal point of each reflector. These photons are sampled from different locations of the Cherenkov light pool. Therefore, an array of detectors separated by distances in the range of 10 m to 100 m is required to collect Cherenkov photons in coincidence. The arrival direction of the shower is determined by the relative time of arrival of the Cherenkov shower front at the individual detectors. Previous experiments like Themistocle and CELESTE in France, Solar Tower Atmospheric Cherenkov Effect Experiment (STACEE) in USA and Pachmarhi Array of Cherenkov Telescopes (PACT) in India, and currently the HAGAR Telescope array (see Chapter 2) in India made use of this technique.
1. Introduction: Blazars in the high energy Universe

1.2.3.2 Imaging Technique

Imaging Atmospheric Cherenkov Technique is the most powerful way of detecting VHE photons. Imaging Air Cherenkov Telescope (IACT) collects the Cherenkov photons on its large mirror surface, and points them on a camera kept in the focal plane. The camera consists of PMTs to convert the photons into electric signal. The recorded event is the geometrical projection of atmospheric showers. Cherenkov photons emitted at different heights form images at different positions of the camera. The image contains the information of longitudinal development of EAS from the number of photons and arrival time of the images. When the telescope is pointed towards a VHE source on the sky, images are formed near the camera center by the upper part of the shower, where the secondary particles are more energetic. The images of the photons from the lower part of the shower are formed away from the center of the camera. The direction and energy of the primary photons are reconstructed from the shower images.

This technique was pioneered by the Whipple Telescope (Weekes et al., 1989), and later on by the High-Energy-Gamma-Ray Astronomy (HEGRA) at La Palma and is currently used by the Very Energetic Radiation Imaging Telescope Array System (VERITAS), High Energy Stereoscopic System (HESS) and Major Atmospheric Gamma-ray Imaging Cherenkov Telescope (MAGIC) Telescopes.

1.2.4 The TeV sky

Thanks to the high sensitivity of the current generation of IACTs, we now have an unprecedented view of the VHE universe (Figure 1.11). More than 175 galactic and extragalactic sources have been discovered at the highest energies (Wakely & Horan, 2016), with around a third (~ 60) of them being blazars, the dominant extragalactic VHE sources. Galactic sources include supernova remnants, X-ray binaries and pulsars. Around 42 sources are still unidentified.

![Figure 1.11: Map of the TeV sky (taken from Condon (2016)).](image)

Figure 1.11: Map of the TeV sky (taken from Condon (2016)).
1.3 Radiative mechanisms

In this section, we briefly mention the major sources of continuum radiation incurred in astrophysical situations.

1.3.1 Electromagnetic Processes

Most of the observed radiation comes from electromagnetic losses incurred by electrons and positrons in astrophysical plasmas. Excellent descriptions of these phenomena can be found in Blumenthal & Gould (1970); Rybicki & Lightman (1986); Longair (2011).

1.3.1.1 Blackbody emission

Photons emitted by matter in thermal equilibrium with radiation is known as blackbody radiation. Such systems follow a characteristic spectrum known as Planck spectrum with specific energy density given by

\[ u_\nu(\Omega) = \frac{2h\nu^3/c^2}{e^{(h\nu/k_BT)}-1} \text{ergs cm}^{-3}\text{Hz}^{-1}\text{sr}^{-1} \]  \hspace{1cm} (4)

where \( \nu \) is the emitted photon frequency, \( \Omega \) the solid angle along the normal to the emission surface, \( c \) the speed of light, \( h \) the Planck constant, \( k_B \) the Boltzmann constant and \( T \) the effective blackbody temperature. The peak photon frequency at which the energy density is maximum for a given temperature \( T \) is given by Wien's law, \( \nu_{\text{peak}} = 2.82(k_B/h)T \). Integrating Equation (4) over the entire photon frequency and the solid angle, we get the Stefan-Boltzmann law for the energy density of a blackbody spectrum

\[ u(T) = aT^4 \]  \hspace{1cm} (5)

where \( a = 4\sigma/c \) with \( \sigma \) the Stefan-Boltzmann constant. Any continuum emission spectrum which cannot be accounted for by a blackbody spectrum is, usually (and in this thesis), referred to as non-thermal spectrum. Examples of blackbody radiation include the observed spectrum of stars and planets, and the thermal component from the host galaxy in AGN spectra.

1.3.1.2 Synchrotron emission

Radiation emitted as a result of radial acceleration of charged particles in magnetic fields is known as synchrotron radiation. The power radiated at frequency \( \nu \) by an electron of energy \( \gamma m_e c^2 \), moving at a speed of \( \beta (= \nu/c) \) in a magnetic field \( B \) at a pitch angle (angle between magnetic field and particle velocity) of \( \alpha \) is given by
1. Introduction: Blazars in the high energy Universe

\[ P(\nu, \gamma) = \frac{3e^2B\sin(\alpha)}{m_e c^2} F\left(\frac{\nu}{\nu_c}\right) \]

(6)

\[ \nu_c = 1.5\gamma^2 \nu_L \sin(\alpha) \]

(7)

where \( \nu_L = eB/2\pi m_e c \) is the Larmor frequency and \( \nu_c \) the critical frequency. The synchrotron power function, \( F(x) \) is given by

\[ F(x) = x \int_x^\infty K_{5/3}(z)dz \]

(8)

with \( K_{5/3} \) the modified Bessel function of fractional order 5/3. The shape of the spectrum is governed by \( F(\nu/\nu_c) \) which peaks at \( \sim 0.29(\nu/\nu_c) \) (Figure 1.12). The total radiated power by an electron with a given pitch angle \( \alpha \) can be found from Equation 7 and 8

\[ P(\gamma, \alpha) = 2c\sigma_T\beta^2\gamma^2B^2/8\pi \sin^2\alpha \]

(9)

where \( \sigma_T \) is the Thomson scattering cross-section. For an isotropic velocity distribution, the average power radiated per particle can be obtained by averaging over the velocity field as

\[ P_{\text{syn}}(\gamma) = \frac{1}{4\pi} \int P(\gamma, \alpha)\sin\alpha d\Omega \]

(10)

\[ = \frac{1}{8\pi} c\sigma_T\beta^2\gamma^2B^2 \]

(11)

For an isotropic power-law electron distribution described by

\[ N(\gamma) = K\gamma^{-\delta} \]

(12)

the resulting synchrotron spectrum can be shown to be a power-law with spectral index \( -(\delta - 1)/2 \). Examples include the radio emission of our galaxy, supernova remnants and extragalactic radio sources, and the non-thermal low energy continuum of the Crab Nebula and most quasars.

- **Synchrotron Self Absorption**

Relativistic charged particles, in addition to emitting synchrotron radiation, can also get energized via absorbing the emitted synchrotron photons. This absorption process is known as **synchrotron-self absorption** (SSA). This leads to the emitted synchrotron spectrum getting modified at the low energy end. For a uniform source without any input, the observed spectrum is given by

\[ I_\nu = S_\nu (1 - e^{-\tau_\nu}) \]

(13)
1.3. Radiative mechanisms

Figure 1.12: Synchrotron spectrum of a single electron in terms of $F(x)$ (Equation 8) plotted in for different scales (taken from Condon (2016)). Although they all plot the same spectrum, they convey or suppress information in different ways. (1) Simply plotting $F(x)$ versus $x$ on linear axes (lower left panel) completely obscures the spectrum below the peak of $F(x)$ at $x \sim 0.29$. (2) Replotting on logarithmic axes (upper left panel) shows that the low-frequency spectrum has a slope of $1/3$, but it obscures the fact that most of the power is emitted at frequencies near $x >> 1$ because $F(x)$ is the spectral power per unit frequency, not per unit log(frequency). (3) The power per unit log($x$) is $F[\log(x)] = \ln(10)xF(x)$, which is plotted on logarithmic axes in the upper right panel. It has a slope of $4/3$ at low frequencies, making it clearer that most of the power is emitted near $x >> 1$. (4) The lower right panel plots $F(\log(x))$ with a linear ordinate but a logarithmic abscissa to expand the low-frequency spectrum lost in the lower right panel. It is clearly consistent with the approximation that all emission is near $x = 1$ but doesn’t clearly show that the low-frequency spectrum is a power law. Note also that the peak of $F(\log(x))$ is at $x = 1.3$, not $x \sim 0.29$. Areas under the curves in the two lower panels are proportional to the power radiated in given frequency ranges. For example, both lower panels show clearly that about half of the power is emitted at frequencies below the critical frequency and half at higher frequencies.
1. Introduction: Blazars in the high energy Universe

Figure 1.13: The spectrum of a homogeneous synchrotron source in terms of the frequency $\nu_1$ at which $\tau = 1$ (taken from Condon (2016)). Note the change in the slope due to self absorption.

where $S_\nu(= j_\nu/\kappa_\nu)$ is the source function for the synchrotron process and $\tau_\nu$ is the optical depth at the emitted frequency. It may be possible for a source to be optically thick ($\tau_\nu > 1$) at low frequencies but optically thin ($\tau_\nu < 1$) at high frequencies. The total synchrotron spectrum will then be a broken power-law with spectrum changing from $\nu^{5/2}$ at lower frequencies to $\nu^{(\delta-1)/2}$ at high frequencies (Figure 1.13). The frequency at which the index changes is called the synchrotron self absorption frequency. For AGN jet emission this frequency is observed to be within a range of few GHz.

1.3.1.3 Inverse Compton

Scattering of low energy photons to high energies by highly relativistic particles is known as inverse Compton (IC) mechanism. If the energy of the incident photon in electron’s rest frame is much smaller than the electron rest mass energy, then one can ignore the recoil of electron and the scattering process leave the photon energy unchanged in electron’s rest frame. In such case the scattering process is described by Thomson cross section with differential cross section given by

$$\frac{d\sigma_T}{d\Omega} = \frac{1}{2} r_e^2 (1 + \cos^2\theta)$$

(14)
Here \( r_e \) is the classical electron radius and \( \theta \) is the angle between the incident and the scattered photon directions. On the other hand if the recoil of the electron becomes considerable, then the scattering cross section is described by Klein-Nishina (KN) cross section. The differential cross section in this case will include the quantum effects and is given by

\[
\frac{d\sigma}{d\Omega} = \frac{r_e^2 \varepsilon_s^2}{2e^2} \left( \frac{\varepsilon_s}{\varepsilon} + \frac{\varepsilon_s}{e} - \sin^2(\theta) \right)
\]  

(15)

where \( \varepsilon \) and \( \varepsilon_s \) are the energies of the incident and the scattered photon. Figure 1.14 shows a schematic diagram depicting the dependence of the Klein-Nishina cross-section upon photon energy. Expressing in terms of \( \varepsilon \) and the Lorentz factor \( \gamma \) of the relativistic electron \( \gamma \)

\[
\gamma \varepsilon \ll m_e c^2; \quad \text{for Thomson regime}
\]  

(16)

\[
\gamma \varepsilon \gg m_e c^2; \quad \text{for extreme KN regime}
\]  

(17)

Moreover, in the extreme KN regime, the electron loses almost its entire energy to the photon in a single scattering, whereas the electron loses only a small fraction of energy in each scattering in the Thomson regime. Thus, the scattered photon frequency varies between

\[
\varepsilon_s \approx \gamma^2 \varepsilon; \quad \text{for Thomson regime}
\]  

(18)

\[
\varepsilon_s \gg \gamma m_e c^2; \quad \text{for extreme KN regime}
\]  

(19)

giving rise to a very steep spectrum in the extreme KN limit. IC scatterin is believed to be the major process in the production of \( \gamma \)-rays in blazar jets. The background low energy photons can be a sum of contributions from several different components, e.g., synchrotron radiation from the same population of electrons responsible for the IC emission, emission from thermal dust, the cosmic microwave background radiation (CMBR), and so forth.

- **Synchrotron Self Compton**
  The process of scattering of their own synchrotron emission to high energy by relativistic charged particles is known as **synchrotron-self Compton** (SSC). For an isotropic power-law particle distribution (Equation 12), it can be shown that the resulting SSC spectrum follows a power-law distribution with index changing from \( \nu \left( \frac{\delta - 1}{2} \right) \) (Thomson regime) to \( \nu^{-6} \) (extreme KN regime).

- **External Compton**
  The process of scattering of ambient photons from an external origin to high energy by relativistic charged particles is known as **External Comptonization** (EC). The seed photons for EC may come from the BLR, the IR torus, CMBR, etc. See [Dermer](#).
1. Introduction: Blazars in the high energy Universe

Figure 1.14.: A schematic diagram showing the dependence of the Klein-Nishina cross-section upon photon energy; it equals the Thomson cross section at low energies but steeply falls off with increasing energy (taken from Longair & Menon (2009); Georganopoulos et al. (2001) for detailed calculations of the EC emissivity for various distributions of the external radiation field.

1.3.1.4 Bremsstrahlung Radiation

Bremsstrahlung or free-free radiation is the electromagnetic radiation produced by the deceleration of a charged particle when deflected by another charged particle, typically an electron or atomic nucleus. In fact, the bremsstrahlung process can be considered as Compton scattering of incoming electrons with the virtual photons of the Coulomb field of a scattering center. The total power radiated per unit frequency per unit volume from a medium with ion density \( n_i \) and electron density \( n_e \) is given by

\[
\frac{dE}{dt dV d\omega} = \frac{16\pi e^4}{3\sqrt{3}c^3m_e^3\nu} n_e n_i q_i^2 g_{ff}(\nu, \omega)
\]  

where \( q_i \) is the charge of an ion and \( g_{ff} \) is known as Gaunt factor which is a function of electron energy and the emitted photon energy. The bremsstrahlung emission from a thermal particle distribution gives rise to a flat spectrum with an exponential cutoff at about \( h\nu \sim kT \) (Figure 1.15).

Examples include the radio emission of compact regions of hydrogen at temperatures \( T \sim 10^4 K \), and X-ray emission of binary sources at \( T \sim 10^7 K \).
1.3. Radiative mechanisms

![Intensity spectrum (arbitrary units) of bremsstrahlung radiation due to a thermal electron distribution at temperature 100 keV. Note the exponential cutoff at high energies. Figure reproduced from Sunder Sahayanathan (2011).](image)

**Figure 1.15.:** Intensity spectrum (arbitrary units) of bremsstrahlung radiation due to a thermal electron distribution at temperature 100 keV. Note the exponential cutoff at high energies. Figure reproduced from Sunder Sahayanathan (2011).

1.3.2 Hadronic Processes

If protons are accelerated to sufficiently high energies, hadronic interactions and synchrotron emission start to play a significant role. The characteristic frequency of the emitted synchrotron radiation by a proton of energy $\gamma pc^2$ is $(m_p/m_e)^{3} \sim 6 \times 10^9$ times smaller than the characteristic frequency of synchrotron photons emitted by an electron of the same energy. The hadronic models have been discussed extensively by several authors, (see, for eg: Aharonian (2004) and Kelner et al. (2006) for discussions and references). Here, we briefly list the most dominant processes.

1.3.2.1 Bethe-Heitler Process

A gamma ray photon ($\gamma$) can interact with a nucleon $N$ to give rise to an electron positron pair according to the equation,

$$ N + \gamma \rightarrow N + e^+ + e^- $$

These electron-positron pairs can undergo cascading giving rise to a hadronically induced secondary synchrotron and IC emission components. The threshold energy for this process in the nucleon rest frame is the sum of the rest mass energies of the electron and positron, 1.022 MeV.
1. Introduction: Blazars in the high energy Universe

1.3.2.2 Pion and meson decays

Inelastic $p-p$ interactions of high energy protons and other nuclei with the ambient matter produce pions and mesons whose subsequent decay gives rise to high energy gamma rays via the following channels,

\[
\begin{align*}
\eta &\rightarrow 2\gamma \quad (22) \\
\eta &\rightarrow 3\pi^0 \quad (23) \\
\pi^0 &\rightarrow 2\gamma \quad (24) \\
\pi^+ (\pi^-) &\rightarrow \mu^+ (\mu^-) + \nu_\mu (\bar{\nu}_\mu) \quad (25) \\
\mu^+ (\mu^-) &\rightarrow e^+ (e^-) + \nu_e (\bar{\nu}_e) \quad (26)
\end{align*}
\]

Protons also interact with high energy gamma rays (above the threshold energy of 145 MeV) to produce neutral and charged pions, which further decay as shown above.

1.4 BLAZARS EMISSION MODELS

The inferred high luminosities, apparent superluminal velocities and observed rapid variabilities provide us with reasonable evidence that the broadband non-thermal continuum from blazar jets is produced from a small ($R < 1$ day) emission region propagating relativistically at a small angle to our line of sight. While the origin of the low-energy component of the SED is well established to be caused by synchrotron emission from relativistic electrons gyrating in the magnetic field of the jet, the physical mechanisms responsible for the high-energy emission are still under debate. If the protons are not accelerated to sufficiently high energies to reach the threshold for $p\gamma$ pion production, the high-energy radiation will be dominated by IC emission from the ultra-relativistic electrons in the jet (leptonic models). In the opposite case, the high-energy emission will be dominated by proton, pion and muon synchrotron and/or cascades initiated from proton-proton interactions (hadronic models). A comprehensive review of these mechanisms may be found in Boettcher (2010). However, with current spectral information, it is difficult to rule out any of these models (Figure 1.16).

1.4.1 Leptonic models

In leptonic models, the high-energy emission is produced via IC scattering of soft photons by the same ultra-relativistic electrons which are producing the synchrotron emission. The seed photons for the up-scattering may be the synchrotron photons themselves (SSC; eg: Marscher & Gear (1985); Maraschi et al. (1992); Böttcher et al. (2009)) or
1.4. Blazars emission models

the ambient photons outside the jet (EC). The sources of EC photons, which play an important role in our understanding of the AGN environments, include:

- Photons from the accretion disk (Dermer et al., 1992; Dermer & Schlickeiser, 1993)
- Reprocessed optical-UV emission from the BLR (Sikora et al., 1994; Blandford & Levinson, 1995; Ghisellini & Madau, 1996; Dermer et al., 1997)
- IR photons from the dusty torus (Błażejowski et al., 2000)

In its simplest case, emission is assumed to come from a single emission zone of specified geometrical shape, mostly spherical, with an adhoc specified electron distribution. A more realistic approach consists of self-consistent steady-state solution of the Fokker-Planck equation including a physically motivated (e.g., from shock-acceleration theory) acceleration of particles and all relevant radiative and adiabatic cooling mechanisms (Weidinger et al., 2010; Acciari et al., 2009c; Ghisellini & Tavecchio, 2009). Time dependent SSC/SSC+EC models have been developed which incorporate electron dynamics and radiation transfer factors to reproduce the observed variabilities (Li & Kusunose, 2000; Kataoka et al., 2000; Sikora et al., 2001; Böttcher & Chiang, 2002). Hadrons are assumed to be cold, and are involved only in the propagating the kinetic energy of the jet.

While leptonic models are highly successful in reproducing the blazar SEDs and lightcurves in most cases, specially the correlated X-ray/TeV variability usually seen in most HBLs (Coppi & Aharonian, 1999), some recent observations pose a serious challenge. Detection of minute scale flux doubling time scales (Paliya et al., 2015a; Aharonian et al., 2007c) requires a size of the emitting region that might be smaller than the Schwarzschild radius of the central black hole of the AGN (Begelman et al., 2008). Intrinsic TeV spectra of distant blazars have been found to require very “hard” particle indices (< 1.5), which is not possible to accommodate within known acceleration theory models (Aharonian et al., 2006b). Observations of “orphan” flares at TeV energies are also puzzling.

1.4.1.1 Inhomogeneous jet models

To address some of the failures of the simple one zone models, phenomenological multi-zone models have been introduced by several authors. Tavecchio & Ghisellini (2008), in order to explain the minute scale VHE flares from PKS 2155+304, proposed a spine-sheath model where the γ-ray emission originates from a small spine of ultra-relativistic plasma within a larger, slower moving jet. Georganopoulos & Kazanas (2003) used a decelerating-jet model where differential relativistic motion between various emission zones leads to Doppler boosting of one zone’s emission into the rest frame of another zone. This can reduce the requirements of extreme bulk Lorentz (and Doppler) factors inferred from simple one-zone leptonic modeling, and reproduce SEDs with more “reasonable” sets of
1. Introduction: Blazars in the high energy Universe

parameters. Even further improvements upon these models have been carried out in the shock-in-jet models (Böttcher & Dermer, 2002; Joshi, 2009; Mimica et al., 2004; Sokolov & Marscher, 2005), where the time dependent evaluation of retarded radiation fields originating from all parts of the shocked regions of the jet are considered.

1.4.2 Hadronic models

As an alternate to leptonic models, hadronic models have been proposed where a significant fraction of the jet power is converted into the acceleration of relativistic protons in a strongly magnetized environment. The acceleration of protons to the necessary ultra-relativistic energies ($E_p > 10^{19}$ eV) requires high magnetic fields of several tens of Gauss. In the presence of such high magnetic fields, the synchrotron radiation of the primary protons, and secondary muons and pions, also need to be accounted for (Rachen & Mészáros, 1998; Mücke et al., 2000; Mücke & Protheroe, 2001). Electromagnetic cascades are then generated as discussed in Section 1.3.2 (Mannheim & Biermann, 1989, 1992).

Hadronic models are difficult to investigate in a time-dependent way due to the required computer intensive Monte Carlo simulations. However, observations of rapid time variabilities seem inconsistent with the radiative cooling time scales of protons. Correlated X-ray/TeV flares are also difficult to explain within the ambit of hadronic models. On the other hand, “orphan” flares and “hard” TeV spectra can be naturally explained.

1.5 Open questions about AGN jets

Despite the considerable volume of work available in this field, the physics of the ubiquitous astrophysical jets remain heavily shrouded in debate. The jet formation, collimation and acceleration are still only vaguely understood. The observed rapid variability suggests that the emission region is compact and located close to the nucleus (Dondi & Ghisellini, 1995), which lies below the resolution limit of modern facilities. Thus, even the sites of production of radiation at different energies are also not well known. AGN activity is triggered by galaxy mergers/interactions. As such, AGN activity is directly linked to the structure formation in the Universe. Also, outflows, jets, and high-energy radiation produced in AGN may substantially influence the surrounding (galactic and intergalactic) medium, modifying therefore the structure formation itself via some complex feedback process. Studying how AGN evolve with redshift is therefore important for understanding cosmological evolution of galaxies in general. In this section, we list some of the most exciting unsolved questions in this field, which we hope can be resolved in the upcoming years.
1.5. Open questions about AGN jets

1.5.1 Jet formation

Theoretical models for the production of relativistic jets from active galactic nuclei predict that jet power arises from the spin and mass of the central supermassive black hole, as well as from the magnetic field near the event horizon (Blandford & Znajek, 1977). The physical mechanism underlying the contribution from the magnetic field is the torque exerted on the rotating black hole by the field amplified by the accreting material. It has been shown by Ghisellini et al. (2014) that while there is a clear linear relationship between the accretion disk luminosity and the gamma ray power of their jets, the jet luminosity outshines that of the disk by more than an order of magnitude, implying that disks alone cannot power the jets; the black hole’s spin must also be involved. However, it may also be possible that the magnetic field extracts power out of the accretion disk, thus making it appear less bright. Difficulties in measuring the blackhole spin presently pose problems in our understanding of the jet launching mechanisms, and present observations are far from resolving the launch region for any blackhole.

1.5.2 Jet propagation and acceleration

How and why jets remain collimated over such large distances (~ 100 kpc) is an unsolved question. Calculations of the jet power are subject to various uncertainties, like the amount of $e^+e^-$ pairs and the contribution of hot protons. Are jets matter or Poynting
flux dominated? To the best of knowledge, particles are accelerated at relativistic shocks inside the jets, but an absence of observational proof prevents us from establishing this fact. Here, polarization mapping might give us more hints on the constraining magnetic field, and clearly higher-resolution, higher-cadence radio observations along with higher fidelity numerical modeling are our pathway towards understanding jet structures (Beckmann & Shrader, 2012a).

1.5.3 Questions specific to blazars

While the unified AGN model is reasonably accepted by the scientific community, it needs to be subjected to stringent observational results. We do not well understand why some AGNs are radio-loud and some radio-quiet. Though Fermi has much revolutionised our understanding of the γ-ray emission from blazars, the location and structure of γ-ray emitting regions in AGN jets are not well known. The origin of seed photons for IC scattering are not well clear. It needs to be understood if there are multiple emission zones, or a single one, as well as the underlying electron energy spectra and the particle acceleration processes involved. Since high quality SEDs are obtained only during flaring state, we have a very poor understanding of the average emission state of blazars. Thus, why and how blazars flare remain largely unknown. The observed variability patterns over all timescales are yet to receive a proper theoretical treatment. The hard TeV spectra seen in distant blazars after deconvolution with theoretical EBL models (see Chapter 7) are a challenge for current acceleration theories. Alternatively they may indicate a problem with our understanding of cosmological EBL models.

1.6 AIM OF THIS THESIS

The aim of this thesis is to investigate the energy content of the jets, specifically looking at the validity of the leptonic models. By concentrating on the multi-wavelength spectral and temporal variability of two TeV blazars, we try to understand the underlying particle spectra and the means to achieve the same. A study of the long term flux distribution and variability also gives us interesting new clues into the probable jet launching mechanisms. We also obtain a model independent estimate of the EBL from a statistical study of all detected TeV blazars.

- Chapter 1 provides a brief introduction into the exciting world of blazar physics, with emphasis on the high energy radiation and detection mechanisms at the highest energies.

- Chapter 2 describes the instrumentation, data reduction and analysis methods for the HAGAR Telescope Array, an ACT array at Hanle, Ladakh.
1.6. Aim of this thesis

- Chapter 3 details the sources of multi-wavelength data and associated data reduction algorithms.
- Chapter 4 describes our long term study of Mkn 421 from 2009-2015, and results from the same.
- Chapter 5 focusses specially on the huge and rapid X-ray flare seen from the aforementioned source in April 2013.
- Chapter 6 reports on a multi-epoch multi-frequency spectral study of 1ES 1011+496 to understand a plausible origin for a curved particle distribution.
- Chapter 7 elucidates a novel method of estimating the EBL from a statistical study of TeV blazars.
- Chapter 8 concludes with our findings and some prospects for the future.
“Equipped with his five senses, man explores the universe around him and calls the adventure Science.”

Edwin Hubble

2

The HAGAR Telescope Array

The High Altitude Gamma Ray (HAGAR) Telescope Array (Figure 2.1) is a hexagonal array of ACTs which uses the wavefront sampling technique to detect celestial gamma rays. It is located at the Indian Astronomical Observatory site (32° 46' 46" N, 78° 58' 35" E), in Hanle, Ladakh in the Himalayan mountain ranges at an altitude of 4270 m above mean sea level. Since the Cherenkov photon density of a shower increases with altitude, a low energy threshold is achieved by operating at such high altitudes. Proposal for HAGAR experiment was made in 2001, and the first telescope installed in 2005. Regular science runs are being conducted since September 2008.

In this chapter, we discuss the design and instrumentation of the HAGAR telescope, the simulations carried out to understand the performance parameters, the observation methods, and the data reduction and analysis techniques.

2.1 THE TELESCOPE ARRAY: DESIGN AND INSTRUMENTATION

The HAGAR Telescope Array [Chitnis et al., 2011] consists of seven telescopes, with six telescopes located at the vertices of a hexagon and one at the center. The separation between two nearest telescopes is 50m, and opening angle (Field of View) of the HAGAR telescopes is 3°. The total reflector area per telescope is ~ 4.45 m² with the average mirror reflectivity at ~ 80%. Figure 2.2 shows a schematic layout of the HAGAR array. Each of the seven telescopes has seven para-axially mounted front coated parabolic mirrors of diameter 0.9 m (and f / d ~ 1), with a fast, high gain UV-sensitive Photonis photo-multiplier tube (PMT), XP2268B, at the focus of individual mirrors. These PMTs have good sensitivity to photons in the ultraviolet to blue range, with a peak quantum
2. The HAGAR Telescope Array

Figure 2.1.: The HAGAR Telescope Array located at Hanle, Ladakh. (Photo Credits: Ajay Talwar)

Figure 2.2.: Schematic layout of the the HAGAR Array. The hexagonal array has a radius of 50m, and each telescope has 7 PMTs in a hexagonal array.
2.2. Data Acquisition system (DAQ)

HAGAR operates on an interrupt driven CAMAC based DAQ. The PMT high voltages of ~1700 V, controlled using a C.A.E.N. controller model SY1527, are adjusted for a PMT rate of 5 kHz. This equality of the PMT rates ensures equal efficiency for each channel. The seven PMT pulses of a telescope are amplified 10 times using an amplifier module, and

efficiency of about 24 % at 400 nm. At typical operating voltages (~1700 – 1800 V), the rate of afterpulses was found to be negligible (~1 – 2%).

Each of the seven telescopes uses an alt-azimuthal mounting, with each axis of the telescope driven by a stepper motor. The telescope movement control system consists of two 17-bit Rotary encoders, two stepper motors and a micro-controller based Motion Control Interface Unit (MCIU). Steady state pointing accuracy of the servo is ±10 arc-sec with maximum slew rate of 30 deg/minute. The resulting blind spot size while tracking the stars near zenith is found to be less than 0.6 deg. The telescope movement is manoeuvred by a control software written on a Linux platform. The pointing of the telescopes is continuously monitored and corrected in real time during tracking. A detailed pointing model was developed by Gothe et al. (2013) to attain good pointing accuracy of mean direction of 7 mirrors in each telescope as well as low spread in pointing directions of mirrors about this mean.

To check the pointing accuracy of each mirror, regular bright star scans (BS Scans), are carried out where the telescope is aligned to an isolated bright star (around V-band magnitude ~2 – 2.5), then moved to the West by 5°, and the telescope tracking switched off. The counting rates of each PMT are monitored. The star is allowed to drift into the field of view of the mirrors and out of it. The PMT count rates corresponding to each mirror are then used to find the pointing offset. However, this method can be used to measure the offset only in the East-West direction.

A better method is to use the RA-Dec scans, which can give the pointing offsets along both axis. At the beginning of the RA scan, the telescope control program acquires and tracks the bright star. Then, a series of manual offsets in the stars RA coordinates are introduced while holding onto the star’s declination (i.e. declination offset = 0°), and the PMT monitoring rates recorded. Similarly, for a Dec scan, a series of manual offsets in declination coordinates are introduced while holding onto the RA coordinate of the star (i.e. RA offset = 0°) and the PMT pulse rates recorded. The PMT count rate is plotted as a function of the offset angle, and the central value of the profile gives the offset between the telescope and the mirror pointing direction. This offset is manually corrected by mechanical re-alignment of the mirrors, and the scan repeated till satisfactory profile obtained. Figure 2.3 shows a typical profile obtained during a bright star scan. The overall pointing accuracy of HAGAR telescope mirrors achieved by this method is 0.23° ± 0.10°, as shown in Fig 2.4.
2. The HAGAR Telescope Array

Figure 2.3: PMT count rates from a Bright Star scan conducted in May 2013, for a typical misaligned and well aligned mirror, respectively.

Figure 2.4: Pointing offset for HAGAR mirrors after alignment for three separate star scans in September 2015.
2.3 Observations

then linearly added to form a telescope output called the Royal Sum (RS) pulse, which is brought to the control room (situated below the central telescope) via low attenuation coaxial cables of types LMR-ultraflex-400 and RG 213 with total length of about 85m. The corresponding information of the RS pulses from each telescope are recorded. Data recorded for each event consist of relative arrival times of Cherenkov shower front at each mirror, as measured by Time to Digital Converters (TDC) with a resolution of 0.25 ns. A real time clock (RTC) module synchronized with GPS is used to record the absolute arrival time of these events, accurate up to $\mu$s. The pulse height information of the showers is measured using 12 bit Charge to Digital Converters (QDC). Information of the triggered telescopes and other house-keeping information are also recorded. The PMT count rates are monitored using at regular intervals using a monitor interrupt arriving at 1 Hz frequency.

An event trigger is generated on coincidence of at least 4 out of 7 telescope pulses in narrow coincidence window of 60 ns, above a pre-assigned discriminator threshold of around 200 mV. This corresponds the condition Number of Triggered Telescopes (NTT) $\geq 4$. Plot of observed trigger rate vs discriminator threshold is shown in Figure 2.5. The discriminator biases are adjusted to keep the RS rates within 25-35 kHz to maintain a chance coincidence rate within a few percent of the trigger rate. The diagrams showing all the modules of the telescope electronics and trigger distribution in DAQ are shown in Figure 2.6 and Figure 2.7 respectively. The TDC start pulses are generated on an event trigger. Since there is finite delay required to form the trigger, the RS pulses are delayed using ECL-based digital delays before they are fed into individual TDC stops. A Common QDC gate is also generated on event trigger. Analog RS pulses from a Fan-in/Fan-out module are delayed using cables and taken to Phillips QDC module.

In addition to the main DAQ system, a parallel DAQ (4 channel modules of ACQIRIS make model DC271A) using commercial 8 bit waveform digitizers with 1 GHz bandwidth with 50 ohm resistance and a sampling rate of 1 GS/s is also being used. The seven RS pulses from the seven telescopes are input to this module. This is enabling us to study the pulse shape, and use the same to reduce the NSB contribution by restricting the time window around the Cherenkov pulse.

2.3 Observations

Observations with the HAGAR telescope array are carried out during clear moonless night, roughly 7-10 days centered around each new moon. Since the commencement of regular science observations in September 2008, a total of 4740 hrs of observation have been carried out (till March, 2016). Observations are generally carried out for more the 70 % of the total available time. Different types of observations (Figure 2.8) are carried out each season, the details of which are outlined below:-

1. ON-source run
2. The HAGAR Telescope Array

Figure 2.5.: Plot of observed trigger rate as a function of the discriminator bias voltage for four fold trigger rate. The chance rate dominates over the shower generated trigger rate at low voltages, but becomes negligible at high voltages.

Figure 2.6.: Flowchart of telescope electronics in the HAGAR DAQ.
2.3. Observations

When all the telescopes track a γ-ray source in the sky, the corresponding run is called an ON-source run. Each ON-source run is taken for a period of 60-120 mins depending on the transit time of the source. Observations are carried out for zenith angle < 45°.

2. OFF-source run

Each ON-source run is followed (or preceded) by an OFF-source or Background run of the same duration and the same zenith angle. This is to ensure the same energy threshold for the two runs. OFF-source runs track a position in the sky where there are no known (or candidate) TeV sources.

3. Fixed angle run

When all the telescopes point towards a dark position of the sky without tracking, its called a fixed angle run. These runs are used to calibrate the time-offsets of the telescopes, as described in Section 2.5.1. T0s have been seen to show a seasonal variation within a couple of ns, and thus, have to be calibrated during each season. Fixed angle runs are taken pointing towards the zenith (termed *vertical* run), 10 degree north (10N), 20 degree north (20N), 10 degree south (10S), and 20 degree south (20S). Different fixed-angle runs are used for analysis of different sources depending upon their average zenith angle during observations.

4. Calibration runs

Various calibration runs, like the star scans described in Section 2.1, are regularly carried out for understanding instrument performance.

Figure 2.7.: Flowchart of trigger setup and its distribution in the DAQ.
2. The HAGAR Telescope Array

Figure 2.8.: Bar chart showing the amount of HAGAR observation time spent on different observation types. ON and OFF source runs are conducted for both galactic and extragalactic sources. Calibration runs include fixed angle runs, bright star scans, etc.

2.4 SIMULATIONS

Simulations play a crucial role in the HAGAR experiment. Since we cannot produce VHE gamma rays in the laboratory, direct calibration of the telescope is impossible. Rather, the HAGAR performance parameters, like for all other ACTs, are understood through detailed Monte Carlo simulations (Saha et al., 2013). Simulations for HAGAR have two principal components:

1. Showers simulations: Extensive Air Showers propagating in the atmosphere are simulated using the CORSIKA simulation package (v. 2.720) developed by the KASCADE group (Heck et al., 1998). Spectral index of the primary $\gamma$-rays is used in accordance to the measured Crab nebulae spectrum (Aharonian et al., 2000), which is the standard candle for all VHE experiments. Electron, proton, alpha particle showers are simulated according to the measured cosmic ray spectrum between the energy ranges 20 GeV to 5 TeV, 50 GeV to 5 TeV and 100 GeV to 10 TeV, respectively. The VENUS code is used for high energy hadronic interactions, GHEISHA for low energy ones. For electromagnetic interactions, the EGS4 code is used. Showers are simulated for various inclination angles from 0° to 45°. Due to the absence of atmospheric profile measurements at Hanle, US standard atmospheric profile is used.
2. **Detector simulations**: The CORSIKA simulations provide information about the arrival time and directions of the Cherenkov photons at detector plane. A background of optical light is present even on clear moonless nights and is termed as the night sky background (NSB). Man made light pollution and natural causes like zodiacal light, airglow and diffuse light from unresolved sources contribute to the NSB. NSB measurements carried out at Hanle indicate a flux of $2.0 \times 10^8$ ph/str/m$^2$/s in the wavelength range 200 - 650 nm. Simulated NSB photons are added to Cherenkov photons from the CORSIKA showers. This information is then passed through the detector simulation program, and corresponding detector responses are studied. The detector simulation program has been developed indigenously by the HAGAR collaboration, and takes into account the various details of the HAGAR system like the PMT characteristics, cable response, trigger formations, etc. The output obtained from the detector simulation is analysed to estimate the performance parameters of the detector, and compare simulation results with observed parameters.

2.4.1 **Performance parameters**

HAGAR performance parameters are estimated for various trigger conditions and for different zenith angles. HAGAR data are taken for trigger condition $NTT \geq 4$, whereas the analysis done in this thesis corresponds to trigger condition $NTT \geq 5$. This ensures better stability of the data due to a smaller chance coincidence rate. The estimated trigger rate agrees well with the observed trigger rate of 13 Hz. The expected gamma-ray rate for a Crab like source at near vertical position is 6.3 counts/min ($NTT \geq 4$) and 3.9 counts/min ($NTT \geq 5$). Energy threshold for HAGAR is obtained from the differential rate plot (Figure 2.9). The energy corresponding to the peak of the differential rate curve is conventionally quoted as energy threshold, and is around 208 GeV and 238 GeV for $NTT \geq 4$ and $NTT \geq 5$, respectively. Gamma-ray flux sensitivity of an ACT system is defined as the lowest gamma-ray flux that can be detected over the isotropic cosmic ray background at a predefined level of significance ($n\sigma$) which can be expressed as

$$n\sigma = \frac{N_{ON} - N_{OFF}}{\sqrt{N_{ON} + N_{OFF}}}$$

(27)

where $N_{ON}$ and $N_{OFF}$ correspond to the number of showers from source and background regions, respectively. This can be expressed in terms of the trigger rates of photons ($R_\gamma$), protons ($R_p$) and alpha particle ($R_\alpha$) as $N_{ON} = (R_\gamma + R_\alpha + R_p)t$ and $N_{OFF} = (R_\alpha + R_p)t$, implying equation 27 can be written as

$$n\sigma = \frac{R_\gamma}{\sqrt{R_\gamma + 2(R_\alpha + R_p)}}\sqrt{t}$$

(28)
2. The HAGAR Telescope Array

Figure 2.9: Differential rate plots for different zenith angles for the $\geq 4$ (red), $\geq 5$ (brown), $\geq 6$ (blue) and $= 7$ (green) trigger conditions; taken from Saha et al. (2013).

Thus, the integration time required to obtain a significant detection depends on the flux level of the source. Figure 2.10 shows the observation duration needed for HAGAR to detect a source at $5\sigma$ significance level as a function of the source flux in units of the Crab flux, implying that HAGAR will be able to detect a Crab Nebula like source at a significance level of $5\sigma$ in 17 hours of observation duration. This sensitivity could be further improved if more cosmic ray background events are rejected by imposing additional criteria.

2.5 DATA REDUCTION AND ANALYSIS

Data reduction technique for HAGAR telescope is derived from the method used for the data analysis of PACT experiment at Pachmarhi (Bose et al., 2007). Analysis codes are developed in-house in IDL language with Python wrapper routines. Source flux is computed by comparing the number of cosmic shower events from the source region with similar background region.

2.5.1 Space Angle Estimation

The difference between the reconstructed arrival direction and the telescope pointing direction (space angle) is computed in two steps, by first correcting for fixed time offsets in the system (T0) and then the estimation of the direction of air shower is done by measuring the relative arrival time of Cherenkov wavefront induced by the shower at each telescope. The details of the steps are outlined below:

1. Computation of T0:
To calibrate the system, we first need to find out the fixed time offset ($T_0$) for each of the telescopes. These time offsets originate due to cable delays, intrinsic PMT delays, delays in the electronics, etc. Since the reconstruction of the arrival direction depends critically on the measurement of the relative arrival times, it is crucial to calculate the offsets precisely.

The relative time difference between, $T_{ij}^{\text{theoretical}}$ between a pair of telescopes, $i$ and $j$, is expressed as

$$T_{ij}^{\text{theoretical}} = T_{0i} - T_{0j}$$

where $T_{0i}$ and $T_{0j}$ are the time offsets for the telescope $i$ and $j$, respectively. Observed values of $T_{ij}$ are obtained from fixed angle runs, ($T_{ij}^{\text{measured}}$). The relative time offset for each telescope is obtained by minimising the total $\chi^2$,

$$\chi^2 = \sum_{i,j=1; i \neq j}^{7} W_{ij} (T_{ij}^{\text{theoretical}} - T_{ij}^{\text{measured}})^2$$

$$= \sum_{i,j=1; i \neq j}^{7} W_{ij} (T_{0i} - T_{0j} - T_{ij}^{\text{measured}})^2$$

where $W_{ij} = \frac{1}{\sigma^2}$ is the statistical weight factor, taken to be the observed $1\sigma$ error on the $T_{ij}^{\text{measured}}$ for the given telescope pair. Demanding

$$\frac{\partial \chi^2}{\partial T_0} = 0$$

we get seven equations, which can be used to write a set of six coupled equations for the seven unknown $T_{0i}$ ($i = 1 \ldots 7$). Thus, the values of time offsets for 6
2. The HAGAR Telescope Array

Telescopes are obtained with respect to the seventh (central) telescope. Monthly averaged $T_0$s, calculated for zenith angle closest to source declination during transit, are used during analysis.

2. Reconstruction of Arrival Direction:

The arrival direction is reconstructed assuming the Cherenkov shower front to be well approximated by a plane wave. Since the radius of curvature of the shower front at HAGAR altitude is $\sim 5000$ m, and the diameter of the HAGAR array is 100 m, this is a reasonable assumption. In such a scenario, the arrival direction of shower front, can, in principle, be reconstructed using just two telescopes, $A$ and $B$. Assuming the distance between the two telescopes separated by a distance $D$, a shower front inclined at an angle $\theta$ (see Fig. 2.11) will have a relative arrival time difference of $\delta t$, such that

$$\sin \theta = \frac{c \delta t}{D}$$

(33)

However, in real life, we have an array of seven telescopes, and the arrival time information from all seven telescopes need to be used to calculate the direction cosines of the incident shower. If $l$, $m$ and $n$ are the direction cosines, and $t_i$ is the arrival time at the $i^{th}$ telescope, then we can write,

$$lx_i + my_i + nz_i + c(t_i - t_0) = 0$$

(34)

where $x_i$, $y_i$ and $z_i$ are the position co-ordinates of the $i^{th}$ telescope, and $t_0$ the time at which the shower front passes through the origin of the coordinate system. Values of $l$, $m$ and $n$ and $t_0$ can thus be obtained in terms of the observed arrival time $t_i^{measured}$ at the $i^{th}$ telescope, by minimising the $\chi^2$,

$$\chi^2 = \sum_{i=1}^{7} w_i (lx_i + my_i + nz_i + c(t_i^{measured} - t_0))^2$$

(35)

with respect to $l$, $m$, $n$ and $t_0$. Here, timing measurement of $i^{th}$ telescope is weighted by its uncertainty ($\sigma$) in the relative timing measurement, $w_i = \frac{1}{\sigma^2}$. It should be noted that an additional constrain is imposed from the condition $l^2 + m^2 + n^2 = 1$.

The arrival direction of the shower front is obtained in terms of the direction cosines thus estimated. The difference between the arrival direction of the shower front and the telescope pointing direction, termed as the spaced angle, is then computed. The space angle $\psi$ is computed in terms of the direction cosines as,

$$\psi = \cos^{-1}(l_1l_2 + m_1m_2 + n_1n_2)$$

(36)
2.5. Data Reduction and Analysis

Figure 2.11.: Two telescopes A and B are separated by a distance D. The shower arrives at an angle $\theta$ w.r.t zenith. The shower front arrives first at B, and at A after a time delay of $\delta t$.

where $(l_1, m_1, n_1)$ and $(l_2, m_2, n_2)$ represent the direction cosines of the shower axis and telescope pointing axis respectively.

2.5.2 Data Selection

Stringent data selection cuts have to be imposed at various stages of the analysis to ensure good quality data. Firstly, the trigger rate stability is checked as a function of the recording time. Periods having fluctuating trigger rates, generally occurring due to instrumental effects or poor sky conditions, are removed from the analysis. Next, for each triggered event, the normal to the fitted shower plane is compared to the source direction. If the residue (observed - expected) delay is greater than 3 ns then same event is reprocessed after rejection of the telescope data which has maximum deviation and this iteration continues till it reaches a pre-decided limit. In this process, almost 5-10% of the events get rejected, which probably originated due to spurious triggers. Source and background runs taken on the same night are then paired with overlapping hour angles. In order to ensure that there is no significant differences in the trigger rates between an ON and an OFF run, the difference between the mean trigger rates of an ON and an OFF run is restricted to be less than 2 Hz. Also, large off axis events are rejected by imposing cuts on zenith and azimuth angle distributions.
2.5.3 Signal Extraction

Gamma-ray events are separated from the isotropic background of cosmic rays by comparing the space angle distributions of ON-source runs and OFF-source runs. By choice of OFF region, OFF-source runs are devoid of $\gamma$-ray events, and contain only cosmic ray events, whereas, ON-source runs contain both $\gamma$ and cosmic ray events. However, a simple subtraction of the number of OFF-source events ($N_{OFF}$) from the number of ON-source events ($N_{ON}$) cannot be used to obtain the source signal. Since the ON-source runs and OFF-source runs are taken at two different times in the same night, the sky conditions may be different for two different runs and we need to normalize $N_{OFF}$ w.r.t. $N_{ON}$.

The space angle distributions are compared for ON and OFF source events. $\gamma$-ray events from the source are expected to come only within the narrow Cherenkov cone large space angle events should be only cosmic-ray triggered events, in both ON and OFF runs. Figure 2.12 shows the space angle distributions for a typical ON and OFF source runs. The region beyond the FWHM of the ON-source distribution is taken as the lower normalisation region (LNR), and the common end point as upper normalization region (UNR). Number of events in the normalization region are typically around 15-20%, depending upon the sky brightness and operating conditions. The normalisation constant, $C$, is computed as

$$C = \frac{\sum_{LNR}^{UNR} N_{ON}}{\sum_{LNR}^{UNR} N_{OFF}}$$ (37)

Excess/deficit signal ($S$) is then calculated from events which lie between the telescope axis (0-degree) and LNR, given by

$$S = \sum_{0}^{LNR} (N_{ON} - C N_{OFF})$$ (38)

The normalization constant is estimated for each selected ON-OFF pair and then the excess/deficit signal is calculated. The LNR and UNR cuts have been optimised to get null signal for analysis of dark runs. Only run pairs having $C$ within the range 0.8 – 1.2 are retained during analysis.

2.6 Results

Routine observations of AGNs, pulsars and supernova remnants are being carried out with HAGAR. While for the first two years observations could not be carried out for about three months during winter due to lack of manpower at site, observations are being taken throughout the year since 2010. Almost 38% of the observation time has been spent on galactic sources, with majority of the time spent on the Crab Nebula for calibration purposes, and also to search for pulsations. VHE photons of energies
2.6. Results

Figure 2.12.: Typical space angle distribution for ON (in red) and OFF (in green) source regions (for a Mkn421 run pair) showing the lower normalization region (LNR), upper normalization region (UNR).

<table>
<thead>
<tr>
<th>Source Name</th>
<th>ON</th>
<th>OFF</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mkn 421</td>
<td>315.4</td>
<td>347.9</td>
</tr>
<tr>
<td>Mkn 501</td>
<td>215.8</td>
<td>335.6</td>
</tr>
<tr>
<td>1ES 2344+514</td>
<td>175.8</td>
<td>201.1</td>
</tr>
<tr>
<td>BL Lac</td>
<td>118.3</td>
<td>123.3</td>
</tr>
<tr>
<td>1ES 1218+304</td>
<td>95.3</td>
<td>105.8</td>
</tr>
<tr>
<td>1ES 1011+496</td>
<td>38.6</td>
<td>35.7</td>
</tr>
<tr>
<td>H 1426+428</td>
<td>28.7</td>
<td>29.3</td>
</tr>
<tr>
<td>3C 454.3</td>
<td>16.1</td>
<td>16.3</td>
</tr>
<tr>
<td>1ES 1959+650</td>
<td>29.2</td>
<td>32.2</td>
</tr>
</tbody>
</table>

Table 2.1.: Observations of extragalactic sources with HAGAR

greater than 234 GeV from the Crab nebula have been detected by the HAGAR array at a statistical significance of $17.6\sigma$ using data from 103.8 hours spanning six years (2008-2014) of observation [Chitnis et al. 2015]. Preliminary results indicate pulsed emission from the Crab has been detected at above $5\sigma$ significance. The Geminga Pulsar, widely acknowledged to be a candidate TeV pulsar [Neshpor et al. 2001; Ahnen et al., 2016a], has been observed for over 200 hrs without any significant signal.

An important science objective for HAGAR is the regular monitoring of bright TeV blazars like Mkn 421 and Mkn 501. AGNs have been observed with HAGAR for over 2260 hrs, comprising various sources (Table 2.1). This has lead to significant detections of Mkn 421, both during flare [Shukla et al. 2012] and low activity [Sinha et al. 2016b] states. More details of Mkn 421 observations are discussed in Chapter 4. Mkn 501 also has been detected at $5.1\sigma$ [Shukla et al. 2015], and $3\sigma$ flux upper limits have been computed for various blazars like 1ES 1011+496 [Sinha et al. 2016a], 1ES1426+428, 1ES1218+304 and 3C454.3 [Hazarika et al. 2015].
Multiwavelength Instrumentation and Data Analysis

The aim of this thesis is to perform a multiwavelength study of TeV blazars to understand their broadband spectral and temporal properties, with emphasis on the high energy emission. To this effect, we have used data from a variety of space and ground based instruments, mostly available under the “Fermi Multiwavelength Observing Support Program”. A brief and compact description of the data, instruments and their analysis procedures is given in the following sections, starting from the $\gamma$-rays and going down to radio wavelengths.

3.1 Fermi-LAT

The Fermi Gamma-ray Space Telescope (Fermi) spacecraft, formerly known as the Gamma-ray Large Area Space Telescope (GLAST) was launched on June 11, 2008 into a low earth orbit by NASA. The Fermi spacecraft carries two scientific payloads, the Large Area Telescope (LAT) and the Gamma-ray Burst Monitor (GBM). While the LAT is the principal instrument on board, the GBM, operating in the energy range of 8 keV to 40 MeV, complements the LAT in its observations of $\gamma$-ray transients. Details of the GBM can be found in Meegan et al. (2009).

The LAT is a pair production telescope operating in the energy range of 20 MeV to over 300 GeV. It has a 4 x 4 modular design, each module made of a precision tracker and calorimeter. The trackers comprise 18 layers of paired Silicon Strip Detector planes with interleaved tungsten foils. These trackers measure the electron-positron tracks resulting from interactions, allowing the reconstruction of the energy and direction of the primary radiation.
3. Multiwavelength Instrumentation and Data Analysis

Figure 3.1.: Schematic diagram of the Large Area Telescope, taken from Atwood et al. (2009).

![Large Area Telescope Schematic Diagram](image1)

Figure 3.2.: Counts map in the celestial coordinate system from a 10° region centered around a typical blazar (Mkn421) integrated over the entire LAT energy band.

![Counts Map](image2)

from pair production of the incoming $\gamma$-ray, and thus reconstruct the source direction. The calorimeters are made of Thallium-doped Cesium Iodide crystals, and absorb the energy of the electromagnetic showers. The calorimeters also provide a reasonable 3D imaging resolution. The entire LAT is covered by an anti-coincidence shield, used to eliminate the strong charged cosmic ray background. A schematic of the LAT detector is drawn in Figure 3.1 and further details can be found in Atwood et al. (2009).

The LAT has a large FoV ($\sim 2.4$ sr), and observes 20% of the sky at any given time. It operates mostly in the survey mode, covering the entire sky every three hours. It has an energy resolution of $\sim 10\%$, angular resolution of $\sim 0.6\%$, and a timing resolution of $< 10\mu s$ (all values quoted at 1 GeV). LAT data and associated analysis softwares are freely available to the scientific community from the Fermi Science Support Center.

http://fermi.gsfc.nasa.gov/ssc/

2
The LAT data used in this thesis are extracted from a region of 20° centered on the source. The standard data analysis procedure as mentioned in the Fermi-LAT documentation is used. Events belonging to the energy range 0.2−300 GeV and SOURCE class are used. Good time intervals are calculated from the spacecraft file by imposing a filter “DATA_QUAL>0”, && “LAT_CONFIG==1”. Only events with less than 105° zenith angle are selected to avoid contamination from the Earth limb γ-rays. The galactic diffuse emission component gll_iem_v05_rev1.fits and an isotropic component iso_source_v05_rev1.txt are used as the background models. The unbinned likelihood method included in the pylkelihood library of Science Tools (v9r33p0) and the post-launch instrument response functions P7REP_SOURCE_V15 are used for the analysis. All the sources lying within 10° region of interest (ROI) centered at the source and defined in the third Fermi-LAT catalog, are included in the model xml file. All the parameters except the scaling factor of the sources within the ROI are allowed to vary during the likelihood fitting. For sources between 10° to 20° from the centre, all parameters were kept frozen at the default values. Integrated Fermi-LAT counts map centered on Mkn421 in shown in Figure 3.2.

### 3.2 NuSTAR

Launched in June 2012 under the NASA Small Explorer satellite program (SMEX-11), the Nuclear Spectroscopic Telescope Array (NuSTAR) features the first space-based focusing hard X-ray telescope. NuSTAR provides sub-arcminute imaging with excellent spectral resolution in the 3 - 79 keV band over a 12-arcminute FoV, at a temporal resolution of 2 µs. It consists of two co-aligned, depth-graded multilayer coated Wolter I conical approximation X-ray optics which focus onto two independent solid-state focal plane detectors. Each detector unit is comprised of four Cadmium-Zinc-Telluride (CdZnTe, or CZT) detectors, and is surrounded by a CsI anti-coincidence shield to veto off-axis events.

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3 http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/
3. Multiwavelength Instrumentation and Data Analysis

![NuSTAR Image of Mkn421](image)

**Figure 3.4.**: NuSTAR image of Mkn421 from a single observation showing the source (12 pixels, in black) and background (40 pixels, in white) extraction regions.

A schematic diagram of the instrument is shown in Figure 3.3 and detailed description of the electronics can be found in [Harrison et al.] (2013).

*NuSTAR* data available at the HEASARC data portal[^1] are downloaded and processed with the NuSTARDAS software package v.1.4.1 available within HEASOFT package (6.16). The latest CALDB (v.20140414) is used. After running nupipeline v.0.4.3 on each observation, nuproducts v.0.2.8 is used to obtain the light curves and spectra. Circular regions of 12 pixels centered on the source and of 40 pixels centered on a source free region are used as source and background region respectively (Figure 3.4). Spectra from the two detectors A and B are combined using addascaspec. Data from various observations are added using addascaspec and then grouped (using the tool grppha) to ensure a minimum of 30 counts in each bin. Spectra are analyzed in XSPEC simultaneous with *Swift*-XRT spectra.

### 3.3 *Swift*

The *Swift* satellite, launched on 20 November 2004 by NASA, is a multiwavelength observatory with simultaneous observational capabilities from optical-UV to hard X-ray energies. While mainly designed to study gamma ray bursts (GRB), the *Swift* has also made huge advances in the field of blazars ([Ghisellini], 2015). As shown in the schematic diagram in Figure 3.5 it has three co-aligned instruments on board; the Burst Alert Telescope (BAT), the X-ray Telescope (XRT), and the Ultraviolet/Optical Telescope (UVOT).

3.3. **Swift**

3.3.1 **Swift-BAT**

The BAT (Barthelmy et al., 2005) is a coded aperture mask imaging telescope with a large FoV of 1.4 sr, designed primarily to monitor a large fraction of the sky for GRB occurrences. It consists of a CdZnTe (CZT) detector occupying an area of 5240 cm$^2$. It operates in photon counting mode in the energy regime of 15 - 150 keV, and has a timing resolution of 100 µs. It operates in two modes: burst mode which produces burst position, and survey mode which conducts all-sky hard X-ray survey and monitors for hard X-ray transients. Daily binned sources counts from the survey mode in the 15 – 50 keV range are made publicly available on the Swift-BAT webpage.

3.3.2 **Swift-XRT**

The XRT is a focusing X-ray telescope with a 110 cm$^2$ effective area, 23.6 x 23.6 arcmin FoV and 18 arcsec resolution, operating in the energy regime 0.2 - 10 keV. It uses a grazing incidence Wolter I telescope to focus X-rays onto a Charge-Coupled Device (CCD). The FWHM energy resolution of the CCD decreases from $\sim$190 eV at 10 keV to $\sim$50 eV at 0.1 keV. The complete mirror module for the XRT consists of the X-ray mirrors, thermal baffle, a mirror collar, and an electron deflector. The XRT accommodates a wide dynamic range of more than seven orders of magnitude in flux to measure the source flux, spectrum and lightcurve by automatically switching between the various readout modes:

1. **Imaging mode (IM):** The IM mode is used to obtain the first X-ray position of a new GRB, with an exposure time of 0.1 or 2.5 seconds. It produces an integrated charge image without any X-ray event recognition.

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Figure 3.5.: Schematic diagram of the Swift telescope.
3. Multiwavelength Instrumentation and Data Analysis

Figure 3.6.: Windowed Timing (WT) and Photon Counting (PC) images of the same blazar BL Lac from different observations.

2. **Photo-Diode mode (PD):** The PD mode used to provide a high speed light curve with time resolution of 0.14 ms for fluxes below 60 Crabs, without any spatial resolution. This mode has been disabled since May 2005.

3. **Photon-Counting mode (PC):** The PC mode retains the full imaging and spectroscopic resolution of the instrument, but with a time resolution of 2.5 seconds. This is used for low count rates (below 10 mCrab).

4. **Windowed Timing mode (WT):** The WT is a high gain mode which produces a full spectral resolution, high timing resolution of 1.7 ms, but a 1-dim image. This is used for high count rates (over 10 mCrab).

Examples of WT (of Mkn421) and PC (of BL Lac) images are shown in Figure 3.6. Further details about the XRT instrumentation can be found in Burrows et al. (2005).

The XRT data used in the present work are downloaded from the HEASARC data portal and processed with the XRTDAS software package (v.3.0.0) available within HEASOFT package (6.16). Latest calibration files from the Swift CALDB are used. Observations are available both in WT and PC modes, and full grade selections (0-2 for WT; 0-12 for PC) are used. Event files are cleaned and calibrated using standard procedures (xrtpipeline), and xrtproducts is used to obtain the light curves and spectra. Circular regions of 20 pixels centred on the source and of 40 pixels from a source-free region are used as source and background regions respectively.

Many of the observations are significantly affected by pileup (count rate > 100 cts/s(WT); > 0.5 cts/s(PC) ) (Romano et al., 2006), and is corrected for by following the procedure outlined in the Swift analysis threads. For the PC mode, the XRT Point Spread Function is modelled by a King function

$$PSF(r) = [1 + (r/r_c)^2]^{-\beta}$$  \hspace{1cm} (39)

with $r_c = 5.8$ and $\beta = 1.55$ (Moretti et al., 2005). Depending on the source brightness, annular regions are chosen to exclude pixels deviating from the King’s function. For eg, [http://www.swift.ac.uk/analysis/xrt/pileup.php](http://www.swift.ac.uk/analysis/xrt/pileup.php)
3.3. Swift

Figure 3.7: Pileup in XRT: PC Mode observations for 1ES1011+496 (id 00035012032) is significantly affected by pileup. The PSF is fitted by a Kings function, where the deviation from the model is seen for regions smaller than 16 arc seconds, which are thus excluded from the source region.

Figure 3.8: Swift-XRT image of 1ES1011+496 showing the annular region chosen for source extraction, as calculated from Figure 3.7.

for observation id 00035012032 (see Figure 3.7), an annular region of 16-25 arc seconds (Figure 3.8) centered on the source position is taken as the source region. For WT mode, an annular region with an inner radius of 2 pixels and an outer radius of 20 pixels is taken. The tool xrtmkarf is then executed with PSF correction set to “yes” to create an ARF corrected for the loss of counts due to the exclusion of this central region.

The light curves are finally corrected for telescope vignetting and PSF losses with the tool xrtlccorr. The spectra from different pointings are combined using the tool addspec and grouped using the tool grppha to ensure a minimum of 30 counts. Spectral analysis is performed using the X-ray spectral fitting package, XSPEC. To correct for the line of sight absorption of soft X-rays due to the interstellar gas, the neutral hydrogen column density ($N_H$) is fixed to its Galactic value [Kalberla et al., 2005].

3.3.3 Swift-UVOT

The UVOT is a diffraction-limited, 30 cm (12” aperture) modified Ritchey-Chretien reflector operating in the range of 160 - 800 nm with a 17 x 17 arcmin FoV. A filter wheel carries seven broadband filters: three in the optical range (V, B and U) and three in the UV (UVW1, UVM2 and UVW2) covering the whole wavelength range (Table 3.1). In
3. Multiwavelength Instrumentation and Data Analysis

<table>
<thead>
<tr>
<th>Filter</th>
<th>Central Wavelength (nm)</th>
<th>FWHM (nm)</th>
</tr>
</thead>
<tbody>
<tr>
<td>V</td>
<td>546.8</td>
<td>76.9</td>
</tr>
<tr>
<td>B</td>
<td>439.2</td>
<td>97.5</td>
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<tr>
<td>U</td>
<td>346.5</td>
<td>78.5</td>
</tr>
<tr>
<td>UVW1</td>
<td>260.0</td>
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<td>UVM2</td>
<td>224.6</td>
<td>49.8</td>
</tr>
<tr>
<td>UVW2</td>
<td>192.8</td>
<td>65.7</td>
</tr>
</tbody>
</table>

Table 3.1.: Swift-UVOT filter characteristics taken from Poole et al. (2008). The central wavelength is the midpoint between the wavelengths at half maximum.

![Figure 3.9.](image)

Figure 3.9.: Swift-UVOT B-band field of BL Lac showing the source region (in white) and annular background region (in green) chosen for flux extraction.

In addition there are two grisms, a magnifier and a blocked filter in the filter wheel. It uses a fast readout, micro-channel-plate intensified, photon-counting CCD detector to achieve a temporal resolution of 11 ms. Details about the UVOT instrumentation and filter calibration can be found in Roming et al. (2005) and Breeveld et al. (2010).

Individual exposures from different observations are summed using `uvotimsum`, and `uvotsource` tool is used to extract the fluxes from the images using aperture photometry. A circle of radius 5" centered on the source is chosen as the source region, and an annular region of inner radius of 27" and outer radius of 35" is chosen as the background (e.g. Figure 3.9). The observed magnitudes are corrected for Galactic extinction using the dust maps of Schlegel et al. (1998) and converted to flux units using the zero-point magnitudes and conversion factors of Breeveld et al. (2011).

3.4 MAXI

The Monitor of All-sky X-ray Image (MAXI) on board the International Space Station (ISS; Matsuoka et al. (2009)) is an X-ray slit camera conducting a full sky survey every 96 mins. Its operated by the Japan Aerospace Exploration Agency (JAXA) and has a detection sensitivity of \( \sim 20 \) mCrab (at a 5-\( \sigma \) level) per orbit. Daily binned source counts in 4 energy bands between 2 – 20 keV are publicly accessible from their website.

7 [http://maxi.riken.jp/](http://maxi.riken.jp/)
3.5 CCD-SPOL

Optical photometric, spectrophotometric, and spectropolarimetric observations of Fermi-LAT monitored sources are regularly carried out at the Steward Observatory at the University of Arizona. Flux calibrated spectra between 400 – 760 nm, photometric V and R band magnitudes, and linear polarization measurements carried out using the SPOL CCD Imaging/Spectropolarimeter are made publicly available on the SPOL website\textsuperscript{8}. Information about the sample selection, observations and data reduction are detailed in Smith et al. (2009). The project is funded via Fermi Guest Investigator Program grants NNX08AW56G, NNX09AU10G, and NNX12AO93G.

The observed magnitudes are corrected for Galactic extinction using the dust maps of Schlegel et al. (1998) and converted to flux units using the zero-point magnitudes and conversion factors of Bessell et al. (1998).

3.6 OVRO

One of the largest university operated radio telescopes in the world, the Owens Valley Radio Telescope (OVRO) is located at an altitude of 1222m above sea level near Bishop, California. As a part of the “Fermi Multiwavelength Support Program”, the 40m dish at OVRO has been routinely monitoring over 1800 blazars at 15 GHz, and the observed fluxes are made publicly available on their website\textsuperscript{9}. Details of the telescope and data reduction method can be found in Richards et al. (2011). The project is funded in part by NASA under awards NNX08AW31G and NNX11A043G, and by the NSF under awards AST-0808050 and AST-1109911.

\textsuperscript{8} http://james.as.arizona.edu/$\sim$psmith/Fermi/
\textsuperscript{9} http://www.astro.caltech.edu/ovrobazars/
The nearby and the most well studied blazar, Markarian 421 has been the subject of several multiwavelength campaigns both during flare and quiescent states. In 1992, the Whipple collaboration reported the discovery of Mkn 421 (RA: 11 04’ 27.3”; Dec: 38° 12’ 32”; z = 0.031) (Punch et al. 1992), making this the first extragalactic source detected at TeV energies. It is one of the brightest BL Lac objects seen in the UV/X-ray/γ-ray bands, thus making it an ideal candidate for both longterm statistical studies and short term high cadence observations during its numerous flares. In this chapter we report on the long term study of Mkn 421 carried out with the HAGAR telescope array during 2009-2015 (Sinha et al. 2016b), while in the next chapter we describe the largest X-ray flare seen from this source in the past decade (Sinha et al. 2015).

4.1 Brief review of past results

Apart from being the first detected TeV blazar, Mkn 421 has a rich and interesting history of paving the way forward in many different wavebands. Mkn 421 was identified with the radio galaxy B2 1101+38 in the year 1975 by Ulrich et al. (1975). It was shown to have a featureless, non-thermal, but highly polarised optical spectrum, leading to a conclusion that Mrk 421 is a normal elliptical galaxy with a central, compact, non-thermal nucleus, quite similar to the source BL Lacertae (BL Lac). Soon, Ricketts et al. (1976), discovered a highly variable soft X-ray component from this source using data from the Aerial V satellite. This was the first time a BL Lac object was associated with an X-ray source. It is also the first BL Lac object to be detected by the Energetic Gamma Ray Experiment
4. Mkn 421: Longterm spectral and temporal study

Figure 4.1.: Historical VHE (E > 1 TeV) light curve (taken from the γ-ray light curve archive at DESY [www-zeuthen.desy.de/multi-messenger/GammaRayData] of Mrk 421 since its first detection in 1992 (Punch et al., 1992), as measured by different VHE γ-ray instruments. The red solid line indicates the flux of the Crab Nebula.

Telescope (EGRET; [Lin et al., 1992]) at energies above 100 MeV. It has been a prominent source in all the Fermi Catalogs (Abdo et al., 2010b; Nolan et al., 2012; Acero et al., 2015), and is generally detected at a more than 5σ level by the Fermi-LAT each week. It shows a typical double hump SED structure, and according to the blazar sequence classification (Urry & Padovani, 1995), is a HBL, with it synchrotron spectrum peaking in the X-ray regime. Highly variable across all time scales at all energy bands, it has been the subject of various co-ordinated campaigns during the past decade. Tluczykont et al. (2010) compiled and studied the long-term VHE light curve (Figure 4.1) from 1992-2009 and found significant correlation (~68%) with X-ray data from RXTE-ASM. Liu et al. (1997) constructed the historical light curve of this object from 1900 to 1991 in the optical B band, the analysis of which revealed a possible time period of 23.1 ± 1.1 yrs in the flux variations. After the launch of the Fermi satellite, Abdo et al. (2011a) studied the quiescent state emission from this source with the best-sampled SED to date. Recently, Bartoli et al. (2015) have reported on extensive multiwavelength observations of this source from 2008-2013. They found the VHE flux to be strongly correlated with the X-ray flux, but partially correlated with the GeV flux. Such moderate X-ray-GeV correlation is typical of most HBLs (Li et al., 2013).

Radio observations of this source show an unresolved core surrounded by a diffuse halo. Blasi et al. (2013) imaged Mkn 421 at the highest spatial resolution till date with the VBLA at 43 GHz in 2011. A bright nucleus and a one-sided jet extending towards the north-west for a few parsecs was clearly noted (Figure 4.2). Significant Intra-Day Variability (IDV) have been seen in the near-IR band (Gupta et al., 2004). Optical images show the presence of the companion galaxy, Mrk 421-5, at around an observed distance of 13” towards the north-west (Figure 4.3). Probable correlation between the > 1 PeV IceCube neutrinos and photon fluxes have also been claimed (Petropoulou et al., 2016), which may be a strong indication for hadronic models.
4.1. Brief review of past results

Figure 4.2.: VLBA image of Mkn 421 at 43 GHz corresponding to April 2013 observation of the Boston University monitoring program (Blasi et al. 2013)

Figure 4.3.: Optical R-band image (size 78'' by 78'') of Mkn 421 as seen by the Nordic Optical Telescope (Nilsson et al. 1999). The companion galaxy Mrk 421-5 can be clearly seen in the north-west.
4. Mkn 421: Longterm spectral and temporal study

4.2 DATA ANALYSIS

During the period from 2009-2015, Mkn421 has been simultaneously observed by many instruments across the entire electromagnetic spectrum. Alongside data from HAGAR, we analyse data from the Fermi-LAT, the NuSTAR and the Swift X-ray and UV telescopes. In addition, we include X-ray observations by the MAXI telescope, optical observations in the V and R band by SPOL CCD Imaging/Spectropolarimeter at Steward Observatory, and radio data at 15 GHz from the OVRO for the present study. The analysis procedures of these observations are described below.

4.2.1 HAGAR

Mkn 421 has been regularly monitored by HAGAR since its setup in 2008. Analysis of all data up to 2015, spanning 21 observation seasons with data taken between January-April each year, yields 101 hrs of clean data. Monthly averaged $T_0$s, computed from $10^\circ$ N runs, are used for reconstruction of arrival direction of the shower front and the source counts computed according to the procedure outlined in Chapter 2. To minimize systematic errors, we only retain events with signals in at least five telescopes, for which the energy threshold is estimated to be $\sim 250\text{GeV}$. Mkn 421 is detected at a mean level of 80% (3.1 cts/s), at a significance of $9.7\sigma$. The maximum flux, of $\sim 7$ Crab units, was detected during a huge TeV flare in Feb 2010. A detailed multiwavelength study of this flare has been carried out in Shukla et al. (2012). The HAGAR lightcurve is shown in Figure 4.4, and excess counts over background in each HAGAR season listed in Table 4.1.

To study the spectral variations, multiwavelength SEDs are constructed contemporaneously with each HAGAR season.

![Figure 4.4: HAGAR longterm lightcurve for Mkn 421. The dotted line denotes the Crab Unit.](image-url)
4.2. Data Analysis

<table>
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<tr>
<th>State</th>
<th>Start date</th>
<th>ISO MJD</th>
<th>End date</th>
<th>ISO MJD</th>
<th>Total Duration mins</th>
<th>Excess counts</th>
<th>Count rate</th>
<th>Significance</th>
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<td>-0.16 ± 1.45</td>
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</tbody>
</table>

Table 4.1.: The 21 states contemporaneous with HAGAR time periods for which SED has been constructed. The Crab flux corresponds to 3.9 counts/min.

4.2.2 Other multiwavelength data

Fermi-LAT data from 2009-2015 are extracted and analysed according to the procedure described in Chapter 3.1. A simple power law spectral model, with index and normalisation as the free parameters, is used to model the source. The light curve is binned over ten days, and spectra within 0.2-300 GeV are extracted in six logarithmically binned energy bins for the 21 different states contemporaneous with the HAGAR observation seasons. The spectral parameters are listed in Table 4.2. Fluxes and hardness ratios were computed with 10 day binnings in two energy bands, 0.2-2 GeV and 2-300 GeV.

X-ray spectral analysis is carried out with data from NuSTAR and Swift-XRT, while publicly available daily binned source counts in the 15 – 50 keV range are taken from the Swift-BAT, and in the 2 – 20 keV range from MAXI. There are 594 Swift pointings between January 2009 and June 2015. The XRT data are processed using the mentioned in Chapter 3.3. Pileup correction is carried out for the observations during the flare in April 2013. Since the X-ray data lies at the peak of the synchrotron spectrum, significant departure from a simple power law is needed to model the X-ray spectrum. Following Sinha et al. (2015), we fit the observed spectrum with a log parabola given by

\[ \frac{dN}{dE} = K \frac{E}{E_b}^{-\alpha} e^{-\beta \log(E/E_b)}, \]  

where \( \alpha \) gives the spectral index at \( E_b \). The point of maximum curvature, \( E_p \) is given by

\[ E_p = E_b 10^{(2-\alpha)/2\beta}. \]
The multiwavelength light curve of Mkn 421 from all available instruments during 2009-2015 is given in Figure 4.5. The integration time for each panel is chosen according to the instrument sensitivities. HAGAR points are averaged over each observation season (~ 10 days), likewise the Fermi-LAT, Swift-BAT, and MAXI points are also averaged over 10 days. Each Swift-XRT and Swift-UVOT point corresponds to one pointing (~ hours) and (~ minutes), respectively, and the CCD-SPOL and OVRO points have integration times of a
few seconds. As can be clearly seen, the source is variable across all wavelengths and many flares can be identified. The most dramatic flare in the GeV band occurred during in 2012 (MJD $\sim 56140 - 56180$; calendar dates 2012-08-01 to 2012-09-10), which is reflected in the radio band after a gap of one and half months (MJD $\sim 56193$, Calendar date 2012-09-23). In contrast, the largest X-ray/optical flare happened during April 2013, which has been studied in detail by various authors ([Sinha et al., 2015], [Pian et al., 2014], [Paliya et al., 2015a]). In this section, we study the flux correlations between the various frequencies and quantify the nature of the variability.

### 4.3.1 Variability and correlations

We quantify the variability using the fractional variability amplitude parameter $F_{var}$ ([Vaughan et al., 2003], [Chitnis et al., 2009]). It is calculated as

$$F_{var} = \sqrt{\frac{S^2 - \sigma_{err}^2}{\bar{x}^2}},$$

(42)

where $\sigma_{err}^2$ is the mean square error, $\bar{x}$ the unweighted sample mean, and $S^2$ the sample variance. The error on $F_{var}$ is given as

$$\sigma_{F_{var}} = \sqrt{\left(\sqrt{\frac{1}{2N}} \frac{\sigma_{err}^2}{\bar{x}^2 F_{var}}\right)^2 + \left(\sqrt{\frac{\sigma_{err}^2}{N}} \frac{1}{\bar{x}}\right)^2}.$$

(43)

Here, $N$ is the number of points.

The $F_{var}$ values derived from the light curves in Figure 4.5 are plotted in Figure 4.6. To investigate the dependence of variability on the range of timescales, $F_{var}$ was computed with 1-day, 10-day, 30-day and 3-month binning (Table 4.3). Owing to sensitivity issues, $F_{var}$ at daily binning cannot be computed for $\gamma$-rays, i.e., with the Fermi-LAT and HAGAR. The results remained roughly similar with differences showing up mainly in the X-ray bands. For the optical/GeV bands, the difference is $\sim 5\%$. This shows that the low variability seen in the optical/GeV bands is not an artifact of the binning, but is intrinsic to the source. The variability is maximum in the X-ray/VHE bands, $\sim 80\%$/$\sim 100\%$, and goes down with frequency. The GeV and UV data show a similar variability index of $\sim 40\%$, which suggests a similar origin for the X-ray and VHE, and for the UV and GeV spectrum. Similar results have been reported in [Aleksić et al., 2014a].

We compute the hardness ratios from Swift-XRT data, which are defined as the ratio of the flux in the $2 - 10$ keV band to the flux in $0.3 - 2$ keV band. As can be seen in Figure 4.7, while there is clear trend of spectral hardening with flux seen in the X-ray band ($\rho = 0.83$, prob $= 2.1 \times 10^{-16}$), no such evidence is seen in the $\gamma$-ray band ($\rho = 0.06$ prob$=0.33$), again suggesting different origin for the X-ray and GeV data.

To study the lags between the various unevenly sampled energy bands, we use the z-transformed discrete cross correlation function, freely available as a FORTRAN 90
Figure 4.5.: Multiwavelength light curve of Mkn421 from 2009-2015 showing in panel 1: radio fluxes at 15GHz from the OVRO; panel 2: optical V-band flux from the CCD-SPOL; panel 3: degree and angle of the optical polarization using data from CCD-SPOL; and panel 4: UV flux in the Swift-UVOT UW2 band. Fluxes in the UW1 and WM2 bands follow a similar trend, and thus only one band has been plotted to avoid cluttering. Panel 5: Swift-XRT count rates; panel 6: MAXI count rate (averaged over 10 days); panel 7: Swift-BAT count rates (10 days averaged); panel 8: Fermi-LAT flux in $10^{-7} \text{ph/cm}^2/\text{sec}$ averaged over ten days; and panel 9: HAGAR counts/min, averaged over each observation season. The black dotted line denotes the Crab count rate.
4.3. Multiwavelength temporal study

![Graph showing fractional variability $F_{\text{var}}$ as a function of frequency.](image)

**Figure 4.6.** Fractional variability $F_{\text{var}}$ as a function of frequency.

<table>
<thead>
<tr>
<th>Waveband</th>
<th>1 day</th>
<th>10 days</th>
<th>1 month</th>
<th>3 months</th>
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<tbody>
<tr>
<td>OVRO (15GHz)</td>
<td>0.22 ± 0.01</td>
<td>0.20 ± 0.01</td>
<td>0.19 ± 0.01</td>
<td>0.19 ± 0.01</td>
</tr>
<tr>
<td>Optical R</td>
<td>0.32 ± 0.01</td>
<td>0.31 ± 0.01</td>
<td>0.31 ± 0.01</td>
<td>0.29 ± 0.02</td>
</tr>
<tr>
<td>Optical V</td>
<td>0.37 ± 0.01</td>
<td>0.36 ± 0.01</td>
<td>0.37 ± 0.01</td>
<td>0.35 ± 0.02</td>
</tr>
<tr>
<td>UV UW1</td>
<td>0.44 ± 0.01</td>
<td>0.39 ± 0.02</td>
<td>0.37 ± 0.01</td>
<td>0.37 ± 0.03</td>
</tr>
<tr>
<td>UV UM2</td>
<td>0.47 ± 0.01</td>
<td>0.42 ± 0.02</td>
<td>0.41 ± 0.02</td>
<td>0.40 ± 0.03</td>
</tr>
<tr>
<td>UV UW2</td>
<td>0.48 ± 0.01</td>
<td>0.43 ± 0.03</td>
<td>0.40 ± 0.03</td>
<td>0.41 ± 0.03</td>
</tr>
<tr>
<td>Swift-XRT (0.2-10keV)</td>
<td>0.71 ± 0.01</td>
<td>0.61 ± 0.04</td>
<td>0.57 ± 0.04</td>
<td>0.54 ± 0.03</td>
</tr>
<tr>
<td>MAXI (2-20keV)</td>
<td>0.81 ± 0.01</td>
<td>0.79 ± 0.10</td>
<td>0.74 ± 0.08</td>
<td>0.67 ± 0.02</td>
</tr>
<tr>
<td>Swift-BAT (15-150keV)</td>
<td>1.08 ± 0.01</td>
<td>0.95 ± 0.16</td>
<td>0.90 ± 0.10</td>
<td>0.81 ± 0.04</td>
</tr>
<tr>
<td>Fermi-LAT (0.2-2GeV)</td>
<td>—</td>
<td>0.44 ± 0.08</td>
<td>0.41 ± 0.06</td>
<td>0.38 ± 0.05</td>
</tr>
<tr>
<td>Fermi-LAT (2-300GeV)</td>
<td>—</td>
<td>0.48 ± 0.14</td>
<td>0.42 ± 0.08</td>
<td>0.38 ± 0.07</td>
</tr>
<tr>
<td>HAGAR (&gt; 200GeV)</td>
<td>—</td>
<td>1.07 ± 0.24</td>
<td>1.07 ± 0.24</td>
<td>—</td>
</tr>
</tbody>
</table>

**Table 4.3.** Fractional variability ($F_{\text{var}}$) in different wavebands with different time binnings.

![Graph showing hardness ratio in the X-ray (Swift-XRT) and GeV (Fermi-LAT) bands.](image)

**Figure 4.7.** Hardness ratio in the X-ray (Swift-XRT) and GeV (Fermi-LAT) bands. While the trend of spectral hardening with flux is clear in the X-ray band, no such trend is seen in the GeV band.
routine with the details of the method described in Alexander (1997). A minimum of 11 points are taken in each bin and points with zero lag are omitted. Since many of the HAGAR seasonal points correspond to upper limits, we avoid the use of HAGAR data in detailed temporal studies. The computed z-DCFs are plotted in Figure 4.8. A lag of $73 \pm 20$ days is observed between the optical V band and the ultraviolet UW2 band with a strong correlation of $0.80 \pm 0.04$. The Fermi low- (0.2-2 GeV) and high- (2-300 GeV) energy bands are highly correlated ($z$-DCF $= 0.67 \pm 0.34$) with no visible lag, whereas the low (2-20 keV; MAXI) and high (15-150 keV; Swift-BAT) energy X-ray bands are less strongly correlated ($z$-DCF $= 0.28 \pm 0.02$) at a lag of $7.1 \pm 0.5$ days (Figure 4.8a). There is no correlation between the Fermi and the X-ray bands (Figure 4.8b). The Fermi flux does not show any lag with the optical flux ($z$-DCF $= 0.52 \pm 0.06$), but leads the UV flux by $80 \pm 1$ days ($z$-DCF $= 0.57 \pm 0.07$) (Figure 4.8c). Interestingly, there is strong radio-$\gamma$-ray correlation ($z$-DCF $= 0.69 \pm 0.05$) as seen in Figure 4.8d, where the radio flux lags behind the $\gamma$-ray flux by $52 \pm 20$ days. Such strong radio-$\gamma$ ray correlations due to large dominant flares have been previously seen in long-term studies of blazars (Mufakharov et al., 2015; Wu et al., 2014).
Lognormality is an important statistical process found in many accreting sources like X-ray binaries (Uttley & McHardy, 2001). Lognormal fluxes have fluctuations, that are, on average, proportional to the flux itself, and are indicative of an underlying multiplicative, rather than additive physical process. It has been suggested that a lognormal flux behaviour in blazars could be indicative of the variability imprint of the accretion disk onto the jet (McHardy, 2008). This behaviour in blazars was first clearly detected in the X-ray regime in BL Lac (Giebels & Degrange, 2009) and has been seen across the entire electromagnetic spectrum in PKS 2155−304 (Chevalier et al., 2015).

To investigate lognormality, we fit the histograms of the observed fluxes with a Gaussian and a lognormal function (Fig. 4.9). The reduced chi-squares from the fits are given in Table 4.4. The lognormal function is clearly preferred over the Gaussian, indicating a lognormal trend in the flux distribution. We further plot the excess variance, $\sigma_{EXCESS} = \sqrt{\frac{S^2 - \sigma_{err}^2}{\sigma_{true}^2}}$, versus the mean flux in Fig. 4.10. Data is binned over a period of 100 days to get sufficient statistics. To test the rms-flux relationship, following Giebels & Degrange (2009) and Chevalier et al. (2015), the scatter plot is fit by a constant and a linear function. The linear fit is clearly preferred over the constant with $r$ as the measure of the correlation coefficient. Spearman’s rank correlation ($\rho$) is also computed, the result of which shows that the errors are generally proportional to the flux. While lognormality is clearly detected for the survey instruments, Fermi-LAT, Swift-BAT, and MAXI, the correlations decrease for the other instruments. This is likely because the observations from the pointing instruments are biased towards the flaring states. In fact, the histogram of the flux distribution clearly shows two peaks for the OVRO and the R-band data (Figure 4.11), the second of which can be attributed to the flare states. These flares may be caused by separate “short-term” phenomena, as compared to the long-term flux modulations. This hypothesis is supported by the fact that lognormality is clearly seen by MAXI, but not by Swift-XRT, where the two instruments sample similar energy regimes. Also, the measured radio flux from OVRO is the combined emission from the jet and radio lobes, the latter of which may contribute to the second component.

4.4 SPECTRAL MODELLING

Twenty-one SEDs were extracted over the past seven years. We do not bias our SEDs over any flare/quiescent states as in Bartoli et al. (2015), but choose epochs contemporaneous with HAGAR time periods. During these epochs, the total bolometric luminosity varied almost by a factor of 10. The broadband emission is assumed to originate from a single
Figure 4.9.: Histograms of the fluxes (shown in black) at different wavebands. In all of the cases, a lognormal distribution (blue line) fits better than the Gaussian distribution (red line). The reduced $\chi^2$ are given in Table 4.4.
4.4. Spectral modelling

Figure 4.10.: Excess rms vs. the mean flux for the different wavebands. The black lines show the best-fit linear regression line.
4. Mkn 421: Longterm spectral and temporal study

<table>
<thead>
<tr>
<th></th>
<th>Gaussian</th>
<th>Lognormal</th>
<th>Constant</th>
<th>Linear</th>
<th>$r$ (prob)</th>
<th>$\rho$ (prob)</th>
</tr>
</thead>
<tbody>
<tr>
<td>OVRO (15 GHz)</td>
<td>45.3</td>
<td>36.2</td>
<td>3.4</td>
<td>2.8</td>
<td>0.48 (0.12)</td>
<td>0.58 (0.01)</td>
</tr>
<tr>
<td>SPOL (R band)</td>
<td>14.9</td>
<td>10.0</td>
<td>4.9</td>
<td>4.3</td>
<td>0.26 (0.39)</td>
<td>0.21 (0.49)</td>
</tr>
<tr>
<td>SPOL (V band)</td>
<td>6.3</td>
<td>4.0</td>
<td>5.7</td>
<td>4.3</td>
<td>0.61 (2.9E-3)</td>
<td>0.51 (0.02)</td>
</tr>
<tr>
<td>Swift-UW1</td>
<td>8.3</td>
<td>6.7</td>
<td>11.3</td>
<td>10.1</td>
<td>0.24 (0.31)</td>
<td>0.14 (0.51)</td>
</tr>
<tr>
<td>Swift-UW2</td>
<td>6.0</td>
<td>5.3</td>
<td>12.9</td>
<td>12.1</td>
<td>0.35 (0.14)</td>
<td>0.23 (0.33)</td>
</tr>
<tr>
<td>Swift-UM2</td>
<td>6.1</td>
<td>4.9</td>
<td>9.9</td>
<td>8.1</td>
<td>0.20 (0.39)</td>
<td>0.21 (0.21)</td>
</tr>
<tr>
<td>Swift-XRT (0.2 - 10 keV)</td>
<td>2.6</td>
<td>1.7</td>
<td>66.9</td>
<td>46.4</td>
<td>0.77 (3.7E-4)</td>
<td>0.72 (1.1e-3)</td>
</tr>
<tr>
<td>MAXI (2 - 20 keV)</td>
<td>19.3</td>
<td>1.5</td>
<td>2.2</td>
<td>0.95</td>
<td>0.86 (2E-16)</td>
<td>0.91 (7.9E-8)</td>
</tr>
<tr>
<td>Swift-BAT (15-150 keV)</td>
<td>3.8</td>
<td>0.9</td>
<td>1.7</td>
<td>0.82</td>
<td>0.78 (9.0E-4)</td>
<td>0.90 (4.4E-6)</td>
</tr>
<tr>
<td>Fermi-LAT (0.2-300 GeV)</td>
<td>1.9</td>
<td>1.2</td>
<td>2.5</td>
<td>1.6</td>
<td>0.57 (4.8E-3)</td>
<td>0.74 (4.5E-5)</td>
</tr>
</tbody>
</table>

Table 4.4.: Reduced $\chi^2$ for the fit of a Gaussian function to the flux distribution (column 2); lognormal distribution to the flux distribution (column 3); a constant line to the excess variance vs. flux (column 4) and a linear function (column 5) for the excess variance vs. flux in the various wavebands. Columns 6 and 7 give the Pearsons $r$ and Spearmans $\rho$ correlation coefficients, respectively. The values in the brackets denote the null hypothesis probabilities.

![R-band: Lognormal + Gaussian](image)

Figure 4.11.: Mkn 421 R-band flux distribution: Fit by sum of Lognormal and Gaussian; Likely a second component biased during flaring states
4.4. Spectral modelling

spherical zone of radius $R$ filled with a tangled magnetic field $B$. A non-thermal population of electrons, with a broken power-law spectral shape,

$$N(\gamma)d\gamma = \begin{cases} 
K\gamma^{-p_1}d\gamma, & \gamma_{\text{min}} < \gamma < \gamma_b \\
K_b\gamma_{b}^{(p_2-p_1)}\gamma^{-p_2}d\gamma, & \gamma_b < \gamma < \gamma_{\text{max}}
\end{cases}$$

(44)

is assumed to lose its energy through synchrotron and self-Compton (SSC) processes. As a result of the relativistic motion of the jet, the radiation is boosted along our line of sight by a Doppler factor $\delta$. This simple model is most commonly used in literature to model the broadband spectrum [Ghisellini et al. (1996); Krawczynski et al. (2004)]. Correction for attenuation of TeV photons due to the extragalactic background light (EBL) is accounted for by deconvolving the obtained spectrum with the EBL model of Franceschini et al. (2008). Mankuzhiyil et al. (2012) used the Levenburg-Marquadt algorithm to fit the numerical model to the observed spectrum. We incorporate the numerical SSC model of Saha & Bhattacharjee (2015) in the XSPEC spectral fitting software to perform a $\chi^2$ minimization. More details about incorporating SSC model in XSPEC can be found in Appendix A. Swift-XRT fluxes are averaged over $\sim 6$ spectral bins (and similarly for NuSTAR) to avoid biasing the fit towards the X-ray energies. The tool $\text{flux}_2\text{xsp v.2.1}$ was used to convert the fluxes to pha files for use in XSPEC. Since we are dealing with several different instruments over a broad energy range, we assume model systematics of 5%.

A good sampling of the entire SED from radio to $\gamma$-rays allows one to perform a reasonable estimation of the physical parameters [Ghisellini et al. 1996; Tavecchio et al. 1998] in terms of the observed fluxes. The radius $R$ of the emission region has to be independently estimated from the light travel time argument, $R < c\delta t_{\text{var}} / (1 + z)$, where $t_{\text{var}}$ is the observed flux doubling timescale. However, Mkn 421 shows different flux doubling timescales over different time periods, and since we are dealing mainly with quiescent state emission, we keep $R$ fixed at $6.0 \times 10^{16}$ cm, which was used by Aleksic et al. (2014a). This roughly corresponds to a $t_{\text{var}} \sim 1$ day for $\delta = 21$, which is also frozen during the fitting. The minimum particle Lorentz factor, $\gamma_{\text{min}}$ can be fixed at a reasonably low value without affecting the modelling (Cerruti 2015a), and is assumed to be 1000. The maximum Lorentz factor, $\gamma_{\text{max}}$, is kept fixed at $10\gamma_b$.

The ratio of the electric ($U_E$) and magnetic ($U_B$)field energy density is parameterized by the equipartition parameter $\eta = U_E / U_B$, where $U_B = B^2 / 2\mu_0$ and $U_E = m_e c^2 \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} \gamma N(\gamma)d\gamma$. The best fit SEDs are shown in Fig. 6.6 and the fit parameters and the reduced $\chi^2$ listed in Table 4.5. During all the epochs, the energy density in the jet is matter dominated with the model parameters a factor of 10 away from equipartition. However, this ratio may be improved by choosing a lower value of $\delta$ or $R$. For all the SEDs studied here, the one-zone model provides a very good fit to the observed data and does not motivate the need for a second emitting region.
4. Mkn 421: Longterm spectral and temporal study

(a) s1
(b) s2
(c) s3
(d) s4
(e) s5
(f) s6
(g) s7
(h) s8
4.4. Spectral modelling

(a) s9

(b) s10

(c) s11

(d) s12

(e) s13

(f) s14

(g) s15

(h) s16
Figure 4.12.: SED during the different states fit with a one zone SSC. Inverted triangles correspond to upper limits. The last panel shows all the model SEDs for all 21 states along with the model SED during the February 2010 flare (Shukla et al., 2012), plotted in thick black line for reference.
4.5. Results and discussions

4.5.1 Spectral variability

The similar variability in the optical-GeV bands, and the X-ray-VHE bands indicates a similar origin for the optical and Fermi-LAT bands and for the X-ray-VHE bands. In the framework of the SSC model, this is attributed as the first index, \( p_1 \) contributing to the optical-GeV bands (synchrotron and SSC respectively), and the second index \( p_2 \) for the X-ray-VHE bands. As can be seen from the fit parameters in Table 4.5, some of the states require a very hard particle index \( p_1 < 2.0 \). Such an index cannot originate from a single shock acceleration, but may originate from multiple shocks (Malkov & Drury, 2001), which can produce particle indices as hard as 1.5, which is close to the hardest spectrum \( (p_1 = 1.6) \) obtained in our fits. Alternatively, stochastic acceleration in resonance with plasma wave turbulence behind the relativistic shock front can also harden the injection index (Vainio et al., 2004). The two indices, \( p_1 \) and \( p_2 \), show a weak correlation with \( \rho = 0.42, \text{prob} = 0.05 \) (Figure 4.13a). In particular, \( p_2 \) is much steeper than what would be expected from \( p_2 = p_1 + 1 \), thus ruling out the broken power-law spectrum as originating from a cooling break. There is a significant correlation between the total bolometric luminosity \( L \) and the first index \( (\rho = 0.66, \text{prob} = 0.001) \), and a very strong correlation between \( L \) and the particle break energy \( \gamma_b \) \( (\rho = 0.79, \text{prob} = 3.2 \times 10^{-5}) \) (Fig 4.13b). However, no significant trend is seen between the magnetic field \( B \) and \( L \).

Table 4.5: Fit parameters for the different SED states with \( R = 6.0 \times 10^{16} \) cm, \( \delta = 21, \gamma_{\text{min}} = 1000, \) and \( \gamma_{\text{max}} = 10\gamma_b \)

<table>
<thead>
<tr>
<th>( p_1 )</th>
<th>( p_2 )</th>
<th>( \ln(\gamma_b) )</th>
<th>( B ) (G)</th>
<th>( U_E ) (ergs/cc)</th>
<th>( \eta = U_E / U_B )</th>
<th>( L ) (ergs/sec)</th>
<th>( \chi^2 )</th>
</tr>
</thead>
<tbody>
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<td>s1</td>
<td>2.2</td>
<td>4.0</td>
<td>11.79</td>
<td>2.94E-02</td>
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<td>13.15</td>
<td>3.79E-02</td>
<td>4.47E-04</td>
<td>7.79</td>
<td>8.28E+45</td>
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<td>s3</td>
<td>1.8</td>
<td>3.7</td>
<td>10.62</td>
<td>4.22E-02</td>
<td>4.33E-04</td>
<td>6.12</td>
<td>6.41E+45</td>
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<tr>
<td>s4</td>
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<td>10.38</td>
<td>3.99E-02</td>
<td>4.50E-04</td>
<td>7.10</td>
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<td>12.17</td>
<td>3.58E-02</td>
<td>6.28E-04</td>
<td>12.3</td>
<td>9.40E+45</td>
</tr>
</tbody>
</table>
4. Mkn 421: Longterm spectral and temporal study

![Graphs showing p1 vs. p2 and Luminosity vs. \( \gamma_b \)]

**Figure 4.13.** Cross plot of the fit parameters for the one-zone SSC. The black dotted line in the first corresponds to the relation \( p_2 = p_1 + 1 \), which is what would have been expected from a synchrotron cooling break. The second panel shows the variation of the synchrotron peak frequency with the total bolometric luminosity. A strong correlation is clearly observed.

![Schematic diagram explaining the observed time delay between the radio and \( \gamma \)-ray flare](image)

**Figure 4.14.** Schematic diagram explaining showing the plausible origin for observed time delay between the radio and \( \gamma \)-ray flare [Pushkarev et al. (2010)].

This implies that the variations in the different flux states occur mainly because of a change in the underlying particle distribution, rather than in the jet environment.

### 4.5.2 Location of the emission zone

We observe that the \( \gamma \)-ray flares lead the radio flares, \( \Delta t_{\gamma, \text{radio}}^{\text{obs}} = 52 \pm 20 \text{ days} \). [Pushkarev et al. (2010)] explained this as originating due to the synchrotron opacity in the nuclear region. Since the radio core is optically thick to synchrotron radiation up to a frequency dependent radius \( r_c \propto \nu^{-1} \), the \( \gamma \)-ray emission zone should be located upstream with respect to the apparent radio core position. Assuming the flares to be caused by the same disturbance, the radio and \( \gamma \)-ray flares are not observed simultaneously because of the opacity effect (Figure 4.14). While the \( \gamma \)-ray photons are emitted immediately. This information can be used to estimate the distance travelled by emission region \( d_{\gamma, \text{radio}} \) using the relation [Ramakrishnan et al., 2015]

\[
\Delta t_{\gamma, \text{radio}}^{\text{obs}} = \frac{\beta_{\text{app}} c \Delta t_{\gamma, \text{radio}}^{\text{obs}}}{\sin(\theta)(1+z)}.
\]
4.5. Results and discussions

### 4.5.3 Implications of lognormality

The observed lognormality of the flux distributions in the different bands and the proportionality between the fluctuations in the flux imply that the variations are lognormal. To investigate our hypothesis that the deviation of lognormal behaviour as seen by pointing instruments (eg: Swift-XRT) occurs due to observation biases, we rebin the Swift-XRT data over 10 days and look at the flux distribution. Swift has a regular monitoring program for Mkn 421, where, subject to visibility constrains, the source is observed every 3 days. However, during flaring activities, Target of Opportunity (ToO) observations are often carried out, thus yielding a large number of observations during high flux states and creating a deviation from a single lognormal distribution. Flux distributions averaged over 10 days should then be expected to preserve the lognormal behaviour. Indeed, we see that the averaged flux distribution (Fig. 4.15a) is clearly preferred to be a Lognormal (chi-sq/dof = 7.3/15) rather than a Gaussian (chi-sq/dof = 29.5/15). As a further verification, we select daily averaged fluxes from MAXI observations from time periods corresponding to Swift-XRT observations (Fig. 4.15b). Again, in accordance

---

**Figure 4.15:** (a) Swift-XRT fluxes averaged over 10 days clearly prefer a Lognormal distribution (solid red line) over a Gaussian distribution (blue dotted line). (b) Flux distribution of MAXI fluxes from times simultaneous with Swift-XRT. A second peak is seen at around $\sim 0.29$ cts/s, leading to a deviation from a Lognormal function (solid red line).

Using $\beta_{app} \sim 1.92$ (Zhang & Bååth, 1996), $\theta = \tan^{-1}(2\beta_{app} / (\beta_{app}^2 + \delta^2 - 1)) \sim 0.5^\circ$ (Ghisellini et al., 1993), and $z = 0.031$, we find the distance travelled by the emission region, $d_{\gamma, \text{radio}} = 9.3$ pc. This corresponds to a projected distance of 0.08 pc, equivalent to an angular size of 0.12 mas. Zhang & Baath (1991) studied the VLBI image of this source at a resolution of $\sim 0.15$ mas and found unresolved core. This, compared to our estimated size of 0.12 mas allows us to constrain the $\gamma$-ray emission site within the radio core.
with our conjecture, we see a deviation from a Lognormal distribution (chi-sq/dof = 21.9/10).

Similar lognormal trends have been found in several accreting galactic sources (Giebels & Degrange, 2009) and also in the Seyfert 1 galaxy, Mkn 766, where the physical process responsible for the X-ray emission is most likely thermal emission from the galactic disk (Vaughan et al., 2003). The results of our SED modelling in Section 5.4 show that the flux variability in the source can be mainly attributed to changes in the particle spectrum rather than jet parameters such as the magnetic field or Doppler factor. This implies that the lognormal fluctuations in the flux are indicative of lognormal processes in the accretion disk, and the lognormal fluctuations in the accreting rate give rise to an injection rate with similar properties.

4.6 CONCLUSIONS

In this chapter, we have presented a 7-year continuous multi-wavelength monitoring of Mkn 421, from March 2009 to April 2015, a period that includes both steady states and episodes of strong flaring activity. The variability increases with energy for both the SED components, thus supporting a SSC emission mechanism. This idea is further supported by the observed optical-GeV and the known X-ray TeV (Bartoli et al., 2015) correlations. A simple one zone model incorporating synchrotron and SSC mechanisms provided a suitable fit to the observed SEDs for all epochs without motivating the need for any additional emitting regions. Interestingly, while the time-resolved UV-X-ray spectra during the April 2013 flare could not be explained by synchrotron emission from a single region (Sinha et al., 2015), the time averaged broadband spectrum during the same time (State s13) can be well fitted by our model (Reduced $\chi^2 = 1.5$). This motivates a need for better time-resolved broadband spectra. The detection of lognormal flux behaviour in a blazar also encourages us to take a new look into our understanding of jet launching mechanisms in supermassive black holes. A long term continuous monitoring program for a set of blazars may turn out very profitable in this regard. The upcoming Major Atmospheric Cherenkov Experiment (MACE; Koul et al., 2011) at Hanle, Ladakh is expected to provide us with excellent time-resolved spectrum at VHE energies, which may throw new light onto the VHE emission from blazar jets.
Mkn 421: Underlying particle spectrum during giant flare

During April 2013, Mkn 421 underwent one of the largest flares in X-rays in the past decade, and was the subject of an intense multiwavelength campaign with both space and ground based observational facilities. The dramatic flare allowed us an unprecedented glimpse into a typical black hole jet - underlying particle distributions (Sinha et al., 2015), peculiar variability patterns (Paliya et al., 2015a), multicomponent, multizone emission states (Pian et al., 2014), etc. In this chapter we use multiwavelength data available during MJD 56392 to 56403, with special emphasis on X-ray data using the Swift and NuSTAR telescopes, to understand the underlying particle energy distribution.

5.1 Behaviour during previous flares

Being one of the brightest and most variable source in the extragalactic sky, Mkn 421 has been extensively studied during its high activity states by several authors (Aleksić et al., 2012b; Shukla et al., 2012; Isobe et al., 2010; Krawczynski et al., 2001; Aleksić et al., 2010; Acciari et al, 2009d; Ushio et al., 2009; Tramacere et al., 2009; Horan et al., 2009; Lichti et al., 2008; Fossati et al., 2008; Albert et al., 2007a; Brinkmann et al., 2003; Singh et al., 2015), a detailed review of which is beyond the scope of this thesis. Its optical brightness was found to change by 1.4 mag in 2.5 hrs during a flare in 1986 (Guangzhong et al., 1988). A very fast flux doubling time of $14.01 \pm 5.03$ minutes, which is on the order of the light crossing time of the black hole's event horizon, has been seen at hard X-rays using NuSTAR data during the rapid flare in April 2013 (Paliya et al., 2015a). Since its detection, the source has been generally very active in the high energy bands, with a big eruption on a timescale of $\sim 2$ years (Bartoli et al., 2015; Cui
5. Mkn 421: Underlying particle spectrum during giant flare

Gaur et al. (2012); Tluczykont et al. (2010). A major outburst is generally seen to be followed by several smaller flares. Gaidos et al. (1996) detected extremely fast VHE outbursts were where the doubling time of the flare events were found to be < 15 minutes. The X-ray emission is known to be highly correlated with the TeV emission (Błażejowski et al. 2005; K. Katarzynski et al. 2005; jie Qian et al. 1998), but like other HBLs, shows moderate correlation with the GeV emission (Li et al. 2013).

In the spring-summer 2006, Tramacere et al. (2009) found that the X-ray flux of Mrk 421 reached its highest record till date. In 2006 April, Mrk 421 underwent a large flare and the X-ray flux was variable (Ushio et al. 2010). In 2010 January and February, big X-ray outbursts were observed from the object Isobe et al. (2010); Shukla et al. (2012). X-ray and TeV outbursts were also reported for the source by Kerrick et al. (1995) and Takahashi et al. (1994; 1995) in 1994 and 1995, respectively.

5.2 Multiwavelength Observations and Data Analysis

The huge X-ray flare of Mkn 421 in April 2013 (2013 April 10 to 21; MJD 56392−56403) was simultaneously observed by the NuSTAR and Swift X-ray and UV telescopes. There were 11 NuSTAR pointings and 15 Swift pointings within the dates of interest, the details of which are given in Table 5.1 and Table 5.2 respectively. Data are processed according to the standard procedures outlined in Chapter 3.2 and Chapter 3.3. To achieve strict simultaneity with Swift-XRT observations, NuSTAR observation id 60002023025 is broken into four parts: 56393.15591890 to 56393.29538714, 56393.29538714 to 56393.91093765, 56393.91093765 to 56393.96788711, and 56393.96788711 to 56394.37822500 MJD.

Swift-UVOT (Roming et al. 2005) operated in imaging mode during this period, and for most of the observations, cycled through the UV filters UW1, UW2, and UM2. The tool uvotsource v.3.3 is used to extract the fluxes from each of the images using aperture photometry. The observed magnitudes were corrected for Galactic extinction ($E_{B-V} = 0.019$ mag) using the dust maps of Schlegel et al. (1998) and converted to flux units using the zero-point magnitudes and conversion factors of Breeveld et al. (2011). The tool flx2xsp v.2.1 is used to convert the fluxes to pha files for use in XSPEC.

The $\gamma$-ray behaviour of this source during this flare is obtained by collecting Fermi-LAT observations covering the period of the X-ray outburst (MJD 56390−56403), analysed according to the procedure described in Chapter 3.1. A simple power law spectral model, with index and normalisation as the free parameters, is used to model the source.

In addition, we also include the X-ray observations by the Swift-BAT and the MAXI telescopes and optical observations by SPOL-CCD. Significant flux brightening at TeV energies is seen with the HAGAR array of Telescopes. Source brightened from the level of 1 Crab unit to about 3 Crab units from March to April observation season Acharya et al. (2013), simultaneous with the X-ray flare (Figure 5.1). Unfortunately, many nights were lost due to poor sky conditions, and detailed analysis could not be carried out.
5.2. Multiwavelength observations and data analysis

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Table 5.1.: Details of NuSTAR pointings

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Table 5.2.: Details of Swift pointings. The exposure times are rounded to the nearest seconds
5. Mkn 421: Underlying particle spectrum during giant flare

The multiwavelength light curve for the ten-day period is plotted in Figure 5.2 from optical to gamma ray energies, along with the optical polarization measurements. While there were two huge flares in X-rays (on MJD 56395 and 56397), where the flux increased by a factor of 10, the fluxes in the other bands were not very variable on the timescale of days. We compute the z-transformed discrete correlation using a freely available Fortran 90 code with the details of the method employed described in Alexander (1997). We find no lag between the soft (0.3–10 keV, Swift-XRT) and the hard X-ray (3.0–79 keV NuSTAR) bands (Figure 5.3a). There is no correlation seen between the UV flux and the X-ray flux, \( z_{dcf_{max}} = 0.62 \pm 2.3 \), at a lag of 2.2 days). Moreover, while the UV flux does not show a correlation with the optical polarization \( z_{dcf_{max}} = 0.61 \pm 1.1 \), at a lag of 2.4 days), the X-ray flux shows a tighter correlation \( z_{dcf_{max}} = 0.81 \pm 0.6 \), at a lag of 3.5 days) with the latter (Figure 5.3b). There is also a strong change in the angle of polarization during the two X-ray flares.

The hardness ratios (computed here as the ratio between the 10–79 keV count rate and the 3–10 keV count rate (Tomsick et al., 2014) are plotted in Figure 5.4. A trend of spectral hardening with increasing flux (Spearman rank correlation, rs=0.58, \( p = 5.0 \cdot 10^{-8} \)) is observed, and the same is often reported for this source (e.g. Baloković et al., 2013; W. Brinkmann et al., 2001). Moreover, the correlation is much tighter during the rising part of the two flares (rs=0.92, \( p = 4.0 \cdot 10^{-5} \)). These interesting features encourage us to perform a more detailed spectral study, which we describe in Sect. 5.4.

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**Figure 5.1.** Flux brightening at X-ray and GeV/TeV energies as seen by the MAXI, Swift-BAT, Fermi-LAT and HAGAR. The points in the first three panels are averaged over weekly timescales, and the last panel, over each observation season.

5.3 **Multiwavelength Temporal Study**

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80
5.3. Multiwavelength temporal study

![Multiwavelength light curve during MJD 56390 to 56403 showing in panel 1 the V-band magnitude, in panel 2 the UV flux in mJy, in panel 3 the degree and angle of optical polarization, in panel 4 the Swift-XRT flux in counts/sec, in panel 5 the MAXI flux in counts/sec, in panel 6: the NuSTAR flux in counts/sec, in panel 7 the Swift-BAT flux in counts/sec, and in panel 8 the Fermi-LAT flux in $ph/cm^2/sec$. One Swift-XRT (or NuSTAR) point is plotted for each snapshot.](image-url)
5. Mkn 421: Underlying particle spectrum during giant flare

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**Table 5.3.:** The $F_{rms}$ for each energy band between MJD 56390 to 56400.

The fractional variability amplitude parameter $F_{var}$ (Chapter 4.3.1, computed on daily timescales, is used to quantify the multiwavelength variability. The variability amplitude at the different wavelengths is tabulated in Table 5.3 and is found to be the highest for the X-ray bands ($F_{var} \sim 0.75 \pm 0.10$) and significantly lower for the UV bands ($F_{var} \sim 0.08 \pm 0.02$), suggesting that the emission may probably arise from different components in the two bands. The variability in the GeV range is also weak ($F_{var} \sim 0.16 \pm 0.07$). This contradicts the general trend found in blazars that $F_{var}$ is highest for the $\gamma$-ray band and decreases with frequency (Zhang et al., 2005; Paliya et al., 2015b). Moreover, there is an indication of a TeV flare with rapid flux variations during this time (Cortina & Holder, 2013; Pian et al., 2014).

We scan the *Swift*-XRT and the *NuSTAR* light curves for the shortest flux-doubling timescale using the following equation (Foschini et al., 2011):

$$F(t) = F(t_0) \cdot 2^{(t-t_0)/\tau},$$

where $F(t)$ and $F(t_0)$ are the fluxes at time $t$ and $t_0$, respectively, and $\tau$ is the characteristic doubling or halving timescale. The fastest observed variability in the *NuSTAR* band is $1.69 \pm 0.08$ hours between MJD 97.06438 to 97.08573. This is similar to the very fast variability observed in this source with the *Beppo*-SAX (Rossati et al., 2000).

This study was only performed for those periods where the flux difference was significant, at least at the 3$\sigma$ level.

5.4 X-RAY SPECTRAL ANALYSIS

The close simultaneity between *Swift*-XRT and *NuSTAR* observations allows us to perform a joint spectral fitting using XSPEC package v. 12.8.2. The time periods that are fitted together are shown in Figure 5.5. The bin widths were selected as one bin per *Swift*-XRT observation (except for Obs. id. 00035014062 and 00035014069, which lasted only for a few minutes), leading to 13 time bins that we denote as f1 - f13. The
Figure 5.3.: (a) The z-dcf between the NuStar and the XRT counts. The blue points show the data, and the green line is the best fit Gaussian. There is no lag between the soft and the hard bands. (b) The z-DCF between the NuStar counts and the degree of polarization. The red points show the data, and the green line is the best fit Gaussian. The flux is well correlated with the degree of polarisation, with a lag of 3.5 days.

Figure 5.4.: Plot of the hardness ratio as observed by NuSTAR FPMA. The upper panel shows the hardness ratio, and the lower panel the flux(counts/sec). There is a trend of spectral hardening with flux.
5. Mkn 421: Underlying particle spectrum during giant flare

Figure 5.5.: Thirteen time bins for which spectra have been extracted.

state \( f_3 \) has no \textit{Swift}-XRT data, whereas the state \( f_{13} \) has no NuSTAR data. Again in Table 5.4 we list the \textit{Swift}-XRT and corresponding NuSTAR data that were combined.

While fitting the broadband X-ray spectrum (0.3 \( \text{–} \) 79 keV), the XRT and the NuSTAR spectral parameters are tied to each other, except for the relative normalization between the two instruments. To correct for the line-of-sight absorption of soft X-rays due to the interstellar gas, the neutral hydrogen column density is fixed at \( N_H = 1.92 \times 10^{20} \text{cm}^{-2} \) (Kalberla et al., 2005).

5.4.1 Fitting the photon spectrum

It is known that the X-ray spectrum of Mkn 421 shows significant curvature (Fossati et al., 2000; Massaro et al., 2004), and consistently, we also note that the data cannot be fitted satisfactorily by a simple power law. On the other hand, a power law with an exponential cutoff gives a much steeper curvature than observed, yielding unacceptable fits. A sharp broken power-law also gives high \( \chi^2 \) values in most cases, which suggests a smooth intrinsic curvature in the spectrum. Following (Massaro et al., 2004; Tramacere et al., 2007), we therefore fitted the observed spectrum with a log parabola given by

\[
\frac{dN}{dE} = K (E/E_b)^{-\alpha_s - \beta_s \log(E/E_{b,s})},
\]

where \( \alpha_s \) gives the spectral index at \( E_{b,s} \). The point of maximum curvature, \( E_{p,s} \), is given by

\[
E_{p,s} = E_{b,s} 10^{(2 - \alpha_s)/2\beta_s}.
\]
5.4. X-ray spectral analysis

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Table 5.4.: Reduced χ² values for the power-law (po), cutoff power-law (cutoffpl) and the broken power-law (bknpo) models for various time bins (f1 to f13), as marked in Figure 5.5. Obs of XRT and Nustar are also given.

During fitting, $E_{b,s}$ was fixed at 1 keV. In Table 5.4 we list the resulting reduced χ²s for the case of the aforementioned spectral models; while in Table 5.5 we report the fit parameters corresponding to the log parabola model.

Interestingly, there is a strong anti-correlation between $\alpha_s$ and flux ($r_s = -0.98$, $p < 2.2 \cdot 10^{-16}$) and a strong correlation between flux and $E_{p,s}$ ($r_s = 0.97$, $p < 2.2 \cdot 10^{-16}$), which implies that during flares, the spectral index at 1 keV hardens and the peak of the spectrum shifts to higher energies. This behaviour of the source has often been reported (Massaro et al., 2004, 2008). Moreover, there is no correlation between $\alpha_s$ and $\beta_s$ ($r_s = -0.35$, $p = 0.24$), which was reported by Massaro et al. (2004). We also noted that there is no correlation observed between the curvature parameter $\beta$ and the peak of the curvature $E_p$ ($r_s = 0.63$, $p = 0.02$). These cross plots are shown in Figure 5.6.

5.4.2 Emitting particle distribution

The excellent spectral resolution of NuSTAR gives us an unprecedented view of the high-energy X-ray behaviour beyond 20 keV. Coupled with Swift-XRT, we have, for the first time, an uninterrupted, well-resolved spectrum from 0.3–79 keV. This allows us to go beyond only fitting the photon spectrum with various spectral forms. Instead, we here study the underlying particle distributions that give rise to the observed photon spectrum.

We consider the case where X-ray emission arises from a relativistic distribution of electrons emitting synchrotron radiation. The electrons are confined within a spherical zone of radius $R$ filled with a tangled magnetic field $B$. As a result of the relativistic motion of the jet, the radiation is boosted along our line of sight by a Doppler factor.
Table 5.5.: The best fit parameters of the log parabolic photon spectrum. Column 5 shows the relative normalisation between the XRT and the NuStar; Column 6 gives the $2-10\,\text{keV}$ flux in $\text{ergs/cm}^{-2}\cdot\text{s}^{-1}$, Column 6, the reduced $\chi^2$. 

<table>
<thead>
<tr>
<th>fil-iden</th>
<th>$\alpha_s$</th>
<th>$\beta_s$</th>
<th>$E_{p,s}$</th>
<th>relative-norm</th>
<th>flux</th>
<th>$\chi^2$/d.o.f</th>
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<tbody>
<tr>
<td>f1</td>
<td>$2.21 \pm 0.02$</td>
<td>$0.39 \pm 0.01$</td>
<td>$0.534 \pm 0.027$</td>
<td>1.25</td>
<td>$5.47\times 10^{-10}$</td>
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<tr>
<td>f2</td>
<td>$2.21 \pm 0.01$</td>
<td>$0.39 \pm 0.01$</td>
<td>$0.543 \pm 0.023$</td>
<td>0.87</td>
<td>$5.32\times 10^{-10}$</td>
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<tr>
<td>f3</td>
<td>$2.14 \pm 0.05$</td>
<td>$0.27 \pm 0.03$</td>
<td>$0.550 \pm 0.074$</td>
<td>-</td>
<td>$6.72\times 10^{-10}$</td>
<td>0.92</td>
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<tr>
<td>f4</td>
<td>$1.92 \pm 0.01$</td>
<td>$0.38 \pm 0.02$</td>
<td>$1.254 \pm 0.0630$</td>
<td>1.31</td>
<td>$9.62\times 10^{-10}$</td>
<td>1.04</td>
</tr>
<tr>
<td>f5</td>
<td>$1.82 \pm 0.01$</td>
<td>$0.44 \pm 0.01$</td>
<td>$1.585 \pm 0.0229$</td>
<td>0.94</td>
<td>$1.86\times 10^{-09}$</td>
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<tr>
<td>f6</td>
<td>$1.80 \pm 0.01$</td>
<td>$0.46 \pm 0.01$</td>
<td>$1.634 \pm 0.0205$</td>
<td>1.00</td>
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<tr>
<td>f7</td>
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<td>$0.41 \pm 0.01$</td>
<td>$0.805 \pm 0.015$</td>
<td>1.15</td>
<td>$7.33\times 10^{-10}$</td>
<td>1.10</td>
</tr>
<tr>
<td>f8</td>
<td>$1.61 \pm 0.01$</td>
<td>$0.37 \pm 0.01$</td>
<td>$3.272 \pm 0.0668$</td>
<td>0.98</td>
<td>$2.14\times 10^{-09}$</td>
<td>1.14</td>
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<tr>
<td>f9</td>
<td>$1.99 \pm 0.01$</td>
<td>$0.33 \pm 0.01$</td>
<td>$1.018 \pm 0.0201$</td>
<td>1.08</td>
<td>$7.89\times 10^{-10}$</td>
<td>0.93</td>
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<tr>
<td>f10</td>
<td>$1.83 \pm 0.01$</td>
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<td>$0.445 \pm 0.049$</td>
<td>-</td>
<td>$2.59\times 10^{-10}$</td>
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Figure 5.6.: Cross plot of parameters for the logparabolic photon (green stars) and particle (red circles) spectrum. The peak curvature $E_p$ clearly anti-correlates with $\alpha$ and strongly correlates with the flux. However, there is no correlation between $E_p$ and the curvature parameter $\beta$, or between $\beta$ and $\alpha$. 

86
5.4. X-ray spectral analysis

A good sampling of the entire SED from radio to $\gamma$-rays allows one to perform a reasonable estimation of these physical parameters \cite{Tavecchio2008}. For synchrotron emission alone, $R$, $B$, and $\delta$ will only decide the spectral normalization. On the other hand, the shape of the observed spectrum is determined by the corresponding form of the underlying particle spectrum. To obtain further insight into the emitting particle distribution, we developed synchrotron emission models with different particle distributions and incorporated them into XSPEC spectral fitting software. In particular, we here consider the following particle distributions:

(i) Simple power law (SPL): In this case, we assume the electron distribution to be a simple power law with a sharp high-energy cutoff, given by

$$N(\gamma)d\gamma = K\gamma^{-p}d\gamma, \; \gamma < \gamma_{\text{max}}.$$  \hfill (49)

Here $\gamma mc^2$ is the energy of the emitting electron, $p$ is the particle spectral index, $K$ is the normalization, and $\gamma_{\text{max}}mc^2$ is the cut-off energy. Of these parameters, $p$ and $\gamma_{\text{max}}$ are chosen as the free parameters.

(ii) Cutoff power law (CPL): Here the underlying particle distribution is assumed to be a power law with index $p$ and an exponential cutoff above energy $\gamma_mmc^2$ given by

$$N(\gamma)d\gamma = K\gamma^{-p}\exp(\frac{\gamma}{\gamma_m})d\gamma.$$  \hfill (50)

For this distribution, $p$ and $\gamma_m$ are chosen as the free parameters.

(iii) Broken power-law (BPL): The particle distribution in this case is described by a broken power-law with indices $p_1$ and $p_2$ with a break at energy $\gamma_b$ given by

$$N(\gamma)d\gamma = \begin{cases} K\gamma^{-p_1}d\gamma, & \gamma_{\text{min}} < \gamma < \gamma_b \\ K_b\gamma^{(p_2-p_1)}\gamma^{-p_2}d\gamma, & \gamma_b < \gamma < \gamma_{\text{max}} \end{cases}.$$  \hfill (51)

Here, $p_1$, $p_2$ and $\gamma_b$ are chosen as the free parameters.

(iv) Log parabola (LP): For this case, the particle distribution is chosen to be a log parabola, given by

$$N(\gamma)d\gamma = K(\gamma/\gamma_b)^{-\alpha_p-\beta_p\log(\gamma/\gamma_b)}d\gamma,$$  \hfill (52)

with $\alpha_p$ and $\beta_p$ chosen as the free parameters.

We fit the observed combined X-ray spectrum from Swift-XRT and NuSTAR with the synchrotron emission due to these different particle distributions as given above, the reduced $\chi^2$ of which are given in Table 5.6. As an example, we show the best fit parameters corresponding to the state $f_5$ in Table 5.7. A poor fit statistics with large...
5. Mkn 421: Underlying particle spectrum during giant flare

Figure 5.7.: Cross plot of the two indices of the broken power-law particle spectrum. The green points are not from combined spectrum, but are NuSTAR only and Swift-XRT only (see text).

reduced $\chi^2$ is encountered for the case of SPL since it fails to reproduce the smooth curvature seen in almost all spectral states ($f1 - f13$). For CPL, the statistics improved for many states with lowest reduced $\chi^2$ of 1.01 during state $f3$; whereas the largest reduced $\chi^2$ is 1.41 for the state $f6$. The fit statistics improved considerably for many states for the case of BPL except for $f6$ and $f8$, correspond to the peak of the X-ray flare. In Figure 5.7 we show the cross-plot distribution of the power-law indices, $p_1$ and $p_2$, of BPL model during different spectral states. The index $p_1$ is poorly constrained for the state $f3$ because we have no Swift-XRT observation during this period; whereas for state $f11$ neither $p_1$ nor $p_2$ are well constrained because there are no NuSTAR observation. However, for most of the states, a strong correlation between $p_1$ and $p_2$ is observed ($rs = 0.79$ and $p = 0.0018$). Of all these particle distributions, the best statistics is obtained for the LP model with the reduced $\chi^2$ decreased considerably during the flaring states, $f5$, $f6$, and $f8$ (Table 5.6). Furthermore, the reduction of one free parameter in LP with respect to BPL enforces the latter to be the most preferred particle distribution. In Table 5.8 we list the best-fit parameters for the LP particle distribution.

We see similar correlations as discussed in Sect. 5.4.1. In fact, there is a linear relationship between the parameters of the photon spectrum and the particle spectrum,

$$\alpha_p = 2.66\alpha_s + 2.66$$  \hspace{1cm} (53)

$$\beta_p = 6.49\beta_s - 0.51$$  \hspace{1cm} (54)
5.4. X-ray spectral analysis

<table>
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<tr>
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<td>1.06</td>
<td>1.03</td>
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<td>1.19</td>
<td>1.16</td>
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<td>1.06</td>
<td>1.01</td>
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<td>1.16</td>
<td>1.06</td>
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<td>1.20</td>
<td>1.31</td>
<td>1.13</td>
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<td>f10</td>
<td>1.91</td>
<td>1.09</td>
<td>1.10</td>
<td>1.10</td>
</tr>
<tr>
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<td>1.40</td>
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<td>1.06</td>
<td>1.00</td>
</tr>
<tr>
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<tr>
<td>f13</td>
<td>1.25</td>
<td>1.04</td>
<td>1.07</td>
<td>0.92</td>
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Table 5.6.: Reduced $\chi^2$ for the various particle distributions

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<tr>
<th>Model</th>
<th>Photon Spectrum</th>
<th>Particle spectrum</th>
</tr>
</thead>
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<tr>
<td>SPL</td>
<td>$p = 2.21 \pm 0.02$</td>
<td>$p = 2.49 \pm 0.02, \gamma_{\text{max}} = 20 \pm 1.0 \text{ keV}$</td>
</tr>
<tr>
<td>CPL</td>
<td>$p = 1.78 \pm 0.03, E_\text{c} = 10.05 \pm 0.05 \text{ keV}$</td>
<td>$p = 1.25 \pm 0.02, \gamma_{\text{max}} = \text{keV}$</td>
</tr>
<tr>
<td>BPL</td>
<td>$p_1 = 1.80 \pm 0.03, p_2 = 2.60 \pm 0.03, E_\text{b} = 3.4 \pm 0.02 \text{ keV}$</td>
<td></td>
</tr>
<tr>
<td>LP</td>
<td>$\alpha_s = 1.82 \pm 0.01, \beta_s = 0.44 \pm 0.01, E_{p,s} = 1.585 \pm 0.03 \text{ keV}$</td>
<td>$\alpha_p = 2.10 \pm 0.01, \beta_p = 2.35 \pm 0.01, E_{p,p} = 0.95 \pm 0.03 \text{ keV}$</td>
</tr>
</tbody>
</table>

Table 5.7.: Sample parameters of the best fit model for the photon and particle spectrum for the different spectral models for state f5.

<table>
<thead>
<tr>
<th>State</th>
<th>$\alpha_p$</th>
<th>$\beta_p$</th>
<th>$E_p$</th>
</tr>
</thead>
<tbody>
<tr>
<td>f1</td>
<td>3.19 ± 0.06</td>
<td>1.96 ± 0.11</td>
<td>0.50 ± 0.04</td>
</tr>
<tr>
<td>f2</td>
<td>3.18 ± 0.04</td>
<td>1.98 ± 0.09</td>
<td>0.50 ± 0.03</td>
</tr>
<tr>
<td>f3</td>
<td>3.11 ± 0.14</td>
<td>1.25 ± 0.16</td>
<td>0.56 ± 0.06</td>
</tr>
<tr>
<td>f4</td>
<td>2.45 ± 0.06</td>
<td>1.97 ± 0.11</td>
<td>0.77 ± 0.06</td>
</tr>
<tr>
<td>f5</td>
<td>2.10 ± 0.02</td>
<td>2.35 ± 0.04</td>
<td>0.95 ± 0.03</td>
</tr>
<tr>
<td>f6</td>
<td>2.01 ± 0.02</td>
<td>2.50 ± 0.03</td>
<td>1.00 ± 0.02</td>
</tr>
<tr>
<td>f7</td>
<td>2.82 ± 0.03</td>
<td>2.10 ± 0.04</td>
<td>0.64 ± 0.02</td>
</tr>
<tr>
<td>f8</td>
<td>1.66 ± 0.03</td>
<td>1.92 ± 0.04</td>
<td>1.23 ± 0.05</td>
</tr>
<tr>
<td>f9</td>
<td>2.69 ± 0.02</td>
<td>1.62 ± 0.03</td>
<td>0.61 ± 0.02</td>
</tr>
<tr>
<td>f10</td>
<td>2.33 ± 0.02</td>
<td>1.46 ± 0.03</td>
<td>0.77 ± 0.02</td>
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<tr>
<td>f11</td>
<td>3.55 ± 0.04</td>
<td>1.44 ± 0.07</td>
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<td>f12</td>
<td>3.67 ± 0.04</td>
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<td>0.30 ± 0.02</td>
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<td>f13</td>
<td>3.30 ± 0.05</td>
<td>1.78 ± 0.23</td>
<td>0.43 ± 0.06</td>
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</table>

Table 5.8.: The fit parameters for the LP particle distribution.
5. Mkn 421: Underlying particle spectrum during giant flare

\[ E_{p,p} = E_{p,s} + 0.35 \]  \hspace{1cm} (55)

5.5 DISCUSSIONS: EVIDENCE OF MULTICOMPONENT EMISSION

Results of our temporal studies show that the X-ray flare is not significantly correlated with the UV and, in addition, the variability amplitude of the former is considerably larger than the latter. This suggests that the X-ray and UV emission probably belongs to emission from different particle distributions.

A detailed spectral analysis of the X-ray observations over different time periods during the flare suggests that the emission arises from a synchrotron mechanism from log parabola particle distribution. Although this particle distribution can be statistically more appealing, a broken power-law particle spectrum cannot be excluded. Furthermore, we extended the best-fit LP and BPL particle distributions to low energies and predicted the UV synchrotron flux. During low X-ray flux states, the predicted UV flux agrees reasonably well with the observed flux. However, at high X-ray flux states, the observed UV flux is significantly higher that the predicted one by a factor of \(2 - 50\), with the larger deviations corresponding to the LP model. In addition, the variability of the predicted UV flux is much higher (\(F_{\text{var, pred}} = 1.10 \pm 0.10\)) than the one obtained from the observed UV flux. This study again questions the similar origin of X-ray and UV emission.

A plausible interpretation of this inconsistency between X-ray and UV fluxes can be made by associating the UV emission from the putative accretion disk. However, such thermal emission from the disc was never an important contribution in the UV bands.
5.5. Discussions: Evidence of multicomponent emission

Figure 5.9: Fitted spectrum and residuals for the three models for state f6. The differences start showing up above 50 keV.

for Mkn 421 (Abdo et al., 2011a), and the UV spectral detail is not sufficient to support this interpretation (Figure 5.8). Alternatively, the underlying particle distribution might be more complex than those we studied. Nevertheless, such a particle distribution demands a concave spectrum, which is not possible with our present understanding of particle acceleration (Sahayanathan, 2008). Hence, we attribute this unusual X-ray - UV behaviour of the source to a two-population electron distribution. A similar conclusion was obtained by Aleksic et al. (2014a) by studying a flare of the same source in March 2010. Such different electron distributions can be obtained if multiple emission regions are involved in the emission process. If the flaring region is located at the recollimation zone of the jet, then a compact emission region can be created where the recollimation shock meets the jet axis (Tavecchio et al., 2011; Kushwaha et al., 2014). Alternatively, episodic particle acceleration as suggested by Perlman et al. (2006) might be the reason for the second particle distribution. Perlman et al. (2005) have shown that this can also explain the relatively weaker variability of the optical/UV bands as compared to the X-ray.

The same flare was studied by Pian et al. (2014), starting from MJD 56397, with an emphasis on INTEGRAL and Fermi-LAT data. They also found trends of spectral hardening with flux. However, unlike our results, the INTEGRAL spectral data could be well fitted by a broken power-law spectral form. They modelled the broadband SED with a simple one-zone SSC model and required strong variations in the magnetic fields and Doppler
factors to sucessfully fit the SED of different states. In addition, our results do not match those of [Massaro et al. (2004)] because we found no correlation between $\alpha_s$ and $\beta_s$. Thus, our results are inconsistent with statistical particle acceleration.

Our results indicate the potential of using broadband X-ray data to constrain the underlying particle spectrum and distinguish separate variable spectral components, especially if there are simultaneous data in other wavebands. Figure 5.9 shows the energy spectrum (in $\nu F_\nu$) and the residuals for the BPL, the CPL and the LP for the state f6. While the residuals show structure as a function of energy for energies $< 0.7$keV, especially for the CPL and the BPL, the data and model agree within 10% at these energies. Moreover, we also implemented a fit at energies $< 0.7$keV and verified that our results do not change significantly. Thus, this effect is unlikely to be a serious source of error in this work. More importantly, there is a clear systematic deviation from the data for the BPL and the CPL at the higher energies, beyond 50keV.

5.6 Conclusions

We performed a detailed study of the bright X-ray flare of Mkn 421 observed in April 2013 along with information available at other wavebands, which showed that the X-ray flares were probably caused by a separate population that did not contribute significantly to the radiation at lower energies. The major focus of the work has been to demonstrate that, with broadband X-ray spectral coverage, it is directly possible to distinguish between models of the emitting particle spectra. Now that ASTROSAT has started observations, we can have excellent simultaneous X-ray spectra from 0.3 to around 80 keV for a handful of blazars. Application of this technique to the same can throw new light on the emission mechanisms in these large scale jets.
6

1ES 1011+496: Effect of spatial particle diffusion on spectral curvature

1ES 1011+496 (RA: 10 15' 04.1"; Dec: 49° 26' 01"; J2000) is a HBL located at a redshift of $z = 0.212$. It was discovered as a VHE emitter by the MAGIC collaboration in 2007, following an optical outburst in March 2007 (Albert et al., 2007b). At its epoch of discovery, it was the furthest known TeV source, and is often used to constrain the EBL density (Ahnen et al., 2016b). In this chapter, we perform a detailed multi-epoch study of the broadband spectral behaviour of this source, which provides us with valuable information regarding the underlying particle distribution (Sinha et al., 2016a).

6.1 INTRODUCTION

1ES 1011+496 was discovered as a VHE emitter by the MAGIC collaboration in 2007, following an optical outburst in March 2007 (Albert et al., 2007b). Using the Blue Channel Spectrograph at the Multi Mirror Telescope (Brusa et al., 2003), the redshift of the source was determined to be $z = 0.212 \pm 0.002$ (Figure 6.1). The flux above 200 GeV was roughly 7% of the Crab Nebula, and the observed spectrum was reported to be a power law with a very steep index of $4.0 \pm 0.5$. After correction for attenuation of VHE photons by photons of the EBL (Kneiske & Dole, 2010), the intrinsic spectral index was computed to be $3.3 \pm 0.7$ (Figure 6.2a). Albert et al. (2007b) constructed the SED (Figure 6.2b) with simultaneous optical R-band data, and other historical data from Costamante & Ghisellini (2002) and modelled it with a single zone radiating via SSC processes. However, the model parameters could not be constrained due to the sparse sampling and the non-simultaneity of the data. Hartman et al. (1999) had suggested the
HAGAR observations of 1ES 1011+496 were carried out during the February-March 2014 season following an alert by MAGIC and VERITAS collaborations of a VHE flare from this source during 3 February to 11 February \cite{Mirzoyan_2014}. The observations were carried out in clear moon-less conditions, between 19 February to 8 March, 2014 (MJD 56707 to 56724). Each pointing source (ON) run of approximately 60mins duration was followed (or preceded) by a background (OFF) run of the same time duration at the same zenith angle and having similar night sky brightness as source region. A total of 23 run pairs are taken corresponding to a total duration of 1035 mins with common ON-OFF hour angle. The data are reduced following the procedures and quality cuts outlined in
6.2. Data analysis and lightcurves

![Graph showing TeV spectrum and broad energy distribution.]

**Figure 6.2.** Detected TeV spectrum and the constructed SED by Albert et al. (2007b). (a) The measured spectrum (black filled circles), the power-law fit to the data (solid line), the deabsorbed spectrum (brown open circles), and the fit to the deabsorbed spectrum (dashed brown line). The last measured point is a 95% upper limit. In the deabsorbed spectrum, the last spectral point at ≈600 GeV is 1.6σ above the fit and thus not significant. The Crab Nebula spectrum (green dashed line, Aharonian et al. (2000)) is shown for comparison.

(b) Spectral energy distribution of 1ES 1011+496. The two different fits are done by varying the minimum electron energy γ_{min} (see text). The other fit parameters are: R(radius of sphere)=10^{16} cm, δ(Doppler factor)=20, B(magnetic field) = 0.15 G, γ_{max}(maximum electron Lorentz factor)=2 \cdot 10^{7}, γ_{b}(break electron Lorentz factor)=5 \cdot 10^{4}, the slopes of the electron distribution n_{1} = 2 and n_{2} = 5 before and after the break energy, respectively, as well as n_{e}(normalization of the electron energy distribution) = 2 \cdot 10^{4} cm^{-3}.

The model is not intended for describing the radio data, which is assumed to originate from a larger emitting volume to avoid an intrinsic absorption.

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</tbody>
</table>

**Table 6.1.** Observation details (XRT observation ids and the total exposure time) and spectral parameters in the X-ray and GeV bands for the different states for which the SED has been extracted. The X-ray 2–10 keV flux is quoted in 10^{-11} ergs/cm²/s, and the Fermi-LAT 0.2–300 GeV flux in 10^{-8} ph/cm²/s.
No significant signal is seen from the source with 600 mins of clean data. The excess of signal over background is computed to be 706 ± 566 photons, corresponding to a significance of 1.3σ. A 3−σ upper limit of $5.6 \times 10^{-11} \text{ergs/cm}^2/\text{sec}$ for the flux of gamma rays above 234 GeV is calculated from the above data.

Fermi-LAT data from 2009-2015 are extracted and analyzed according to the procedure described in Chapter 3.1. A simple power law spectral model, with index and normalization as the free parameters, is used to model the source. Analysis of all data for this source from 2008 - 2014 yields a spectrum consistent with a simple power law with an index of 1.82 ± 0.01 (Figure 6.3a). The light curve is binned over ten days, and spectra within 0.2-300 GeV are extracted in five logarithmically binned energy bins for three epochs contemporaneous with Swift observations, corresponding to MJD (a) 56005 to 56020 (state s1) (b) 56280 to 56310 (state s2) and (c) 56692 to 56720 (state s3). LAT fluxes and spectral parameters during these epochs are given in Table 6.1. The state s3 corresponds to the period for which the highest gamma ray flux from this source is seen till date. There is no significant trend of spectral hardening with increasing flux (Spearman’s rank correlation, $r_s = -0.25$), which has been seen in many HBLs.

A total of 16 Swift pointings are available during the studied epochs, the ids of which are given in Table 6.1. Observations are available both in Windowed Timing (WT) and Photon Counting (PC) modes, and full grade selections (0-2 for WT and 0-12 for PC) are used. PC observations during the 2014 flare are heavily piled up (counts > 0.5 c/s), and is corrected for by following the procedures mentioned in Chapter 3.3. A slight curvature is detected in the XRT spectrum, and a log parabolic spectral model given by

$$dN/dE = K(E/E_b)^{-\alpha - \beta \log(E/E_b)},$$

is used to model the observed spectrum. Here, $\alpha$ gives the spectral index at $E_b$, which is fixed at 1keV during the fitting. Parameters obtained during the fitting are given in Table 6.1. To correct for the line of sight absorption of soft X-rays due to the interstellar gas, the neutral hydrogen column density is fixed at $N_H = 8.38 \times 10^{19} \text{cm}^{-2}$ (Kalberla et al., 2005).

Swift-UVOT observations cycled through the 6 filters, the optical U, V, B, and the UV UW1, UW2 and UM2. The individual exposures during each of the states are summed using uvotimsum v.1.6, and uvotsource v.3.3 tool is used to extract the fluxes from the images using aperture photometry. The observed fluxes are corrected for galactic extinction using the dust maps of Schlegel et al. (1998), and for contribution from the host galaxy following Nilsson et al. (2007), with a R-mag = 16.41 ± 0.09.

This is supplemented with VHE spectra of this source obtained during its epoch of discovery (Albert et al., 2007b) by the Major Atmospheric Gamma-ray Imaging Cherenkov (MAGIC). These spectral points have been plotted for representative purposes in Figure 6.3b and provide a lower limit for the SED modelling. Daily binned source counts from
the MAXI and flux measurements at 15 GHz from the OVRO are also taken for spectral and temporal analysis.

### 6.3 Temporal Analysis: Detection of Lognormality

The multiwavelength lightcurve for this source, from 2011 to 2014, is plotted in Figure 6.4 and the fractional variability amplitude parameter \( F_{\text{var}} \) (Chapter 4.3.1) computed.

The \textit{Fermi}-LAT flux is found to be variable on a time scale of ten days with a significance of 12.7\( \sigma \) and \( F_{\text{var}} = 0.35 \pm 0.01 \). X-ray counts from the MAXI, binned on monthly timescales, also show high variability, with \( f_{\text{var}} = 1.34 \pm 0.08 \). However, radio flux measurements from the OVRO show negligible variability with \( f_{\text{var}} \sim 0.07 \).

As motivated in Chapter 4.3.2, detection of lognormality in blazars have important implications on the jet launching mechanisms. Since the variability is minimal in the radio band, and the sampling sparse in the X-ray and optical bands, we restrict our study of lognormal flux variability to the Fermi band only. We fit the histogram of the observed fluxes with a Gaussian and a Lognormal function (Figure 6.5a), and find that a Lognormal fit (\( \chi^2/\text{dof} = 11/12 \)) is statistically preferred over a Gaussian fit (\( \chi^2/\text{dof} = 22.8/12 \)). We further plot the excess variance, \( \sigma_{\text{EXCESS}} = \sqrt{S^2 - \sigma_{\text{err}}^2} \) versus the mean flux in Figure 6.5b. The two parameters show a strong linear correlation \( r \) (prob) = 76\% (1.6 \times 10^{-5}), and is well fit by a straight line of slope \( 1.17 \pm 0.18 \) and an intercept of \( (-3.9 \pm 0.8) \times 10^{-8} \) (\( \chi^2/\text{dof} = 24.1/22 \)). This indicates a clear detection of lognormal temporal behaviour in this source.

### 6.4 Spectral Energy Distribution

The broadband SED of 1ES 1011+496, during different activity states, are modelled under the ambit of simple leptonic scenario. This, in turn, helps us to understand the nature of the electron distribution responsible for the emission through synchrotron and SSC processes. We assume the electrons to be confined within a spherical zone of radius \( R \) permeated by a tangled magnetic field \( B \). As a result of the relativistic motion of the jet, the radiation is Doppler boosted along the line of sight. Under appropriate assumptions (Ghisellini et al., 1996; Tavecchio et al., 1998; Sahayanathan & Godambe, 2012), a good sampling of the SED from radio to \( \gamma \)-rays allows one to obtain a reasonable estimation of the physical parameters. Notably, the smooth spectral curvatures, observed around the peak of the SED, may result from a convolution of the single particle emissivity with the assumed particle distribution. Since the synchrotron power function \( F(x) \) can be approximated as (Rybicki & Lightman, 1986),

\[
F(x) = x \int_x^\infty K_{5/3}(\eta)d\eta \sim 1.8x^{1/3}\exp(-x)
\]  

(57)
6. **1ES 1011+496: Effect of spatial particle diffusion on spectral curvature**

![Graph](image_url)

(a) *Fermi-LAT spectrum*

(b) *Extracted SED*

**Figure 6.3.:** (a) Energy spectrum of 1ES 1011+496 from six years of Fermi-LAT data during 2008-2014. The spectrum is well fit by a power law of index $\alpha = 1.82 \pm 0.01$. (b) Spectral energy distribution of 1ES 1011+496 during the 3 epochs studied in the paper, with simultaneous data from Swift-UVOT, Swift-XRT and the Fermi-LAT. The orange inverted triangle gives the HAGAR upper limit during the Feb-March, 2014 season. The green stars show the MAGIC spectrum during its discovery in 2007 ([Albert et al.](2007b)).
Figure 6.4.: Multiwavelength lightcurve during MJD 55600 to 56800 (calendar days 2011-2014) showing from top: Panel 1: OVRO flux in Jy; Panel 2: Optical U band flux in mJy; Panel 3: UV flux in UW2 band in mJy; Panel 4: MAXI flux (with monthly binning) in counts/sec; Panel 5: Swift-XRT flux in counts/sec; Panel 6: Fermi-LAT flux (with 10 days binning) in $\text{ph}/\text{cm}^2/\text{sec}$. The three states for which SED has been studied are marked and labelled as s1, s2 and s3 respectively.
Figure 6.5.: Detection of lognormality in 1ES 1011+496 in the Fermi energy band. The first panel shows the histogram of the observed fluxes (black points) fitted with a Gaussian (dotted blue line) and Lognormal (solid red line) function. A Lognormal fit is clearly preferred. The second panel shows the strong linear relationship seen between the flux and the excess rms. The black points denote data points averaged over 100 days, and the solid gray line the linear fit.
6.4. Spectral Energy Distribution

A sharp break in the particle spectrum will give rise to a smooth curvature in the photon spectrum. On the other hand, the underlying particle distribution itself can show a gradual transition causing the observed curvatures. To investigate this, we model the observed SED with the following choices of particle distributions:

(i) **Broken Power Law (BPL):** In this case, we assume the electron spectrum to be a sharp broken power law with indices $p$ and $q$, given by

$$
N(\gamma)d\gamma = \begin{cases} 
N_0\gamma^{-p}d\gamma, & \gamma_{min} < \gamma < \gamma_b \\
N_0\gamma_b^{(q-p)\gamma^{-q}d\gamma}, & \gamma_b < \gamma < \gamma_{max}
\end{cases}
$$

(58)

(ii) **Smooth Broken Power law (SBPL):** Here, the electron distribution is a smooth broken power law with low energy index $p$ and the high energy index $q$.

$$
N(\gamma)d\gamma = N_0\gamma_b^{-p}(\gamma/\gamma_b)^p + (\gamma/\gamma_b)^q d\gamma, \gamma_{min} < \gamma < \gamma_{max}
$$

(59)

(iii) **Power law with an exponential cutoff (CPL):** The particle distribution in this case is chosen to be a power law with index $p$ and an exponentially decreasing tail, given by

$$
N(\gamma)d\gamma = N_0\gamma^{-p}\exp\left(-\frac{\gamma}{\gamma_b}\right) d\gamma, \gamma_{min} < \gamma < \gamma_{max}
$$

(60)

Here, $\gamma_{min}$ and $\gamma_{max}$ are the minimum and maximum dimensionless energy ($E = \gamma mc^2$) of the non-thermal electron distribution, $\gamma_b$ the electron energy associated with the peak of the SED and $N_0$ the normalization. To reduce the number of unknowns, the radius $R$ is fixed at $1.3 \times 10^{16}$ cm, corresponding to a variability time scale of $t_{var} \approx 1$ day (for the Doppler factor $\delta \approx 10$). In addition, the magnetic field energy density, $U_B = \frac{B^2}{8\pi}$, is considered to be in equipartition with the particle energy density ($U_e$). The resultant model spectra, corresponding to epoch s3, for the above three choices of particle distribution are shown in Figure 6.7 along with the observed fluxes. The governing physical parameters are given in Table 6.2.

Our study shows that the commonly used electron spectrum, the BPL [e.g. Ghisellini et al. (1996); Krawczynski et al. (2004)], cannot explain the smooth curvature observed at the X-ray energies for this source implying that the synchrotron emissivity function alone is not sufficient to give rise to the observed curvature, and that the underlying particle spectrum itself must have a gradual transition as opposed to a sharp break. This suggests that the SBPL and CPL are the better choices to represent the observed SED and in Figure 6.6 we show the model spectra corresponding to these particle distributions for all the three epochs considered in this study. Both these models can well reproduce the observed spectrum, during all three epochs, and the absence of simultaneous hard X-ray and TeV measurements prevents us from distinguishing between the two models. Particularly, with the current sampling, the index $q$ and the $\gamma_{max}$ for the SBPL cannot
6. 1ES 1011+496: Effect of spatial particle diffusion on spectral curvature

Figure 6.6.: Spectral energy distribution of 1ES 1011+496 during the 3 epochs studied in the paper, with simultaneous data from Swift-UVOT, Swift-XRT and the Fermi-LAT. The orange inverted triangle gives the HAGAR upper limit during the Feb-March, 2014 season. The green stars show the MAGIC spectrum during its discovery in 2007 (Albert et al. (2007b)). The SEDs are modelled with a one zone SSC with the underlying electron distribution as (a) A power law with exponential cutoff and (b) A smooth broken power law.

be well constrained, and the latter is fixed at $10^7$. The model parameters describing the observed SED for the three epochs for the SBPL and the CPL are also listed in Table 6.2.

The different flux states can be reproduced by mainly changing the particle indices and the break energy; whereas, the variations in other parameters like the Doppler factor and the magnetic field are minimal. While the total bolometric luminosity, $L$, changes by more than a factor of 3, the variations in $B$ and $\delta$ are less than 10%. This probably suggests, that the variation in the flux states may occur mainly due to changes in the underlying particle distributions, rather than the other jet properties.

6.5 ELECTRON ESCAPE AND SPECTRAL CURVATURES

A detailed study of the multiwavelength spectral behaviour of 1ES 1011+496 during three different epochs under simple synchrotron and SSC models demands an underlying electron distribution with a smooth curvature. Though such a requirement can be satisfied by assuming the underlying electron distribution as either SBPL or CPL, the absence of hard X-ray data prevents one from distinguishing between these two choices. However, the CPL is preferred as it has a lesser number of free parameters (and with better constraints) as compared to the SBPL. In this section, we try to find a plausible origin for such a distribution due to escape of particles from the emission region.

We consider a situation where a non-thermal distribution of electrons, produced by an acceleration mechanism (plausibly at a shock front), is injected into the emission region. This model assumes the acceleration and emission regions to be separated, namely, very little radiation is emitted by a particle whilst in the acceleration zone (Kirk et al. 1998, 1994). Both the magnetic field and the particle distribution function are assumed
6.5. Electron escape and spectral curvatures

Figure 6.7.: The state s3 modelled with the underlying spectrum as a BPL (dotted black line); a SBPL (dashed red line); and a CPL (dashed blue line). The BPL fails to reproduce the smooth curvature of the observed SED (shown in green).

Table 6.2.: Models parameters and the total bolometric luminosity ($L$) for the different particle distributions during the three epochs. While the BPL cannot reproduce the observed spectrum satisfactorily, the SBPL and the CPL can. The last column under CPL gives the $\gamma_c$ as obtained from Equation 64.
homogeneous throughout the emission region. The electrons leave the emission region at some characteristic time scale, $t_{\text{esc}}$, and after escape, a particle no longer radiates. The particle number density, $N(\gamma, t)$, with Lorentz factors between $\gamma$ and $\gamma + d\gamma$ in the emission region can then be conveniently described by the kinetic equation (Kardashev, 1962)

$$\frac{\partial N}{\partial t} - \frac{\partial}{\partial \gamma}(P(\gamma)N) + \frac{N}{t_{\text{esc}}(\gamma)} = Q(\gamma)\Theta(\gamma - \gamma_{\text{max}})\delta(t - t_0)$$

where $P(\gamma)$ is the energy loss rate due to synchrotron and SSC processes, and $Q(\gamma) = Q_0\gamma^{-p}$ is the power law distribution of electrons injected by the acceleration process at time $t_0$ with maximum injected electron energy being $\gamma_{\text{max}}$.

### 6.5.1 Analytic solution: Thomson scattering

For a time independent energy loss rate $P = P(\gamma)$, and an energy dependent escape rate, $t_{\text{esc}} = (\gamma\tau^\xi)$, Equation 61 can be analytically solved when the Inverse Compton scattering is confined to the Thomson regime following the Green’s function method outlined in Section 3.2 of Atoyan & Aharonian (1999),

$$N(\gamma, t) = \frac{K\Gamma_0^{2-p}}{\gamma^2} \exp\left[-\int_0^t dx \frac{\tau(\Gamma_x)}{\tau(\Gamma_x)}\right]$$

where

$$t - x = \int_{\gamma}^{\Gamma_x(\gamma, t)} d\gamma \frac{d\gamma}{P(\gamma)}$$

is the trajectory of the particle in energy space.

The final solution is obtained as

$$N(\gamma, t) = \begin{cases} \frac{Q_0\Gamma_0^{2-p}}{\gamma^2} \exp\left[-\gamma_{\text{max}} \gamma_c^{1/\xi} \left\{ \left( \frac{1}{\gamma} - \frac{1}{\gamma_{\text{max}}} \right)^{\xi+1} \right\} \right] & \text{for } \xi \neq -1 \\ \frac{Q_0\Gamma_0^{2-p}}{\gamma^2} \left(1 - \frac{\gamma}{\gamma_{\text{max}}}\right)^{\gamma_c/\xi} & \text{for } \xi = -1 \end{cases}$$

Here $\Gamma_0 = (1/\gamma - 1/\gamma_{\text{max}})^{-1}$ is the energy of the electron at $t_0$ evolving to $\gamma$ at $t$, and $\gamma_c(t) = (t/\tau)^{1/\xi}$ is the characteristic energy below which particles have not diffused out of the emission region.

### 6.5.2 Numerical solution: Klein-Nishina scattering

However, detection of the source at VHE energies suggests that the Thomson scattering approximation of SSC process may not be valid and one needs to incorporate Klein-Nishina (KN) correction in the cross-section (Tavecchio et al., 1998). Hence, we numerically
6.6. Conclusions

The blazar, 1ES 1011+496, underwent a major γ-ray flare during February, 2014, triggering observations at other wavebands, thereby, providing simultaneous observations of the source at radio/optical/X-ray/γ-ray energies. The TeV flare seen by VERITAS
Figure 6.9: Model curves obtained by changing the energy dependence of the escape time scale for the state s3. The dashed orange line is obtained for a energy independent escape ($\xi = 0$), and fails to reproduce the observed spectrum. The blue curve (dashed-dotted) is obtained for the extreme case of Bohm diffusion ($\xi = -1.0$), and models the data reasonably well. The best match between data and model is obtained for $\xi = -0.7$ and is represented by the solid green line.

Figure 6.10: The solution to Equation 64 with $\xi = -0.7$ (red solid line) resembles a power law with an exponentially falling tail (black dotted line).
between February 3-11, 2014 decayed down by February 19, 2014 as indicated by the HAGAR upper limits. This is also seen in the flux decrease in the Fermi and the X-ray bands. In this work, we analyzed the simultaneous multiwavelength spectrum of the source and obtained the broadband SED during three different epochs. The observed SEDs over these epochs clearly show a trend of the synchrotron peak moving to higher energies during increased flux states, similar to the "bluer when brighter" trend seen by Bottcher et al. (2010) during 5 years of optical observations of this source. However, Bottcher et al. (2010) attributed the observed variability primarily due to magnetic field changes in the jet, whereas our broadband spectral modelling results indicate the spectral behaviour is dominated by changes in the particle spectrum. The spectra during all the states demand a smooth curvature in the underlying particle spectrum, e.g., a SBPL or a CPL. The inferred particle power law index $p \sim 2.1$ indicates that the particles are most likely accelerated at relativistic shocks (Fermi, 1949).

We show a smoothly varying particle spectrum, demanded by the present study, can be easily obtained by assuming an energy dependent particle escape ($t_{\text{esc}} \propto \gamma^\xi$) mechanism in the jet. In particular, an energy dependence of $\xi = -0.7$ closely resembles a CPL and best represents the observed spectrum, suggesting the particle escape is largely governed by Bohm type diffusion process ($\xi = -1$). Non availability of hard X-ray observation prevents us from distinguishing between CPL and SBPL particle spectra. Future observations in the hard X-ray band from the newly launched ASTROSAT (Singh et al. 2014b), can be crucial in resolving this uncertainty.

The detection of lognormal flux variability in the long term (6 yrs) gamma ray flux distribution and the linear flux-rms relation follows similar recent detections in other blazars. While the $\gamma$-ray flux distribution could be modelled by a single lognormal distribution for other HBLs (Mkn421; Sinha et al. (2016b) and PKS2155-304; Chevalier et al. (2015)), the FSRQ PKS 1510-089 (Kushwaha et al. 2016) required a sum of two such distributions. Since similar trends have been seen in the X-ray band in sources like the Seyfert 1 galaxy, Mkn 766 (Vaughan et al. 2003), where the physical process responsible for the X-ray emission originates in the galactic disc, and other compact accreting systems like cataclysmic variables (Giannios 2013), such trends have been claimed as universal signs of accretion induced variability. The other option might be that the underlying parameters responsible for the observed emission (e.g.: the Doppler factor, magnetic field, etc) themselves have a lognormal time dependence (Giebels & Degrange, 2009). Since the result of our spectral modelling indicates that the flux variability is mainly induced by changes in the particle spectrum rather than the other jet properties, it seems reasonable to believe that lognormal fluctuations in the accretion rate give rise to an injection rate into the jet with similar properties. With the Fermi mission now into its ninth year of operation, we have unprecedented continuous flux measurements for a large sample of blazars. A systematic study of the same can throw new light on the origin of the jet launching mechanisms in supermassive blackholes.
7

The Extragalactic Background Light: Estimation using TeV observations

The universe is not as dark as we sometimes imagine; even its largest voids are filled with light. While the total energy content of the universe in the electromagnetic spectrum spans close to 20 decades in wavelength from γ-rays to radio (Figure 7.1), the Extragalactic Background Light (EBL) is usually (and in this thesis) defined as the extragalactic spectrum from Ultraviolet (UV) to Infrared (IR) wavelengths ($\lambda = 0.1 - 1000\mu m$) (Hauser & Dwek [2001]; Dwék & Krennrich [2013]). It is the second most dominant background in the universe after the Cosmic Microwave Background (CMB). It is the relic radiation containing information about the structure formation epoch of the universe, and hence, an important cosmological quantity (Dwek & Krennrich [2013]; De Angelis et al. [2013]). Moreover, VHE photons from distant sources blazars are absorbed en-route by forming electron-positron pairs on interaction with the photons of the EBL, causing the observed spectrum to differ significantly from the intrinsic one. This makes a proper understanding of the EBL crucial for VHE astrophysics.

In this chapter we discuss the challenges in direct measurements and theoretical predictions of the EBL intensity. Novel techniques using the VHE blazar observations have been proposed to indirectly constrain the EBL intensity, and we show how a statistical study of TeV blazars can be used to obtain a model independent estimate of the EBL (Sinha et al. [2014]).

7.1 INTRODUCTION

The cosmological significance of the EBL was recognised almost immediately with the advent of modern astronomy. It was first proposed in its mature form by the German

“It is far better to grasp the universe as it really is than to persist in delusion, however satisfying and reassuring.”
Carl Sagan
The Extragalactic Background Light: Estimation using TeV observations

Figure 7.1: Intensity of the extragalactic background (νI, in units of nW/m² sr⁻¹) as a function of the wavelength in metres as taken from Cooray (2016). The existing measurements from the literature are combined to highlight the best determined estimates for the background from γ-rays to radio.

amateur astronomer, Heinrich Wilhelm Olbers in 1823, who assumed the universe to be a static sphere of radius r, uniformly filled with stars. Since the number of stars at a distance r increases as \( \sim r^2 \), thus cancelling the \( \sim 1/r^2 \) fall-off in the apparent brightness of a single star, he concluded that the night sky should theoretically be expected to be as bright as the daytime sky. Today, this apparent conflict is easily explained by the expansion of the universe, the finite speed of light and, most importantly, the finite lifetimes of stars.

We now understand that while the night sky is far from dark, extragalactic sources contribute less than 1% of the sky brightness in the UV to IR frequencies. The main contamination to the EBL comes from strong foreground contamination by the Galactic and zodiacal light, and attempts to directly measure the EBL intensity depend on the choice of the zodiacal light models (Kelsall et al., 1998; Wright, 1998). However, with the launch of the Galex (UV) and the Spitzer, Akari and Herschel (IR) space observatories, different upper and lower limits on EBL, based on various observations and deep galaxy number counts, have been put forth (Figure 7.2) (Hauser et al., 1998; Domínguez et al., 2011; Madau & Pozzetti, 2000; Helgason & Kashlinsky, 2012). It is known that the EBL SED is bimodal, with the main contributors being the stellar emission (peaking at optical-UV) and the dust emission (peaking at IR).

Several distinct approaches have been used to theoretically model the intensity and spectral distribution of the EBL by evolving stellar populations and galaxies under various
7.2. EBL estimation from VHE observation

En route to Earth, $\gamma$-rays from cosmological sources have to pass through the radiation field of the EBL, thereby causing the observed spectrum to differ significantly from the intrinsic one. The EBL intensity can thus be estimated from gamma ray observations of blazars under various assumptions of the intrinsic spectrum [Madau & Phinney 1996; Coppi & Aharonian 1999].
7. The Extragalactic Background Light: Estimation using TeV observations

Figure 7.3: Comparison of $\tau$ at $z=0.5$, taken from [Mankuzhiyil (2010)]. The blue line corresponds to the model of Gilmore [Gilmore et al. (2009)], red line to Franceschini [Franceschini et al. (2008)], green line to Kneiske [Kneiske & Dole (2010)], cyan line to Raue [Raue & Mazin (2008)], black line to Stecker (2006) (solid line: fast evolution, dotted line: baseline fit).

7.2.1 Interaction of VHE photons with the EBL

A high energy photon of energy $E_\gamma$ interacts with a low energy photon of energy $\epsilon_b$, leading to a creation of a particle anti-particle pair when the total $\gamma$-ray energy in the center of momentum of the system exceeds the rest frame energy of the two particles. The threshold for the creation of an $e^+e^-$ pair is then given by:

$$\epsilon_{th}(E_\gamma, \mu, z) = \frac{2(m_e c^2)^2}{E_\gamma (1-\mu)}$$

where $\mu \equiv \cos \theta$, and $\theta$ is the angle between the two photons, as illustrated in Figure 7.4.

The cross-section for the $\gamma-\gamma$ interaction is given by:

$$\sigma_{\gamma\gamma}(E_\gamma, \epsilon, \mu, z) = \frac{3\sigma_T}{16} (1-\beta^2) \left[ 2\beta (\beta^2-2) + (3-\beta^4) \ln\left(\frac{1+\beta}{1-\beta}\right) \right]$$

where

$$\beta \equiv \sqrt{1 - \frac{\epsilon_{th}}{\epsilon}}$$

7.2.2 EBL estimates computed from VHE observations

Though the broadband emission from blazars is not well understood, various constraints on the EBL density have been derived under different assumptions of the intrinsic blazar...
7.2. EBL estimation from VHE observation

Figure 7.4.: Schematic illustration of the $\gamma - \gamma$ pair production reaction, showing the definition of the angle $\theta$ between the interacting photons.

Figure 7.5.: The cross section for the $\gamma - \gamma$ interaction. Left panel: its dependence on $\beta$ [eq. (7)]. The cross section peaks at a value of $\beta = 0.70$; Right panel: its dependence on $b$ for different angles of incidence. When the photons are moving in the same direction ($\theta = 0$), the cross section collapses to a delta-function at $b = 0$, and the energy threshold becomes infinite.
spectra. However, the estimated EBL depends heavily on the underlying assumptions of the VHE emission mechanisms (Figure 7.6). Assuming that the EBL spectral shape is described by the theoretical estimates, Stanev & Franceschini (1998) used the VHE spectrum of Mkn501 during a flare to constrain the overall EBL intensity and corresponding spectral index. Aharonian et al. (2006b) set an upper limit on the EBL intensity by assuming that the intrinsic VHE spectral index of blazars cannot be harder than 1.5. Similar upper limits on EBL have been put forward by various authors, based on allowed hardness of the intrinsic VHE spectrum (Guy et al., 2000; Mazin & Raue, 2007; Orr et al., 2011). However, caveats to this approach have been extensively discussed in literature (Stecker et al., 2007; Katarzyński et al., 2006; Böttcher et al., 2008; Aharonian et al., 2008b; Krennrich et al., 2008; Lefa et al., 2011; Zacharopoulou et al., 2011). While the GeV energy spectra of most blazars obey the $\Gamma = 1.5$ limit, some extreme blazars (Section 7.3) do indeed exhibit very hard spectra with $\Gamma < 1.5$ (Ackermann et al., 2011).

Before 2000, the number of blazars detected at VHE energies were few ($\sim 4$), primarily due to low sensitivity of first generation atmospheric Cherenkov telescopes (Costamante & Ghisellini, 2002). However, with the advent of new generation high sensitivity telescopes, namely VERITAS, MAGIC and HESS, the number of blazars detected at these energies are more than 55 (Wakely & Horan, 2016). Hence the present period allows one to perform a statistical study of VHE blazars to estimate the EBL, independent of various emission models. A study of similar kind has been performed by Ackermann et al. (2012) using blazars detected by the Fermi-LAT, a satellite based gamma ray experiment. They used the GeV spectrum of $\sim 150$ blazars to estimate the EBL at UV-optical wavelengths.

Figure 7.6.: Limits on the EBL as determined from $\gamma$–ray observations of blazars; taken from Dwek & Krennrich (2013).
7.3 Statistical signature on VHE spectra of blazars

The effect of the absorption of VHE photons by the EBL is to steepen the VHE spectra, hence providing a signature of the EBL (Vassiliev 2000; Mankuzhiyil et al. 2010). Since sources at higher redshifts are more affected by absorption; their average spectra are expected to be steeper than the low redshift ones. To investigate this, we perform a correlation study between the VHE spectral index $\Gamma$, and redshift for a homogeneous set of sources which are detected at VHE. We select all HBLs detected by the HESS, MAGIC and VERITAS telescopes with known redshifts and measured spectral index. We restrict our sample to only HBLs since an intrinsic systematic hardening with source type, from FSRQ to HBLs, has been observed at the GeV energies (Ackermann et al. 2011); moreover, a non-homogeneous sample may lead to spurious correlations. This restricts the farthest source in the sample to be 1ES 0414+009 at a redshift of $z = 0.287$. In Table 7.1 we list all the HBLs detected at VHE along with ones for which the redshift information is uncertain (lower group). Again from the list, we group 8 HBLs (middle group), due to their unusual properties. The de-absorbed VHE spectral index of these sources, obtained considering various EBL models, suggests their spectrum is extremely hard with index $< 2$ (Tavecchio 2014; Tanaka et al. 2014). Moreover, these sources are less luminous as compared to other HBLs with their synchrotron spectrum peaking at energies $> 10keV$. Due to these peculiar properties, these sources have been classified as extreme HBLs (EHBL) and occupy a distinct position in the so called blazar sequence (Costamante & Ghisellini 2002).

In Figure 7.7, we show the variation of $\Gamma$ with redshift for all the sources listed in Table 7.1. A Spearman rank correlation analysis on all sources with known redshift shows that they are well correlated with a rank correlation coefficient, $r$ (prob) = 0.58 ($9.4 \times 10^{-4}$). Repeating the study with EHBLs removed from the list improves the correlation considerably, with $r$ (prob) = 0.75 ($8.02 \times 10^{-5}$). Hence this study again suggests that, probably EHBLs can be treated as a separate class of HBLs; however, poor statistics does not let one to assert this inference strongly.

Although the redshift range of the sample is small, a positive correlation may also occur due to rapid redshift evolution of HBLs, such that the intrinsic VHE spectral index increases with redshift. If so, then the redshift evolution should be expected to have an effect on the spectral shape at other wavelengths. To examine this possibility, we further studied the correlation between X-ray spectral indices with redshift for HBLs using a) 70 months of Swift-BAT catalog consisting of 27 HBLs (Baumgartner et al. 2013), b) six year BeppoSAX catalog consisting of 39 HBLs (Donato et al. 2005) and c) archival X-ray catalog from ASCA, EXOSAT, BeppoSAX, ROSAT and EINSTEIN consisting of 61 HBLs (Donato et al. 2001). We found no evidence for the X-ray spectral index to be correlated with the redshift and obtained the rank correlation coefficient and

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1 We define the spectral index, $\Gamma$, such that $F_E \propto E^{-\Gamma}$, where $F_E$ is the flux density at energy $E$.

2 In this work, we restrict our sample of HBLs to only those with $z<0.5$, consistent with our VHE-HBL sample
7. The Extragalactic Background Light: Estimation using TeV observations

<table>
<thead>
<tr>
<th>Source name</th>
<th>$z$</th>
<th>$\Gamma$</th>
<th>$F_{VHE}$</th>
<th>$\alpha_2$</th>
<th>$\alpha_f$</th>
<th>Ref</th>
</tr>
</thead>
<tbody>
<tr>
<td>Mkn421</td>
<td>0.031</td>
<td>2.72 ± 0.12</td>
<td>0.2 - 10</td>
<td>2.58 ± 0.03</td>
<td>1.771 ± 0.012</td>
<td>1</td>
</tr>
<tr>
<td>Mkn501</td>
<td>0.034</td>
<td>2.79 ± 0.12</td>
<td>0.1 - 2.0</td>
<td>2.42 ± 0.01</td>
<td>1.738 ± 0.027</td>
<td>2</td>
</tr>
<tr>
<td>1ES 2344+514$^*$</td>
<td>0.044</td>
<td>2.95 ± 0.20</td>
<td>0.2 - 2.0</td>
<td>2.62 ± 0.50</td>
<td>1.716 ± 0.08</td>
<td>3</td>
</tr>
<tr>
<td>Mkn180</td>
<td>0.045</td>
<td>3.30 ± 0.70</td>
<td>0.2 - 6.6</td>
<td>-</td>
<td>1.74 ± 0.083</td>
<td>4</td>
</tr>
<tr>
<td>1ES 1959+650</td>
<td>0.048</td>
<td>2.95 ± 0.18</td>
<td>0.2 - 2.5</td>
<td>2.19 ± 0.02</td>
<td>1.937 ± 0.031</td>
<td>5</td>
</tr>
<tr>
<td>1ES 1727+502</td>
<td>0.055</td>
<td>2.70 ± 0.50</td>
<td>0.15 - 2.0</td>
<td>-</td>
<td>2.0 ± 0.2</td>
<td>6</td>
</tr>
<tr>
<td>PKS 0548–322$^*$</td>
<td>0.069</td>
<td>2.86 ± 0.34</td>
<td>0.3 - 4.0</td>
<td>2.28 ± 0.23</td>
<td>-</td>
<td>7</td>
</tr>
<tr>
<td>PKS 2005–489</td>
<td>0.071</td>
<td>3.00 ± 0.22</td>
<td>0.4 - 4.0</td>
<td>2.46 ± 0.01</td>
<td>1.779 ± 0.047</td>
<td>8</td>
</tr>
<tr>
<td>RGB J0152+017</td>
<td>0.080</td>
<td>2.95 ± 0.36</td>
<td>0.1 - 4.0</td>
<td>-</td>
<td>1.788 ± 0.137</td>
<td>9</td>
</tr>
<tr>
<td>BZB J0013-1854</td>
<td>0.095</td>
<td>3.4 ± 0.10</td>
<td>0.2 - 2.0</td>
<td>-</td>
<td>1.96 ± 0.2</td>
<td>10</td>
</tr>
<tr>
<td>1ES 1312-423</td>
<td>0.105</td>
<td>2.85 ± 0.7</td>
<td>0.2 - 4.0</td>
<td>-</td>
<td>1.4 ± 0.4</td>
<td>11</td>
</tr>
<tr>
<td>PKS 2155–304</td>
<td>0.116</td>
<td>3.34 ± 0.10</td>
<td>1.0 - 10.0</td>
<td>2.36 ± 0.01</td>
<td>1.838 ± 0.015</td>
<td>12</td>
</tr>
<tr>
<td>B3 2247+381</td>
<td>0.119</td>
<td>3.20 ± 0.60</td>
<td>0.1 - 2.0</td>
<td>-</td>
<td>1.837 ± 0.113</td>
<td>13</td>
</tr>
<tr>
<td>H 1426+428$^*$</td>
<td>0.129</td>
<td>3.50 ± 0.40</td>
<td>0.3 - 2.00</td>
<td>2.54 ± 0.24</td>
<td>1.316 ± 0.123</td>
<td>14</td>
</tr>
<tr>
<td>1ES 1215+304</td>
<td>0.130</td>
<td>2.96 ± 0.14</td>
<td>0.1 - 1.51</td>
<td>2.29 ± 0.16</td>
<td>2.019 ± 0.036</td>
<td>15</td>
</tr>
<tr>
<td>1ES 0806+524</td>
<td>0.138</td>
<td>3.60 ± 1.00</td>
<td>0.3 - 1.02</td>
<td>2.67 ± 0.08</td>
<td>1.938 ± 0.057</td>
<td>16</td>
</tr>
<tr>
<td>BZB J1010–3119</td>
<td>0.143</td>
<td>3.08 ± 0.42</td>
<td>25.3 ± 30.0</td>
<td>2.15 ± 0.06</td>
<td>2.239 ± 0.142</td>
<td>17</td>
</tr>
<tr>
<td>RX J0648+1516</td>
<td>0.179</td>
<td>4.40 ± 0.80</td>
<td>0.2 - 0.65</td>
<td>2.51 ± 0.06</td>
<td>1.737 ± 0.106</td>
<td>18</td>
</tr>
<tr>
<td>RBS 0413</td>
<td>0.190</td>
<td>3.18 ± 0.68</td>
<td>0.3 - 1.0</td>
<td>2.22 ± 0.07</td>
<td>1.551 ± 0.112</td>
<td>19</td>
</tr>
<tr>
<td>1ES 1011+496</td>
<td>0.212</td>
<td>4.00 ± 0.50</td>
<td>0.15 - 0.8</td>
<td>-</td>
<td>-</td>
<td>20</td>
</tr>
<tr>
<td>PKS 0301–243</td>
<td>0.266</td>
<td>4.60 ± 0.70</td>
<td>0.1 - 5.0</td>
<td>2.51 ± 0.1</td>
<td>1.938 ± 0.031</td>
<td>21</td>
</tr>
<tr>
<td>HESS J1943+213</td>
<td>0.14</td>
<td>3.1 ± 0.30</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>22</td>
</tr>
<tr>
<td>1ES 1440+122</td>
<td>0.163</td>
<td>3.4 ± 0.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>23</td>
</tr>
<tr>
<td>PKS 0447-439</td>
<td>0.175</td>
<td>3.8 ± 0.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>24</td>
</tr>
<tr>
<td>1ES 0502+675</td>
<td>0.341</td>
<td>3.9 ± 0.4</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>25</td>
</tr>
<tr>
<td>PG 1553+113</td>
<td>0.5 ± 0.08</td>
<td>4.1 ± 0.3</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>26</td>
</tr>
<tr>
<td>PKS 1424+240</td>
<td>0.604</td>
<td>4.2 ± 0.7</td>
<td>-</td>
<td>-</td>
<td>-</td>
<td>27</td>
</tr>
</tbody>
</table>

null hypothesis probability for the chosen set of catalogs as, a) \( \text{rs (prob)} = 0.05 \) (Swift-BAT), b) \( \text{rs (prob)} = -0.07 \) (BeppoSAX) and c) \( \text{rs (prob)} = 0.03 \) (archival). The plot of X-ray index vs. redshift for these three catalogs is given in Figure 7.8. Spearman rank correlation study was also performed between low energy gamma ray (GeV) spectral index and redshift (Figure 7.9) for the 62 HBLs listed in the second catalog of Fermi-LAT (Ackermann et al., 2011). For this, we obtained \( \text{rs (prob)} = 0.02 \) (0.85), suggesting these quantities are uncorrelated. Hence, these studies violate the conjecture on redshift evolution of the spectral index of HBLs, and instead support the steepening of VHE spectral index as a result of EBL absorption.

The observed correlation between the VHE spectral index and redshift could also possibly arise due to selection effects. The luminosity is expected to correlate with redshift due to Malmquist bias, and if the index correlates with VHE luminosity then a correlation with redshift may occur. However, for the HBL observed by MAGIC (de Angelis et al. 2009), while the VHE luminosity does correlate with redshift as expected, there is no significant correlation between the VHE index with luminosity. Here we restricted our sample only to MAGIC detected HBL as the threshold energy is different for each experiment. This correlation is shown in Figure 7.10 and a Spearman rank analysis gives \( \text{rs (prob)} = 0.26(0.34) \). At X-ray energies, the correlation study between the spectral index and X-ray luminosity resulted in a) \( \text{rs (prob)} = -0.07(0.15) \) (Swift-BAT catalog); b) \( \text{rs (prob)} = -0.20(0.16) \) and (BeppoSAX catalog) and c) \( \text{rs (prob)} = -0.14(0.28) \) (archival). Similarly, correlation study between GeV spectral index and luminosity for the HBLs from Fermi-LAT catalog gives \( \text{rs (prob)} = 0.11(0.37) \). Based on this study, we can exclude the possibility of selection effect in the observed correlation between the VHE spectral index and redshift. Significant correlation between the difference of the VHE index and the one measured by Fermi-LAT with redshift was reported by several authors (Stecker & Scully, 2010; Prandini et al., 2010; Sanchez et al., 2013). For the HBLs listed in Table 7.1 (top group), we also observed significant correlation between these quantities with \( \text{rs} = 0.71 \) and \( P_{\text{rs}} = 2.2 \times 10^{-4} \); however, this correlation is weaker than the one between VHE spectral index and redshift.

Based on these studies, it is quite evident that the correlation between VHE spectral index and redshift can be attributed solely due to the effect of EBL induced absorption and that the intrinsic spectral index is uncorrelated with redshift.

7.4 EBL ESTIMATION

The observed VHE spectra of the HBL are well reproduced by a power law, and hence the observed flux, \( F_o(E_i) \), from a source at redshift \( z \) will be

\[
F_o(E_i) = F_i(E_i) e^{-\tau(E_i,z)}
\]

\[
\propto E_i^{-\Gamma}
\]
7. The Extragalactic Background Light: Estimation using TeV observations

Figure 7.7.: Distribution of the observed VHE spectral index of the selected HBL with redshift. The black stars correspond to extreme HBL and blue open diamonds are the ones with uncertain redshifts. The lower limits on the redshifts have been shown with solid (blue) arrows. The solid line (green) is the best fit straight line to the HBL denoted by filled circles (red).

Figure 7.8.: Distribution of the observed X-ray spectral index of HBL with redshift. The blue diamonds are from the Swift-BAT catalog (Baumgartner et al., 2013), the green circles from the Beppo-SAX catalog (Donato et al., 2005), and the red stars from archival X-ray catalog (Donato et al., 2001).
7.4. EBL Estimation

Figure 7.9.: Distribution of the observed Fermi-LAT spectral index of blazars with redshift and luminosity, taken from Ackermann et al. (2011). The red points correspond to FSRQs, light blue LBL, green LBL and deep blue points to HBLs, which are the subject of our present study.

Figure 7.10.: Distribution of the observed VHE spectral index with luminosity of the HBL observed by the MAGIC telescope de Angelis et al. (2009).
7. The Extragalactic Background Light: Estimation using TeV observations

where \( F_i(E_i) \) is the de-absorbed flux at energy \( E_i \) and \( \tau \), the optical depth due to EBL absorption given by (Gould & Schréder, 1967)

\[
\tau(E_i, z) = \int_0^z d\epsilon_{z'} \frac{dl}{dz} \int_{-1}^1 d\mu \frac{(1-\mu)}{2} \int_{\epsilon_{th}}^{\infty} d\epsilon_{z'} n(\epsilon_{z'}, \epsilon_{z'}, \mu) \sigma_{\gamma\gamma}(E_i, \epsilon_{z'}, \mu) \tag{69}
\]

Here,

\[
\frac{dl}{dz} = \frac{c}{H_0 \left( 1 + z' \right) \sqrt{\Omega_\Lambda + \Omega_M (1 + z')^3}} \tag{70}
\]

is the distance traveled by a photon per unit redshift with \( c \) as the velocity of light, \( n \) is the number density of the EBL photon of energy \( \epsilon_{z'} = \epsilon_0(1 + z') \) at redshift \( z' \), corresponding to a photon energy \( \epsilon_0 \) at \( z = 0 \), \( \epsilon_{th} = 2m_e^2c^4(1 + z')/(E_i(1-\mu)) \) is the threshold soft photon energy with \( \mu \) the cosine of the interaction angle and the pair production cross section, \( \sigma_{\gamma\gamma} \), is given by

\[
\sigma_{\gamma\gamma}(E, \epsilon, \mu) = \frac{2\pi\alpha^2}{3m_e^2} (1-\beta^2) \times \left[ 2\beta(\beta^2-2) + (3-\beta^4) \ln \left( \frac{1+\beta}{1-\beta} \right) \right] \tag{71}
\]

with \( \beta(E, \epsilon) = \sqrt{1-(2m_e^2c^4)/(\epsilon E(1-\mu))} \) being the speed of the electron/positron in the centre of mass frame, \( \alpha \) is the fine structure constant and \( m_e \) is the electron rest mass. Since VHE sources are detected only at low redshifts, one can neglect the evolution of EBL and hence (Madau & Phinney, 1996),

\[
n(\epsilon_z, z) \approx (1+z)^3 n(\epsilon_z) \tag{72}
\]

For an isotropic EBL distribution, the angle integrated cross section (Gould & Schréder, 1967)

\[
\bar{\sigma}_{\gamma\gamma}(E, \epsilon) = \frac{1}{2} \int_{-1}^1 d\mu (1-\mu) \sigma_{\gamma\gamma}(E, \epsilon, \mu) \tag{73}
\]

peaks at \( E\epsilon = 3.56 m_e^2 c^4 \). Approximating \( \bar{\sigma}_{\gamma\gamma} \) as a delta function along with \( E_z \approx E_i \) and \( \epsilon_z \approx \epsilon_0 \), equation (69) can be simplified to

\[
\tau(E, z) \approx A_{\gamma\gamma} \epsilon n(\epsilon) f(z) \tag{74}
\]

where \( A_{\gamma\gamma} \approx 3.7 \times 10^{-26} \text{ cm}^2 \) is a constant, \( \epsilon \approx \frac{3.6 m_e^2 c^4}{E} \) and \( f(z) \) is given by

\[
f(z) = \int_0^z d\epsilon_{z'} \frac{dl}{dz'} (1+z')^3 \approx \frac{c}{H_0 z} \tag{75}
\]
If the source spectrum is assumed to be a power-law, \( F_i(E) \propto E^{-\zeta} \), then using equations (68) and (74) we obtain

\[
\epsilon n(\epsilon) = k \ln \left( \frac{\epsilon_p}{\epsilon} \right) \quad (76)
\]

where \( k = \frac{1 - \zeta}{A_{\gamma\gamma}(z)} \) and \( \epsilon_p \approx \frac{3.56 m_e^2 c^4}{E^*} \) are source independent constants with \( E^* \) being the energy of the gamma ray photon at which the EBL induced absorption is negligible. While this form of the EBL spectrum is derived for the approximate optical depth equation (74), we have verified numerically that for the range of redshifts considered here, this EBL spectral shape will result in a nearly power-law observed spectrum. In particular, we have verified that if the EBL spectra is defined by equation (76) and the absorption optical depth is given by equation (69), the observed VHE spectrum for a source at \( z = 0.3 \) can be well described as a power-law. The deviation from a power-law for sources with \( z < 0.3 \) is less than 10%. Hence for all calculations in this work we have used equation (69) for the optical depth. It may be noted that Stecker & Scully (2006) obtained a similar form of the optical depth while approximating a theoretical EBL spectrum by an analytic expression. However, here we arrive at this form of the EBL spectrum equation (76) only from the criterion that both the intrinsic and absorbed VHE spectra are well described by a power-law and hence our approach is independent of any cosmological calculations.

The EBL spectrum given by equation (76) is characterized by two constants, namely \( k \) and \( \epsilon_p \), which in turn determines the source spectral index. Since the source spectral index should be uncorrelated with redshift (Section 7.3), the allowed range of \( k \) and \( \epsilon_p \) is restricted. For \( k = 2.4 \times 10^{-3} \text{cm}^{-3} \) and \( \epsilon_p = 4.6 \text{ eV} \), we found that the computed source spectral indices, for the sources listed in Table 7.1 (top group), turn out to be “most” uncorrelated with \( rs = 0.001 \) and a maximum null hypothesis probability \( P_{rs} = 0.99 \). Within \( 1-\sigma \) confidence limit, corresponding to \( P_{rs} > 0.33 \), we obtained the range of \( k \) and \( \epsilon_p \) as \( 2.2^{+1.6}_{-0.7} \times 10^{-3} \text{ cm}^{-3} \) and \( 4.6^{+4.4}_{-3.4} \text{ eV} \), respectively. The resultant EBL spectrum, consistent with these values of \( k \) and \( \epsilon_p \), is plotted in Figure 7.11 along with the constraints derived from various observations (Dwek & Krennrich, 2013) and other theoretical estimates (Gilmore et al., 2009; Franceschini et al., 2008; Finke et al., 2010; Kneiske & Dole, 2010). If we consider all the HBL with known redshift in Table 7.1 (top and middle group), the \( 1-\sigma \) confidence limit of \( k \) and \( \epsilon_p \) are \( 2.8^{+2.6}_{-1.8} \times 10^{-3} \text{ cm}^{-3} \) and \( 5.2^{+4.8}_{-4.0} \text{ eV} \), respectively.

Alternatively, a linear fit over source spectral index versus redshift can be used to constrain the constants \( k \) and \( \epsilon_p \). A linear fit between \( \Gamma \) and redshift resulted in a straight line of slope \( 6.0 \pm 1.1 \) with reduced chi-square \( \chi^2_{\text{red}} \approx 1.1 \). Since the source spectral index is uncorrelated with the redshift (§7.3), a linear fit between these quantities should result in a constant line (a line with slope 0). Within \( 1-\sigma \) confidence limit, this corresponds to an EBL spectrum with \( k = 2.4^{+1.2}_{-0.8} \times 10^{-3} \text{ cm}^{-3} \) and \( \epsilon_p = 5.2^{+3.8}_{-4.0} \text{ eV} \), for which this condition can be achieved. We find that these constraints on \( k \) and \( \epsilon_p \) are consistent with
7. The Extragalactic Background Light: Estimation using TeV observations

![Figure 7.11.](image)

**Figure 7.11.** The best fit EBL spectrum estimated in this work (thick black line) and the $1-\sigma$ (checkered orange region) and $2-\sigma$ constrains (striped pink region) compared with the different theoretical models of Franceschini (Franceschini et al., 2008), Gilmore (Gilmore et al., 2009), Finke (Finke et al., 2010) and Kneiske (Kneiske & Dole, 2010). The solid grey region shows the observationally constrained upper and lower limits (Dwek & Krennrich, 2013).

the one obtained earlier through nullifying the correlation between source VHE spectral index and redshift. In Figure 7.12, we show the allowed range of $k$ and $\epsilon_p$ obtained by these two methods.

7.5 Implications of the Estimated Spectrum

7.5.1 Comparison with other estimations

The EBL spectrum presented in this work is estimated directly from the observed VHE spectra of HBL with the condition that the source spectrum should be uncorrelated with redshift. The main uncertainty lies in the assumption that the source VHE spectrum is a power law, and that approximate EBL spectral shape is given by Equation 76. However, the latter is verified numerically to reproduce the observed spectrum which can be well represented by a power law. Interestingly, the present estimation does not depend on the nature of the radiative process active in HBL or dust/stellar emission models from galaxies, yet still agrees well with other estimates as shown in Figure 7.11. Moreover, though the 1-\sigma uncertainty range on the EBL spectrum is nearly a factor $\sim 4$, it is
7.5. Implications of the estimated spectrum

Figure 7.12.: The $1-\sigma$ confidence region for the parameters $k$ and $\epsilon_p$ obtained from the correlation study (green forward stripes) and the straight line fit (red backward stripes)

The predicted EBL spectrum is reasonably confined within the upper and lower limits (grey shaded area in Figure 7.11), obtained independently through observations (see §1). When compared with the other EBL estimates, obtained through cosmological evolution models, the present one predicts stronger emission at lower energies but closely agrees at higher energies, though the predicted spectrum is not well constrained in this regime.

Deviation of the source spectrum from a power law may modify the EBL spectral shape described by Equation (76) considerably. In such case, the present formalism needs to be modified by studying the correlation of other suitable observables instead of the power law spectral indices. However, the source spectrum of HBL ($z<0.3$) obtained using various EBL models are fitted reasonably well by a power law and the one presented here agrees closely with these EBL models. To investigate further, we repeat the study considering the EBL spectral shape due to Franceschini et al. (2008), Gilmore et al. (2009), Finke et al. (2010) and Kneiske & Dole (2010). Following Abdo et al. (2010c); Ackermann et al. (2012); H.E.S.S. Collaboration et al. (2013); Reesman & Walker (2013), we define the observed spectrum to be

$$F_o(E) = F_i(E_z) e^{\exp(-\tau_{\text{theory}}(E_z, z) \times b)}$$

(77)
7. The Extragalactic Background Light: Estimation using TeV observations

where \( \tau_{\text{theory}} \) is the optical depth predicted by the above mentioned theoretical models, and \( b \) is a normalization factor required to assure that the de-absorbed spectral index is uncorrelated with the redshift. Then, \( b = 1.0 \) would imply that the particular model is consistent with the non correlation of the source VHE index with redshift. For the models discussed above, we obtained \( b_{\text{Kneiske}} = 1.5^{+0.6}_{-0.7}, \quad b_{\text{Franchini}} = 1.4^{+0.6}_{-0.7}, \quad b_{\text{Finke}} = 1.1^{+0.5}_{-0.6} \) and \( b_{\text{Gilmore}} = 1.6^{+0.5}_{-0.7}. \) From these, one can argue that the EBL model due to Finke et al. (2010) well supports the non correlation of the source VHE index with redshift; whereas, the deviation from this condition is observed to be maximum in case of Gilmore et al. (2009).

The work presented here is similar to the EBL upper limits proposed by Schroedter (2005) and Finke & Razzaque (2009). They studied the steepening of VHE spectral index with increase in redshift and attributed it to the absorption by EBL. Schroedter (2005) suggested an upper limit on EBL by assuming that the source spectral index, \( \zeta \), cannot be harder than 1.8, whereas Finke & Razzaque (2009) considered limits for \( \zeta \) as 1 and 1.5. Following a similar procedure, Yang & Wang (2010) proposed an EBL upper limit by considering Fermi-LAT spectral index as an allowed limit on \( \zeta \). In this work, we systematically study the steepening of the VHE spectra of HBL with respect to redshift and exploit it to estimate the EBL spectrum. In addition, we do not impose any limits on \( \zeta \); instead, the derived value of \( \zeta \), using the current EBL, lies well within our present understanding of blazar emission models (Section 7.5.2).

Lately, various EBL estimates have been proposed, exploiting the properties of TeV blazars under unique techniques. Mazin & Raue (2007) and Meyer et al. (2012) estimated an upper limit on EBL by employing splines. From the observed VHE spectra of blazars, they converged to a particular shape of EBL, which leads to a de-absorbed spectra that are physically acceptable under the present understanding of blazars. Mankuzhiyil et al. (2010); Domínguez et al. (2013) and Singh et al. (2014a) reproduced the broadband SED of VHE blazars under leptonic model and thereby predicting the intrinsic VHE spectra. Comparing this with the observed VHE spectra, they estimated the optical depth for the attenuation of VHE gamma rays. While Mankuzhiyil et al. (2010) used this to show the inconsistency among various EBL models interpreted theoretically, Singh et al. (2014a) showed a systematic deviation of the optical depths towards high energy; between the estimated and the ones predicted by various EBL models. Domínguez et al. (2013) used the estimated optical depths to determine the cosmic gamma ray horizon. Reesman & Walker (2013) considered the EBL models by Franceschini et al. (2008); Gilmore et al. (2009); Domínguez et al. (2011) to estimate the optical depth for the VHE sources at \( z \sim 0.1 \). The optical depth is then scaled by a parameter to reproduce the observed flux for a range of de-absorbed spectral indices. Based on this scaling parameter, they concluded that these EBL models are consistent with the observed spectra, though the error on the parameter is large. Unlike these models, the work presented here does not have any bias on blazar emission models or a particular EBL shape. Instead, it relies
upon the observed correlation between the VHE spectral index and redshift, along with the assumption that the de-absorbed VHE spectra is a power law.

7.5.2 Consistency with blazar radiative models

The EBL spectrum estimated in this work can be used to find the intrinsic spectral index of HBL, which can then be compared with the one predicted by the radiative models of HBL. Under leptonic models, the spectral energy distributions of HBL are usually well reproduced by considering synchrotron and synchrotron self Compton emission from a broken power-law distribution of electrons. In such a case, the VHE spectrum corresponds to the high energy tail of the electron distribution, whereas the Fermi spectrum generally corresponds to the low energy electron distribution. The X-ray spectrum lying beyond the synchrotron peak is also governed by the high energy end of the electron distribution. Indeed, the X-ray-TeV correlation observed during flares further suggests that the same electron distribution is responsible for the emission at these energies (Takahashi et al., 1996). Hence, it can be argued that the spectral index at these energies is related to the high energy particle spectral index of the underlying electron distribution. If the Compton scattering responsible for the VHE emission occurs in the Thomson regime, then the corresponding spectral index \( \zeta \) will be same as the X-ray spectral index, \( \alpha_2 \). On the other hand, if the scattering process happens at the extreme Klein-Nishina regime, then the VHE spectral index will be \( 2\alpha_2 - \alpha_1 \) (Tavecchio et al., 1998), where \( \alpha_1 \) is the optical spectral index reflecting the low energy electron spectral index. In general, the VHE index is expected to lie in between these two limits. To examine this, we compare the intrinsic VHE spectral index, computed in this work, with the X-ray spectral indices of the sources for which simultaneous/contemporaneous observations are available from Swift-XRT/Suzaku/XMM-Newton/Swift-BAT observations (Table 7.1). In Figure 7.13a we plot the intrinsic VHE spectral indices against the X-ray spectral indices with the limiting lines corresponding to Thomson and extreme Klein-Nishina regimes. For the latter limit, we assume the optical spectral index as \( 1/3 \) since this limits the hardest synchrotron spectrum attainable (Pacholczyk, 1973). Moreover, since the Fermi energy range corresponds to the first (low energy) index of the broken power law, and the VHE regime to the second (high energy) index, the difference is expected to be positive. In Figure 7.13b the dotted line corresponds zero difference. Interestingly, all the sources are constrained well within these limits, thereby supporting the afore mentioned interpretation.

7.5.3 The Gamma Ray Horizon

The interaction between VHE and EBL photons produces a “gamma-ray horizon”, thus creating an energy dependent distance to which VHE sources can be detected. This limit was earlier believed to correspond to \( \tau \sim 1 \), roughly to a limit of \( z \sim 0.2 \). However, with
the discovery of VHE sources at higher redshifts, this limit is constantly being revised. 3C 279 \((z = 0.536)\) is the most distant VHE emitting blazar with a spectroscopically measured redshift. A firm lower limit of \(z > 0.6035\) has been computed for the redshift of PKS 1424+240. VHE photons from these blazars traverse optical depths of more than 4 enroute to earth (Figure 7.14). Recently, the MAGIC collaboration has detected VHE emission from a gravitationally lensed blazar, S3 0218+357, located at a distance of \(z = 0.944\) Mirzoyan (2014). Such observations pose a serious doubt on our understanding of EBL models MAGIC Collaboration et al. (2008).

Since our estimated EBL agrees closely with the standard ones, our model also predicts very large opacities for VHE photons from distant sources. This is evident from Figure 7.7 where deviation of the observed VHE index from the best fit line is large for distant sources. Moreover, as can be seen in Figure 7.15, this leads to an exponential rise in the VHE spectrum of these sources. Such upturns are not possible to accommodate within our present understanding of blazar emission mechanisms. This remains an open problem and may possibly be related to VHE emission through secondary processes resulting from the development of electromagnetic and hadronic cascades in the intergalactic medium (Essey & Kusenko, 2010) or more exotic scenarios associated with creation of axion like particles (de Angelis et al., 2009). With the help of present high sensitivity VHE telescopes and future telescopes, like CTA, these uncertainties can be cleared, providing more insight into the history of our cosmic evolution.

7.6 CONCLUSIONS

In this chapter we studied the interaction of VHE photons with the photons of the EBL. We found that the very high energy (VHE) gamma ray spectral index of high energy peaked blazars correlates strongly with its corresponding redshift whereas no such correlation is observed in the X-ray or the GeV bands. Attributing this correlation to a result of photon-
7.6. Conclusions

Figure 7.14.: The highest energy points of the VHE detected blazars with published VHE data and spectroscopic redshifts beyond 0.2 taken from Furniss et al. (2013). The close proximity of VHE blazars is a result of the gamma-ray opacity of the Universe. The $\tau = 1 - 5$ gamma-ray horizon contours are shown as bands, including model errors, representing the energy and redshift dependent $e^{-\tau}$ suppression of the VHE flux for extragalactic sources as calculated from Dominguez et al. (2011). The VHE detection of PKS 1424+240 is shown with a rightward arrow, indicating the redshift is a lower limit.

Photon absorption of TeV photons with the EBL, we computed the allowed flux range for the EBL, which is independent of previous estimates. The observed VHE spectrum of the sources in our sample can be well approximated by a power-law, and if the de-absorbed spectrum is also assumed to be a power law, then we show that the spectral shape of EBL is $\varepsilon(\varepsilon) \sim k \log_{10} \left( \frac{\varepsilon}{\varepsilon_p} \right)$. We estimated the range of values for the parameters defining the EBL spectrum, $k$ and $\varepsilon_p$, such that the correlation of the intrinsic VHE spectrum with redshift is nullified. The estimated EBL depends only on the observed correlation and the assumption of a power law source spectrum. Our estimate of the EBL depends only on the observed TeV emission and the assumption that the intrinsic TeV spectra are power-laws with indices independent of redshift. Specifically, it does not depend on the spectral modeling or radiative mechanism of the sources, nor does it depend on any theoretical shape of the EBL spectrum obtained through cosmological calculations. The estimated EBL spectrum is consistent with the upper and lower limits imposed by different observations. Moreover, it also agrees closely with the theoretical estimates obtained through cosmological evolution models.

The analysis done in this work was possible because the intrinsic variation of spectral index for HBL is relatively small. The fractional root mean square deviation ($f_{\text{rms}}$) of the de-absorbed VHE indices is 0.16, which is comparable to that of the X-ray ($f_{\text{rms},\text{X}} = 0.14$) and the low energy GeV gamma-rays ($f_{\text{rms,GeV}} = 0.12$). The VHE index $f_{\text{rms}}$ is significantly less than the index change due to absorption $\Delta \Gamma \sim 2$ at a redshift of...
7. The Extragalactic Background Light: Estimation using TeV observations

(a) Sources with known redshift

(b) PKS 1424+240; with lower limit on redshift

Figure 7.15.: Significant upturn in the absorption corrected VHE spectra of distant sources. The first panel corresponds to 1ES 1011+496 (Albert et al. 2007b), S5 0716+714 (Anderhub et al. 2009a), PKS 1222+21 (Aleksić et al. 2011), 3C 66A (Abdo et al. 2011b) and 3C 279 (MAGIC Collaboration et al. 2008). The second panel contains data from Furniss et al. 2013 and gives the gamma-ray peak of the spectral energy distribution of PKS 1424+240, with LAT (squares and power-law fit contour) and VERITAS observations (black circles). The blue lines correspond to model spectral lines. The absorption-corrected VHE spectrum clearly shows a sharp exponential turnover.
$z = 0.266$. If the variation of index was comparable to the change due to absorption, the effect would not have been detectable. Since $f_{\text{rms}}$ is considerably smaller than $\Delta \Gamma$, this leaves the exciting possibility that the uncertainty in EBL, predicted by the present study, can be significantly reduced with increased number of blazars detected at VHE energies. Future experiments, like the CTA, can play an important role in achieving this.
Conclusions: A summary and the way forward

With all the new information accumulated over the past few years, blazars remain as enigmatic as before. Simultaneous $\gamma$-ray and X-ray observations from the *Fermi*-LAT and *Swift* telescopes, along with coordinated observations from ground based instruments have led to a quantum jump in our knowledge of the physics of blazars, and hence, the high energy universe (Ghisellini, 2015). However, while we now have a reasonable understanding of what blazars are, and the origin of their low energy emission, the open questions outlined in Chapter 1.5.3 still remain unanswered.

8.1 SUMMARY OF THESIS

In this thesis, we have tried to set up a general framework for exploring the physical processes and underlying mechanisms using both spectral (SEDs) and temporal analyses as well as modeling based on theoretical understanding of physical processes. We studied both long term variations and bright flares of two HBLs, Mkn 421 and 1ES 1011+496, and found similar variability in the Optical-GeV bands, and the X-ray-VHE bands. This indicates a similar origin for the Optical and Fermi-LAT bands, and for the X-ray-VHE bands. In the framework of the SSC model, this is attributed to the lower energy electrons contributing to the Optical-GeV bands (synchrotron and SSC respectively), and the higher energy ones to the X-ray-VHE bands. Indeed, we find that a synchrotron-SSC model is sufficient to reproduce both low and high activity states of HBLs, without motivating the need for any additional components. However, an important caveat in the SSC model
used in this work is the assumption of stationarity. However, since the synchrotron cooling time scales

\[ t_{\text{cool}}(\gamma) = \frac{3m_e c}{4\sigma_T U_B \gamma \delta} \approx \text{few hours} \]  

(78)  

(79)

is much smaller than the observed flux doubling time scales (few days), the results hold true for the quasi-simultaneous data sampled here. A much better approach would be to self consistently solve the time-dependent radiative process equation as followed in Weidinger & Spanier (2015).

The variations in flux states were found to be mainly due to a change in the underlying particle spectrum, rather than in the underlying jet parameters. While the time-resolved UV-X-ray spectra of Mkn 421 during the April 2013 flare could not be explained by synchrotron emission from a single region, requiring multiple emission zones or injection of a hard, narrow particle distribution, the time averaged broadband spectrum during the same time could be well fit by our model. This motivates a need for better time resolved broadband spectra, specially during flares.

However, our results indicate the need to improve upon the adhoc broken power law particle distribution used in the simplest models. The underlying electron distribution was clearly preferred to have a smooth curvature for 1ES 1011+496, and a similar trend was seen for Mkn 421. Moreover, the second index \( p_2 \) was much steeper than what would be expected from synchrotron cooling, thus ruling out the broken power law spectrum as originating from a cooling break. Plausible origin of intrinsic curvature in the underlying spectrum was investigated, and could be attributed to energy dependent escape time scales in the emission region.

The detection of log normal flux behavior has opened up the debate regarding the origin of the jet launching mechanisms. Log normal flux behaviour implies underlying multiplicative rather, than additive processes, which is expected to originate from the accretion disk. Thus, these observations might imply a strong disk-jet coupling in blazar jets, where lognormal fluctuations in the accreting rate give rise to an injection rate with similar properties. Observation of the same in different classes of blazars has the potential of unfolding the link between accretion disks and jets, and hence, the jet launching mechanisms in supermassive blackholes.

A close agreement was seen between our estimated EBL intensity, and the theoretical estimates obtained through cosmological evolution models. VHE photons from distant blazars should thus be expected to suffer significant absorption leading to an observed flux below the detection limit of our telescopes. Thus, the detection of VHE photons from distant sources continues to be an open problem, and may possibly be related to VHE emission through secondary processes resulting from the development of electromagnetic
and hadronic cascades in the intergalactic medium (Essey & Kusenko, 2010) or more exotic scenarios associated with creation of axion like particles (de Angelis et al., 2009).

8.2 **Future plans**

The future of AGN physics, particularly blazars, looks set to enter an exciting era in the near future, with data coming in from a host of new experiments. With the launch of the Indian multi-wavelength observatory AstroSat (Singh et al., 2014b), on 28th September 2015 on board the Polar Satellite Launch Vehicle (PSLV), we have an unprecedented access to simultaneous, time-resolved spectral data from optical to the hard X-rays energies. Four of the on-board instruments, namely, the Ultra-Violet Imaging Telescope (UVIT; 1300 Å - 5300 Å), the Soft X-ray Telescope (SXT; 2 - 10 keV), the Large Area X-ray Proportional Counter (LAXPC; 3 - 80 keV), and the Cadmium Zinc Telluride Imager (CZTI; 10-100 keV) are co-aligned, while the fifth one, the Scanning Sky Monitor (SSM) is a X-ray sky monitor perpendicular to the viewing axis of the detector. Additionally, there is a Charge Particle Monitor (CPM) to monitor the charged particle background and is used for the safety of certain instruments and to screen the X-ray events. The Performance Verification phase of AstroSat has been completed and all instruments are working flawlessly and as planned (Rao et al., 2016). Since simultaneous multiwavelength observations are essential to our understanding of the broadband emission mechanism and interrelation between multiple emission processes in AGNs, the following unique features of AstroSat will be crucial in opening up new avenues (Paul, 2013):

- The simultaneous coverage of 0.3-150 keV energy band in X-rays and 530 nm - 130 nm in UV/optical bands using all the four payloads (SXT/LAXPC/CZTI/UVIT) onboard ASTROSAT, makes it an ideal platform for studying the sources which emit over several decades of energies, e.g. blazars.

- Multiple photometric points from the VIS, NUV and FUV filters will give us a wideband Optical-UV spectrum for the first time, thus making it possible to cycle through the observable filters to obtain strictly simultaneous observations at X-ray and UV energies.

According to simulations performed, AstroSat will sample the “valley” region for FSRQs, thereby providing excellent means to distinguish between SSC and EC mechanisms, or even, leptonic and hadronic. AstroSat will sample the synchrotron spectrum for HBLs, and, for the first time, accurately constrain the location of the synchrotron peak for the so-called EHBLs, a group of extreme HBLs known for their “unusual” properties, (Costamante et al., 2001). Simulated spectrum for two HBLs, 1ES 1101-232 and 1ES 1959+650 (Figure 8.1), shows that we should be able to obtain high quality spectrum in few ks of observation.

At the highest energies, the scenario looks particularly exciting with two new air Cherenkov experiments scheduled to come up. A large area (21 m) imaging Cherenkov
Figure 8.1: AstroSat simulations of two HBLs, 1ES 1101-232 and 1ES 1959+650, modelled with an absorbed power law spectral model.
8.2. Future plans

Figure 8.2.: Status of the MACE structure development in Hanle, Ladakh as of October 2015. The HAGAR array is seen in the background

telescope Major Atmospheric Cherenkov Experiment (MACE; Koul et al. (2011)) is being setup at Hanle (Figure 8.2) adjacent to the HAGAR array. Once operational, the telescope will be the second largest gamma ray telescope in the world and will help the scientific community enhance its understanding in the fields of astrophysics, fundamental physics, and particle acceleration mechanisms. The imaging camera will comprise of a compact array of 1088 photo-multiplier tube based pixels arranged in a triangular pitch of 55mm corresponding to a pixel size of 0.125°. It is expected to operate at a trigger threshold of ∼ 20 GeV, and be able to detect a Crab-like source at 5σ in a few minutes of observation.

In addition, HAGAR telescope is planned to be used in minimizing the muon background for MACE telescope. At the lower energies muon events mimic γ-ray events and make their identification very difficult. As a muon event is a local phenomena, it will not trigger more than one telescope at a time and should not be detected by MACE and the HAGAR array within a narrow coincidence window. Thus a non-detection in a HAGAR telescope neighboring the MACE telescope can be used to identify muon events.

A major improvement upon all current telescopes will be the next generation ground-based very high energy gamma-ray array of telescopes, the Cherenkov Telescope Array (CTA; Acharya et al. (2013)). With wider energy coverage (∼ 30 GeV - 300 TeV), better angular resolution (∼ 3’ at ∼ 1 TeV ), superior energy and temporal resolution (< 10% and sub-minute resolution at ∼ 1 TeV, respectively), and a wider field of view (∼ 6° - 8°), CTA is expected to provide about 10 times better sensitivity (Figure 8.3) than the present generation of imaging atmospheric Cherenkov telescopes (e.g. MAGIC, HESS, VERITAS). The CTA is expected to open up major discoveries in the field of dark matter detection (Bergstrom, 2013), probes of Lorentz violation (Ellis & Mavromatos, 2013), cosmic ray acceleration (Bell, 2013), high energy emission from supernova remnants (Aharonian, 2013), studies of blazars and AGNs (Reimer & Bottcher, 2013), TeV emission from Gamma Ray Bursts (Meszaros, 2013), and studies of the EBL (Dwek & Krennrich, 2013).

The advancement of experiments always leads to a better theoretical understanding of the workings of our universe. Simultaneous high sensitivity timing and spectral studies
8. Conclusions: A summary and the way forward

Figure 8.3.: Expected sensitivity curve for the CTA (Chadwick et al., 2012), as compared with other air-Cherenkov telescopes (HESS, VERITAS and MAGIC) and the Fermi Gamma-ray Space Telescope.

will be crucial in uncovering the jet composition and propagation mechanisms. Detailed theoretical studies about the origin of log normal flux behaviour will prove crucial at this point to understand the jet launching mechanisms. With the rise in the number of co-coordinated observations at various energies, it is now possible to do a statistical fitting of the broadband spectrum and obtain reasonable estimates on the physical parameters; broadband chi-square fitting of SSC/EC models (Sahayanathan et al., 2016) of a large sample of simultaneous blazar SEDs can be used to constrain the physical parameters in the jet like the magnetic field, Doppler factor and the particle energy density. This can statistically differentiate the physical parameters among the different classes of the so-called “blazar sequence”.

With the release of PASS-8 data of Fermi-LAT in 2015, we now have unprecedented spectral resolution in the 30MeV - 300GeV band. Presence of a “double hump” spectrum at these energies will imply a possible proton/muon synchrotron cascade (Boettcher, 2010; Böttcher et al., 2013). Detection of IceCube PeV neutrinos from γ-ray loud blazars will also be a strong confirmation for hadronic models. Thus, the dichotomy between leptonic and hadronic models is likely to get resolved in the near future. Radio observations with high spatial resolution to study the structure of knots as well as the boundary layers of the jets will shed further light on the jet dynamics, instabilities and the possible particle acceleration sites along the jet.

Analytical/numerical solutions of time dependent kinetic equation to study the evolution of the particle spectra under various assumptions of the acceleration and escape time scales will enable us to understand the origins of various types of particle distributions in the jet. The solutions thus obtained can be used to simulate spectra and lightcurves
8.2. Future plans

which can then be compared with the multi-wavelength spectral and temporal data to understand the physical processes in the jets. With the number of blazars detected at TeV energies expected to increase sharply with the advent of the CTA, rigorous statistical analysis can be done in near future to put sharper constraints on the EBL. This will test models of beyond standard model theories like conversion of photons into axion like particles (de Angelis et al., 2009).

The most exciting possibility is that new observations might uncover unexpected phenomena that may challenge current theoretical concepts, and trigger to deepen our understanding of the extragalactic sky.
Appendices
XSPEC implementation of SSC

Implementation of broadband spectral fitting of blazars using $\chi^2$ minimization (with Levenberg-Marquardt algorithm) in XSPEC for a one zone SSC+EC model was carried out in Sahayanathan et al. (2016). We developed separate additive local models for synchrotron, SSC and EC processes which can be added according to the necessity. For faster convergence and to ease the difficulty of initial guess values, we fit the observed spectral information rather than the direct physical parameters governing the source. The numerical codes for various emissivities are significantly optimized to reduce the machine run time. An added advantage of using XSPEC spectral fitting package, besides being well optimized and widely tested, is to fit the photon counts within the energy bins rather than the fluxes at their mean energy. The developed models were finally tested on the well studied FSRQ, 3C 279.

A.1 OBTAINING APPROXIMATE GUESS VALUES OF PHYSICAL PARAMETERS

For a well sampled SED, the observed parameters like the synchrotron peak flux and frequency, can be related to the underlying physical parameters of the jet, and approximate values of the parameters obtained (Ghisellini et al. [1996]). It is straightforward
A. XSPEC implementation of SSC

to obtain the relation between the source parameters and the observed fluxes due to synchrotron, SSC and EC processes

\[
P^{\text{syn}}_{\text{obs}}(\nu_{\text{obs}}) \approx \begin{cases} 
S(z,p) \delta_{\nu}^{2+} B^{\nu+3} R^2 K \nu_{\text{obs}}^{-\left(\frac{p+1}{2}\right)} & \text{for } \nu_{\text{obs}} \ll \delta_D \gamma_b^2 \nu_L / (1+z) \\
S(z,q) \delta_{\nu}^{2+} B^{\nu+1} R^2 K \gamma_b^{q-p} \nu_{\text{obs}}^{-\left(\frac{q+1}{2}\right)} & \text{for } \nu_{\text{obs}} \gg \delta_D \gamma_b^2 \nu_L / (1+z) 
\end{cases} \tag{80}
\]

\[
P^{\text{ssc}}_{\text{obs}}(\nu_{\text{obs}}) \approx \begin{cases} 
C(z,p) \delta_{\nu}^{2+} B^{\nu+1} R^4 K^2 \nu_{\text{obs}}^{-\left(\frac{p+1}{2}\right)} \log\left(\frac{\gamma_b}{\gamma_{\text{min}}}\right) & \text{for } \nu_{\text{obs}} \ll \delta_D \gamma_b^4 \nu_L / (1+z) \\
C(z,q) \delta_{\nu}^{2+} B^{\nu+1} R^4 K^{2(q-p)} \nu_{\text{obs}}^{-\left(\frac{q+1}{2}\right)} \log\left(\frac{\gamma_{\text{max}}}{\gamma_b}\right) & \text{for } \nu_{\text{obs}} \gg \delta_D \gamma_b^4 \nu_L / (1+z) 
\end{cases} \tag{81}
\]

\[
P^{\text{ec}}_{\text{obs}}(\nu_{\text{obs}}) \approx \begin{cases} 
\mathcal{E}(z,p) \delta_{\nu}^{2+} U_{\gamma} \nu_{\text{obs}}^{-\left(\frac{p+1}{2}\right)} & \text{for } \nu_{\text{obs}} \ll \delta_D \gamma_b^2 \nu_s / (1+z) \\
\mathcal{E}(z,q) \delta_{\nu}^{2+} U_{\gamma} \nu_{\text{obs}}^{-\left(\frac{q+1}{2}\right)} & \text{for } \nu_{\text{obs}} \gg \delta_D \gamma_b^2 \nu_s / (1+z) 
\end{cases} \tag{82}
\]

Here S, C and \( \mathcal{E} \) are the quantities involving physical constants, redshift and particle index, \( B \) the magnetic field in the emission region, R the radius, \( \delta \) the Doppler factor, \( U_s \) the energy density of the external photon field and the particle spectrum a broken power law given by

\[
N(\gamma) \, d\gamma = \begin{cases} 
K \gamma^{-p} \, d\gamma & \text{for } \gamma_{\text{min}} < \gamma < \gamma_b \\
K \gamma_b^{q-p} \gamma^{-q} \, d\gamma & \text{for } \gamma_b < \gamma < \gamma_{\text{max}} 
\end{cases} \quad \text{cm}^{-3} \tag{83}
\]

In Figure A.1, we show the observed flux due to synchrotron, SSC and EC processes (solid lines) for a set of source parameters (described in the caption) along with their approximate analytical solutions (dashed lines). We find that the approximate analytical solution of fluxes closely agree with the actual numerical results (except around the peak) and hence can be used to estimate the source parameters.

A good spectral information on optical/UV/X-ray energies lets us identify the synchrotron peak frequency \( (\nu_{\text{syn,obs}}) \) in the blazar SED and the same can be expressed in terms of the physical parameters as

\[
\nu_{\text{syn,obs}} = \left(\frac{\delta_D}{1+z}\right) \gamma_b^2 \nu_L \tag{84}
\]

Similarly, information at X-rays and gamma rays can plausibly constrain the inverse Compton peak due to SSC and EC processes. In case of SSC, it can be written as

\[
\nu_{\text{ssc,obs}} = \left(\frac{\delta_D}{1+z}\right) \gamma_b^4 \nu_L \tag{85}
\]
A.1. Obtaining approximate guess values of physical parameters

Figure A.1.: The numerical synchrotron, SSC and EC spectrum (solid lines) with their approximate analytical equivalents (dashed lines). The model SED corresponds to the following physical parameters: $z = 0.536$, $p = 0.55$, $q = 1.5$, $K = 1 \times 10^5$, $\gamma_{\text{min}} = 10$, $\gamma_{\text{max}} = 5 \times 10^5$, $\gamma_b = 10^3$, $B = 0.1 \, \text{G}$, $\Gamma = 10.0$, $\delta_D = 10.0$, $\nu_s = 5.86 \times 10^{13} \, \text{Hz}$ equivalent to temperature $1000 \, \text{K}$, $U_s = 7.57 \times 10^{-5} \, \text{erg/cm}^3$ and $R = 10^{16} \, \text{cm}$

and for the EC

$$\nu_{\text{ec,obs}} = \left( \frac{\delta_D \Gamma}{1+z} \right) \gamma_{\text{b}} \nu_{\text{s}}$$

(86)

In addition to these, we can consider the particle energy density ($U_e$) and the magnetic field energy density ($U_B$) are related by

$$U_B = \eta U_e$$

(87)

where

$$U_B = \frac{B^2}{8\pi} \, \text{erg/cm}^3 \quad \text{and} \quad U_e = m_e c^2 \int_{\gamma_{\text{min}}}^{\gamma_{\text{max}}} \gamma N(\gamma) \, d\gamma \, \text{erg/cm}^3$$

Here, $\eta \approx 1$ corresponds to the equipartition condition indicating total energy of the system to be minimum. If the jet viewing angle can be anticipated, then it can constrain the Doppler factor $\delta_D$ and the Lorentz factor $\Gamma$. In case of blazars, we can assume $\delta_D \approx \Gamma$ due to small viewing angle. This, along with the knowledge of $\nu_{\text{syn,obs}}$, $\nu_{\text{ssc,obs}}$, $\nu_{\text{ec,obs}}$ and the fluxes at Optical (Synchrotron; equation (80)), X-ray (SSC; equation (81)) and gamma-ray (EC; equation (82)), and the equipartition condition (87) can, in principle, lets one estimate the source parameters by solving the relevant coupled equations. It should be noted that we do not solve for $\gamma_{\text{min}}$ and $\gamma_{\text{max}}$, which are weak parameters, but rather choose them to be consistent with the observed SED. Besides these, we also
A. XSPEC implementation of SSC

assume the external photon field to be a blackbody, illuminated by the accretion disk. Then $U_{ph}$ and $\nu_*$ can be related by

$$\nu_* = 2.82 f_{ext} K_B \left( \frac{c}{4 \sigma_{SB}} \int U_{ph}(\nu_i) \, d\nu_i \right)^{1/4}$$

where $K_B$ is the Boltzmann constant, $\sigma_{SB}$ is the Stefan-Boltzmann constant, $U_{ph}(\nu_i)$ is the blackbody energy density at frequency $\nu_i$ and $f_{ext}$ is the covering factor.

A.2 XSPEC SPECTRAL FIT

We developed numerical codes to calculate the emissivities corresponding to synchrotron, SSC and EC emission processes which are then used to estimate the observed fluxes after accounting for the relativistic and cosmological transformations. The codes were optimized considerably by incorporating quadrature integrations and different interpolation schemes to reduce the run time. These codes were then added as an additive local models to the XSPEC package following the standard prescription[^1]. The parameters of the combined XSPEC models are the two particle indices $p$ and $q$, minimum and the maximum particle energies $\gamma_{min}$ and $\gamma_{max}$, synchrotron peak frequency $\nu_{syn}^p$, SSC peak frequency $\nu_{ssc}^p$, EC peak frequency $\nu_{ec}^p$, synchrotron flux $F_{syn}$ at frequency $\nu_{syn}^{ref}$, SSC flux $F_{ssc}$ at frequency $\nu_{ssc}^{ref}$, EC flux $F_{ec}$ at frequency $\nu_{ec}^{ref}$ and equipartition factor $\eta$. In order to facilitate a faster convergence as well as to avoid the uncertainty regarding the correct choice of initial guess parameters, we fit the observed fluxes corresponding to synchrotron, SSC and EC processes, and peak frequencies. The physical parameters required to obtain the exact emissivities were then calculated by solving the approximate coupled equations and other conditions described in the earlier section. The same procedure was then used to extract back the best fit physical parameters from the fitted observational quantities. Model systematics of 10% were assumed.

In Figure A.2 show the results of our fitting on the observed SED of 3C 279 during a flare in April 2014.

[^2]: Here onwards all frequencies and fluxes are measured in the observer’s frame.
Figure A.2.: The observed SED of 3C 279 during a flare in April 2014 (Paliya et al., 2015b) fitted with the developed zone SSC+EC module in XSPEC. The bottom panel shows the residual $\chi^2$. 

(a) Observed SED

(b) Best fit XSPEC model
# A Few Acronyms

- **1ES**: 1st Einstein Slew Survey
- **3C**: Third Cambridge Catalogue of Radio Sources
- **ACT**: Atmospheric Cherenkov Telescope
- **AGN**: Active Galactic Nuclei
- **BAT**: Burst Alert Telescope
- **BL Lac**: BL Lacertae object
- **CCD**: Charge Coupled Device
- **CTA**: Cherenkov Telescope Array
- **CZTI**: Cadmium Zinc Telluride Imager
- **EAS**: Extensive Air Showers
- **EBL**: Extragalactic Background Light
- **EGRET**: Energetic Gamma-Ray Experiment Telescope
- **FR I**: Fanaroff-Riley I
- **FR II**: Fanaroff-Riley II
- **FSRQ**: Flat spectrum Radio Quasars
- **HEGRA**: High Energy Gamma Ray Astronomy
- **HAGAR**: High Altitude GAmma Ray
- **HBL**: High frequency peaked BL Lac object
- **HESS**: High Energy Stereoscopic System
- **IACT**: Imaging Atmospheric Cherenkov Telescope
- **IBL**: Intermediate frequency peaked BL Lac object
- **KN**: Klein-Nishina scattering
- **LAT**: Large Area Telescope
- **LAXPC**: Large Area X-ray Proportional Counter
- **LBL**: Low frequency peaked BL Lac object
- **MACE**: Major Atmospheric Cherenkov Experiment
- **MAGIC**: Major Atmospheric Gamma-ray Imaging Cherenkov Telescope
- **Mkn**: Markarain
- **PACT**: Pachmarhi Array of Cherenkov Telescopes
- **PKS**: Parkes Catalogue of Radio Sources
- **PMT**: Photo Multiplier Tube
- **PSLV**: Polar Satellite Launch Vehicle
<table>
<thead>
<tr>
<th>Acronym</th>
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<tbody>
<tr>
<td>SED</td>
<td>Spectral Energy Distribution</td>
</tr>
<tr>
<td>SSA</td>
<td>Synchrotron Self Absorption</td>
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<tr>
<td>SSC</td>
<td>Synchrotron Self Compton</td>
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<tr>
<td>SSM</td>
<td>Scanning Sky Monitor</td>
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<tr>
<td>STACEE</td>
<td>Solar Tower Atmospheric Cherenkov Effect Experiment</td>
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<tr>
<td>SXT</td>
<td>Soft X-ray Telescope</td>
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<tr>
<td>UVIT</td>
<td>UltraViolet Imaging Telescope</td>
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<tr>
<td>UVOT</td>
<td>UltraViolet Optical Telescope</td>
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<tr>
<td>VERITAS</td>
<td>Very Energetic Radiation Imaging Telescope Array System</td>
</tr>
<tr>
<td>VHE</td>
<td>Very High Energy</td>
</tr>
<tr>
<td>XRT</td>
<td>X-ray Telescope</td>
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<tr>
<td>XSPEC</td>
<td>X-Ray Spectral Fitting Package</td>
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