
RADIO EMISSION FROM GAMMA-RAY FLARE SOURCES DISCOVERED BY FERMI-LAT

Degree of Master of Science by research only:

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The cover image shows an artist's impression of an active galaxy called a blazar. The blazar consists of a black hole at its center that accretes local interstellar matter towards itself. The accretion process results in a large quantities of relativistically boosted particles being expelled into space through a highly collimated radio jet.

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DECLARATION

I declare that this Dissertation is my own, unaided work. It is being submitted for the Degree of Master of Science at the University of the Witwatersrand, Johannesburg. It has not been submitted before for any degree or examination at any other University.

University of the Witwatersrand, January 2016

Signed: Pfesesani Victoria van Zyl

on this _____ day of _____ 20____ in _____

ABSTRACT

Quasi-simultaneous observations of a flaring blazar source at multiple frequencies, offer an unprecedented view of the region surrounding a supermassive black hole during a large energy outburst. Blazars are active galaxies that host a super massive black hole releasing large amounts of energy through narrow jets of highly relativistic plasma located along the polar axes. Within these jets, electrons and protons move at relativistic speeds creating interactions that generate radio waves and gamma-rays that travel down the jet towards the observer. Based on the angle of inclination of the source towards the observer ($\theta < 20^\circ$), we can study relativistically boosted emission to peer into regions where high-energy particles (gamma-rays) are thought to be generated. Using high cadence monitoring campaigns, both the slow and fast variations in the source flux can be traced in detail revealing spatial and temporal information about the source state and activity.

In this dissertation I studied the physics behind the variable behavior of the bright blazar PKS 1424-418, also known as J1427-4206. PKS 1424-418 is a Southern Hemisphere blazar that recently underwent a number of flaring events detected by FERMI-LAT. The study was specifically concerned with the behavior of PKS 1424-418 during the outburst/flaring events that occurred between 19 October 2012 and 9 October 2013. PKS 1424-418's daily gamma-ray flux reached an average of $1.4 \pm 0.2 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}$ for $E > 100 \text{ MeV}$, triggering radio follow up observations with the Hartebeesthoek Radio Astronomy Observatory 26 m radio telescope at 2.3-GHz, 4.8-GHz, 8.4-GHz and 12.2-GHz frequencies. The objective was to examine the nature of the relationship between the high-energy gamma rays detected by FERMI-LAT and the low-energy radio waves detected by the Hart26m radio telescope. In the study we investigated the relationship between the two energy regimes using Discrete cross-correlation functions to estimate the time-lags between two corresponding frequencies. We also studied the spectral index variation to establish the source behavior over the observing period at multiple epochs. A Lomb-Scargle periodicity search was also performed to investigate whether some periodic modulation was present in the gamma-ray data as it varied quite dramatically on shorter time-scales. Observations in gamma-rays and radio frequencies

were done using the All-Sky mode and drift scan technique respectively at the different frequencies.

Results indicated the existence of a strong correlation between the gamma-ray and radio data, with the gamma rays leading the radio. With each gamma-ray flaring event the radio spectra indicated some spectral hardening and the possibility of an 86 day gamma-ray period in the shorter term flares was also established in the study.

This study however only shows the large scale relationship between time-series over the entire observing period. On smaller scales, each gamma-ray and radio flare is unique and as such requires individual analysis for each respective component. to successfully achieve this, more data is needed to confirm the individual radio flaring periods. Observations at VLBI scales are extremely useful in this kind of work and instrumental in studying the source structure behavior during flaring and will form part of the future work planned for studying blazar source variability.

ACKNOWLEDGMENTS

*No man is an Island, entire of itself;
every man is a piece of the Continent, a part of the main.*
— John Donne (1572 - 1631)

I would like to take this opportunity to firstly, thank God for opening doors for me I could never have imagined I would walk through. My MSc has been a long and fruitful journey because of all the people he positioned in my life. To my supervisors Prof Sergio Colafrancesco and Dr Aletha de Witt, thank you for your guidance, mentorship, encouragement, your constant support and for going above and beyond the call of duty to push me to complete my dissertation. I'd also like to convey my gratitude to my initial supervisor the late Dr. Michael Gaylard who's immeasurable support and guidance nurtured my love and passion for radio astronomy, and his girlfriend for the support and words of encouragement through his untimely passing. I will forever be grateful. I'd also like to thank the students and staff at HartRAO for their inputs. To Dr Michael Bietenholz, Dr Johnathan Quick, Marion West, Pieter Stronkhorst, Jabulani Maswanganye and Roopesh Ojha thank you so much. Thank you to the National Astrophysics and Space Science Program (NASSP) and the National Research Foundation (NRF) whose generous funding afforded me the opportunity to study astronomy.

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ACRONYMS

AGN Active Galactic Nuclei
ATCA Australian Telescope Compact Array
ATel Astronomer's Telegram
ASCD ASI Science Data Center
BL Lac BL Lacertae
CCF Cross-correlation function
CMB cosmic microwave background
CSV comma separated value
DCF Discrete cross-correlation function
EGRET Energetic Gamma-Ray Experiment Telescope
EM electromagnetic
FITS Flexible Image Transport System
FERMI-GBM Fermi Gamma-ray Burst Monitor
FERMI-LAT Fermi Large Area Telescope
FERMI-GST Fermi Gamma-ray Space Telescope
FOV field-of-view
FSRQ Flat Spectrum Radio Quasar
FWHM Full width at half maximum
GeV Giga electron-volts
HartRAO Hartebeesthoek Radio Astronomy Observatory
HL High-frequency peaked BL Lac

HPBW	half power beam width
HPN	half power north
HPQ	Highly Polarized Quasar
HPS	half power south
HYDRA A	PKS 0915-11
ICRF	International Celestial Reference Frame
ISM	interstellar matter
IVS	International VLBI Service for Space Geodesy and Astrometry
KeV	Kilo electron-volt
LBL	Low-frequency peaked BL Lac
LCP	Left circular polarization
MeV	Mega electron-volts
NASA	National Aeronautics and Space Administration
OVV	Optically Violent Variables
PKS 1424-418	J1427-4206
PSS	point source sensitivity
RBL	Radio-selected BL Lac
RCP	right circular polarization
rms	root-mean-square
RFI	radio frequency interference
SED	spectral energy distribution
SMBH	supermassive black hole
SSC	Synchrotron self Compton
TANAMI	Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry
UDCF	Unbinned cross-correlation function
VLBI	Very Long Baseline Interferometry
XBL	X-ray selected BL Lac
ZDCF	Z-transformed cross-correlation function

CHAPTER

1

INTRODUCTION

The most challenging unanswered scientific questions in the astronomical community today are thought to rely heavily on the understanding of the nature of blazar sources. Blazar sources are extra-galactic objects that form part of a collection of high energy radiators called Active Galactic Nuclei. These sources emit large amounts of energy at any given time, and are believed to be powered by the accretion of interstellar matter (gas and dust particles) onto a supermassive black hole at the center of the active galaxy.

Blazars are the most interesting of all Active Galactic Nuclei classes. They emit non-thermal radiation produced by relativistically moving charged particles. The radiation appears highly variable, strongly polarized and directed towards the observer's line of sight. This is because most of their energy is detected from jet structures which are observed along the polar axes of the active galaxy. To conserve angular momentum during matter accretion some of the material gets accelerated to relativistic speeds along the axis of rotation forming the jets. The exact jet content however is still a hot topic but it is believed that it may be a possible mixture of relativistic electrons, protons, dust particles, photons, ions and strong magnetic fields.

Jets are very powerful and also vary widely in length (they can stretch well over kiloparsec scales) and orientation (some are bent). Because blazar sources are dominated by non-thermal emission this has led to the assumption that Radio and Gamma-ray particles are possibly produced in these objects by processes that create the jets.

Having only been discovered just over a hundred years ago, blazars are the most luminous objects in the Universe ($L > 10^{40}$ ergs), emitting radiation in large quantities at all wavelengths across the electromagnetic spectrum. Blazar sources are also strong radio emitters typically associated with giant elliptical galaxies. In some dramatic cases blazars undergo flaring events (Collaboration et al., 2012; Collmar et al., 2000) lasting anywhere between a few days to a few months. On occasion they also exhibit some periodic variations (Lainela et al., 1999; Nishikawa et al., 1999; Rieger, 2004) that can be seen in the flux density time-series, known as a light curve, of these source during the flaring

event. These variations are more evident at optical and gamma-ray wavelengths and sometimes occur also in the radio. Flaring events in high-energy sources are thought to be the result of the fast injection of high energy particles that then move relativistically into the jet streams. This motion and geometry of the jet direction causes a relativistic beaming effect, making the source to appear brighter than normal for periods of time related to the flare event, before returning back to the source quiescent stage. During this process the light curve at different wavelengths shows variations in flux density that coincide with the flaring events of the source. This variability in flux density has led to suggestions that different physical mechanisms might be playing a role, and more in depth studies of the inner most regions of these sources, where the powerful emission is thought to be generated, are needed. Gamma-ray and radio wave observations in particular allow us to study the source activity at the extreme ends of the electromagnetic spectrum to gain insight into both the fast and slow source variations.

Over the years, blazars have become the main targets of numerous multi-wavelength campaigns aimed at understanding high-energy phenomena (Błażejowski et al., 2005; Blanchard et al., 2012; Donnarumma, 2012; Krawczynski et al., 2004; Tagliaferri et al., 2008) and have also become most highly sought after objects, although currently very little is still known about them. Blazars are the brightest sources in the universe, they make up less than 10% of the total active galaxy content known to date. The light curve of a blazar flaring event is believed to hold a wealth of information on the emission mechanisms powering these energetic sources. Monitoring these flaring events and measuring the delays in the emission output at different frequencies provides the necessary tools needed to create emission models that can describe the evolution and general behavior of these sources.

This dissertation aims to study the physics behind the behavior of the blazar source PKS 1424-418 during a series of flaring events monitored from the 19th of October 2012 to the 9th of October 2013. The focus of this research was to study the nature of the relationship between the radio wave emission and the gamma-ray emission over this period of time. Studying the relationship between different energy regimes affords us the ability to develop tighter constraints on the emission mechanisms and the particle behavior within regions surrounding the black hole. This dissertation is comprised of 6 chapters, including the introduction, and is structured as follows:

Chapter 2 gives a broad background on blazars and the emission processes thought to be responsible for the radio waves and gamma-rays observed from these sources. The motivation and objectives of the study are also discussed.

Chapter 3 presents the technical aspects of the observations, focusing on the telescope structure, the equipment involved and methods used in capturing the data.

Chapter 4 describes the methods used to calibrate and analyze the data.

Chapter 5 presents the results obtained from the study.

Chapter 6 draws conclusions about the behavior observed from the time series of the blazar source PKS 1424-418 and discuss possible future work.

BACKGROUND

Blazars form part of a class of extra-galactic objects known as Active Galactic Nuclei (AGN). The term AGN is specifically used in describing the “active nuclei” at the centers of these galaxies that emit enormous amounts of energy on varied timescales. The energy emitted by these sources is strongly polarized, spanning over decades in frequency from radio to gamma-rays in a broad continuum. Of all the extra-galactic objects known today, AGN are the largest ($\sim 10^6 < M_{\odot} < 10^9$) and brightest, shining with up to 10^4 times the luminosity of a normal galaxy (e.g. the Milky Way). These sources also happen to come in a variety of different sizes and flavours that are grouped into classes. Each class differs from the next mainly due to orientation effects of the observed source with respect to the observer and the strength of the emitted radiation. In some special cases, the AGN eject large quantities of the accreting matter in the form of one or two highly collimated, narrow polarized jets, made up of relativistically moving plasma. When observed perpendicular to the jet direction these galaxies are referred to as radio galaxies, however, when our line of sight lies close to the direction of one of the jets we refer to the AGN as a blazar (Urry, 1996; Fabian, 1999). Blazars are a unique subclass that exhibits non-thermal continuum emission throughout the EM spectrum from radio to gamma rays, with rapid variability and high polarization in the optical and radio. Blazars thus far are the most powerful of all AGN, emitting a large portion of their radiation towards the observer through a narrow beamed cone. However, even with all the advances we have in technology today, it is still a challenge to explain with a high degree of certainty how these objects generate and collimate their emission over large scales through the length of the emitted jet. This is one of the reasons why these objects are one of the most sought out objects in the AGN regime, as understanding them could unlock the long kept secrets to the particle interactions that cause their varied emission.

2.1 Active Galactic Nuclei

2.1.1 General overview

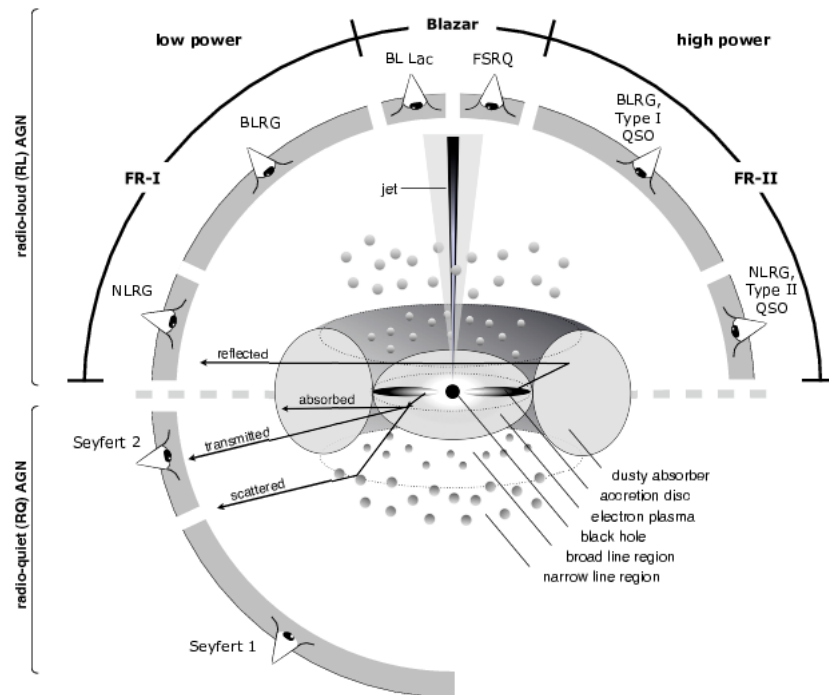


Figure 2.1: The figure shows a schematic representation of AGN objects. Based on the viewing angle of the observer with respect to the normal of the orbital plane, the figure shows the different AGN classes and also shows some of their characteristics. *Image credit: Beckmann & Shrader (2012).*

All AGN classes appear different to a distant observer as shown in figure 2.1. However, they all also seem to generally consist of similar components that are made up of a combination of one or more of the following,

- A nucleus - a supermassive black hole at the center
- An accretion disc – optically thick, producing ultra-violet (UV) emission
- A torus – optically thick, producing infrared (IR) emission
- A broad line region (BLR) - high-velocity clouds located near BH, producing broad emission lines
- A narrow line region (NLR) - low-velocity clouds located near/outside the torus, producing narrow optical emission lines
- Relativistic jets and radio lobes – which can extend ~ 100 s kpc consisting of highly energetic particles.

Depending on the angle of observation, AGN sources can have some components dominating or appearing brighter than others. Based on the dominating components, AGN are then categorized into different classes according to the strength of the emission and the presence or lack of corresponding components. This model, used for unifying the separate observed classes into a single type of physical object is more formally referred to as the unification model. It assumes that all AGN are essentially the same object only different in the amount of material the emission is required to pass through to get to the observer. For instance, when observing an AGN directly down the jet (head on) as with the blazar class, the emission received suffers less absorption effects from surrounding interstellar matter when traveling towards the observer. With a Seyfert galaxy the emission goes through a series of scattering and absorption effects due to the dusty torus meaning only a fraction of the emitted radiation actually makes it to the observer.

2.1.2 Active Galaxy types

AGN sources are divided into two main categories based on the strength of their radio emission relative to that of the optical emission given as, (i) “*radio quiet*” and (ii) “*radio loud*” (Kellermann et al., 1989). If the 5-GHz radio flux of the AGN source is more than 10 times the optical (B-band) flux ($F_5/F_B > 10$) at 6.8×10^{14} Hz (Urry & Padovani, 1995), then the AGN is classified as a radio loud source, otherwise as a radio quiet source. Radio loud sources are more likely to contain a jet. Radio quiet AGN on the other hand are generally considered to be jet free or have weak jet emission.

Radio quiet sources

Radio quiet sources make up $\sim 90\%$ of all AGN that have been observed, appearing mostly in spiral galaxies. These AGN are galaxies wherein the jet emission is generally neglected or undetectable. Radio quiet AGN have two main types, Seyfert 1 (seen face on) and Seyfert 2 (seen edge on) galaxies named after the man who discovered them (Seyfert, 1943). Seyferts galaxies were the first AGN sources to be classified because of their optical spectra. An AGN is called a Seyfert 1 galaxy when both the broad and narrow emission lines can be observed, and Seyfert 2 when only the narrow emission lines are observed. The BLR and NLR regions are high velocity clouds of gas surrounding the nuclei that produce emission lines from a range of gas velocities (from Doppler effect $\Delta\lambda/\lambda = v/c$ where $v \ll c$) between 10^2 kms^{-1} for particles in the NLR and 10^3 kms^{-1} for particles in the BLR. The particle velocities found in the BLR place this region in close vicinity to the BH. Most of the high energy production from AGN sources is suspected to occur in a densely populated region within a radial extent of 1 pc from the BH, a region in which the BLR is neatly tucked in to. So, particles existing in the BLR play a role in the emission detected from the jets of blazar sources.

Radio loud sources

Radio-loud sources however only make up $\sim 10\%$ of the AGN content even though they are the brightest sources in the Universe. Generally, these sources are called Quasi-stellar objects (QSOs) or

Quasars for short. Quasars are bright objects most often observed at very high redshifts (Schmidt, 1963, $z \sim 2 - 6$) and normally found in Elliptical galaxies. They are the most powerful type of AGN due to the presence of the highly relativistic jets. Depending on the strength of the jet emission, these sources are further sub-divided into two main types, Radio galaxies and Blazars (Blazing Quasars). Radio galaxies are galaxies that show weak jet emission, their radio power lies in the VLBI radio core (*Fanaroff and Riley type I*, FR I) of the galaxy and the radio lobes (*Fanaroff and Riley type II*, FR II) where the jets terminate. Radio lobes are extended regions diffuse radio emission found on either side of the polar axis of an AGN. FR I and FR II morphologies are also further sub-divided into groups that are dominated by the lack or presence of broad emission lines respectively as shown in figure 2.1. The Blazars on the other hand, being the objects with the strongest jet presence are only sub-divided into two main groups, BL Lac and Flat Spectrum Radio Quasars (FSRQ). Because blazars are at the heart of this dissertation a detailed discussion on these sources is given in the following section.

2.1.3 Blazar overview

In a “normal galaxy”, each constituent star produces light that contributes to the galaxy’s entire luminosity. Observations at multiple frequencies show this with a superposition of the black body spectrum of each star’s contribution as shown in figure 2.2,

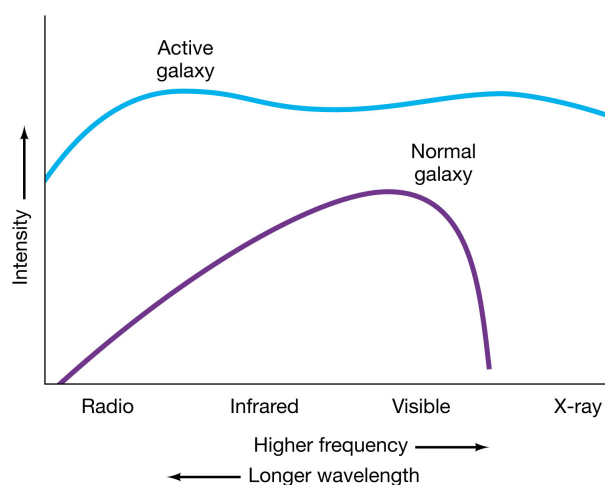


Figure 2.2: Spectral energy distribution schematic for both normal galaxies and AGN from Radio to X-ray wavelengths. A normal galaxy shows an approximately black body emission spectrum whereas an active galaxy shows a continuum emission spectrum spread throughout the EM spectrum. *Image credit: Active galaxies web notes.*¹

However, unlike normal galaxies, AGN produce their luminosity by exhibiting energetic phenomena in their nuclei. The energy radiated is emitted as non-thermal energy due to particle interactions that produce relativistically accelerated particles. The emission from these sources shines over and above the luminosity emitted by their embedded stars, appearing brightest towards the highest and lowest frequencies in a broadband continuum with a luminosity well over a thousand times that of a

¹http://pages.uoregon.edu/jimbrau/BraulmNew/Chap24/6th/24_19Figure-F.jpg

normal galaxy from a region the size of our solar system. Energy generation of this magnitude cannot be attributed to the thermonuclear process in stars, but rather requires some more efficient mechanism. Currently matter accretion (§2.2.2) onto a SMBH seems to be the most accepted explanation of AGN emission.

Although all AGN are extremely interesting objects, blazars exhibit extreme characteristics that still puzzle astronomers today. Blazars, initially discovered in 1929 by Cuno Hoffmeister (Hoffmeister, 1929), were identified as radio emission sources in 1968 (Smitt, 1968). They are highly variable objects that emit non-thermal radiation from a bright nucleus at their center. At times these sources show a large and rapid variation in intensity within very short time scales (DuPuy et al., 1969), sometimes of the order of minutes or less. The high variability produced by these objects makes them very interesting targets to study, sparking interest in the mechanisms responsible for bringing them to life.

BL Lac objects, also known as, Highly Polarized Quasar (HPQs) and Flat Spectrum Radio Quasar (FSRQs), also known as, Optically Violent Variables (OVVs) are the terms used to describe the two main flavors of blazars. BL Lac objects are characterized by very weak or no optical emission lines, being almost completely dominated by continuum emission, whereas FSRQs have stronger line emission. Collectively referred to as blazars, these objects generally appear to have the following distinguishing characteristics:

- A significant amount of their energy radiated above 100 MeV.
- Multi-wavelength variability with a flaring behavior.
- Strong emission lines (in FSRQ).
- And rapidly variable (minutes to months) polarized optical and radio counterparts.

BL Lac objects further separate into 4 distinct types of AGN on the basis of the peak frequency of the synchrotron emission; Radio-selected BL Lacs (RBLs), X-ray selected BL Lacs (XBLs), Low-frequency peaked BL Lacs (LBLs) or red blazars, and High-frequency peaked BL Lacs (HBLs) or blue blazars.

2.2 Energy distribution

2.2.1 Multi-wavelength emission zones

Light emitted by normal galaxies appears brightest at optical wavelengths and fainter towards both ends of the EM spectrum at higher and lower frequencies as seen in the spectral energy distribution (SED) plot in figure 2.2. AGN on the other hand behave differently in that the lower and higher frequency emission appear brighter than in the former case. SEDs of blazars (figure 2.3) show that the continuum emission of blazars is characterized by two peaks, a low-energy peak extending from radio to UV/X-rays, and a high-energy peak that extends from X-rays to GeV/TeV gamma-rays. For RBLs and LBLs the first peak is in the Infrared (IR) to optical range and for HBLs and XBLs the first peak is in the Ultraviolet (UV) to X-rays.

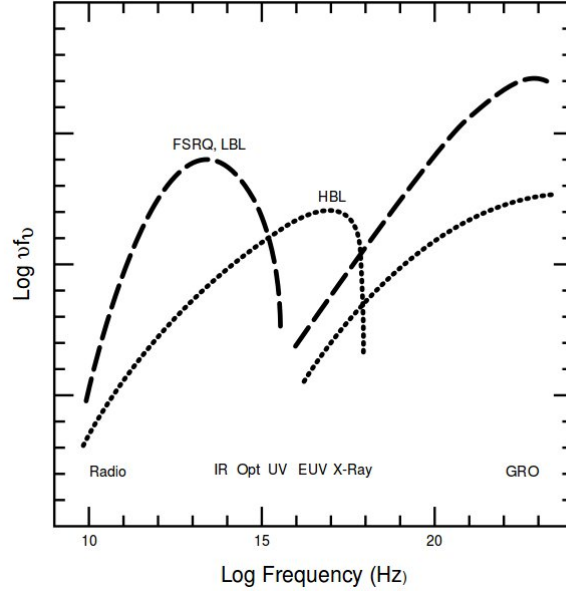


Figure 2.3: SED schematic for different blazar sources showing the $\log \nu$ - $\log \nu f_\nu$ relationship between the frequency and energy of blazar sources. The figure shows the energy distribution from synchrotron and inverse Compton emission in units of $\text{ergs}^{-1}\text{cm}^{-2}\text{Hz}^{-1}$. Where ν is the frequency, and f_ν is the flux density at that frequency. *Image credit: Multiwavelength spectra of blazars web notes.*²

In a simple scenario, the first peak at low frequencies is believed to be due to synchrotron radiation (§2.2.3) in the jet component of the AGN. Synchrotron radiation is responsible for the high polarization and rapid variability of blazars because it is dominated by relativistically moving electron particles. The second peak at GeV and sometimes TeV energies is produced by inverse Compton (IC) scattering of the same electron population as that responsible for synchrotron radiation through a process called synchrotron self Compton (SSC). The process producing this emission is still under debate and forms part of the important science questions that still need to be answered regarding AGN emission zones, particle content and acceleration, and cooling near the vicinity of a black hole. Figure 2.3 shows an SED schematic for the two kinds of blazars discussed. The dashed lines represent the SED for FSRQ and also BL Lac LBL blazar sources which are in general more luminous than BL Lac HBL blazars indicated by the dotted lines in the figure.

2.2.2 AGN energy sources

Matter accretion

Everything that is known about AGN sources is a result of the radiation observed. This radiation is a by-product of a wide variety of processes coming from different locations in the AGN. AGN are believed to emit most of their energy from a highly magnetized central luminous core ($L_{\text{AGN}} \sim 10^{42} - 10^{48} \text{ erg sec}^{-1}$). The energy is released within a small region of about a few parsecs (Fabian,

²<https://ned.ipac.caltech.edu/level5/Urry/Figures/fig2.gif>

1999), sometimes surpassing the luminosity of the host galaxy itself. To sustain this massive energy release over long periods of time the SMBH is fed surrounding ISM, gas and dust particles, at a massive accretion rate ($\dot{M}$)

$$\dot{M} = \frac{L_{AGN}}{\eta c^2} \sim 1 - 2 M_{\odot} \text{ yr}^{-1} \quad (2.1)$$

where η = the energy conversion efficiency and c = speed of light. The accretion of matter onto a black hole can be a large source of power, it is an efficient mechanism for the conversion of gravitational energy into electromagnetic radiation (Blandford, 2002).

As interstellar matter drifts towards the SMBH, it continuously adds contributions of mass and angular momentum to the system during its free fall. The incoming material gravitating towards the SMBH then forms an accretion disk around the black hole because angular momentum needs to be conserved. Part of the material forming the accretion disk gets converted into radiated energy and gets accelerated/ejected in the form of one or more narrow outflows of highly magnetized plasma along the accretion disk rotation axis of the galaxy, forming a jet like structure (Figure 2.1). Matter accretion in AGN sources can generate energy a factor of two or more brighter ($\Delta L > L_{AGN}$) than what is observed from non-active galaxies over timescales of $\sim$ a few hours or less. On these time scales the emission region of size r inferred can never be larger than

$$r \lesssim c \Delta t \quad (2.2)$$

where c is the speed of light and Δt is the variability time scale, and the amount of energy that can be generated from the accretion process can never be greater than the Eddington luminosity (L_{edd})

$$L_{AGN} < L_{edd} = \frac{4\pi G m_p c}{\sigma_T} M \simeq 1.3 \times 10^{38} \text{ erg s}^{-1} \frac{M}{M_{\odot}} \quad (2.3)$$

The L_{edd} is the maximum luminosity required for an object to continue accreting at a steady rate (eq. 2.1). For the source to continue accreting efficiently the gravitational forces (f_g) always need to be larger than the radiated pressure (f_{rad} , $f_g > f_{rad}$). This relationship between the gravitational and radiation forces is governed by the mass M of the source, the mass m_p of the protons and the Thompson cross section σ_T .

However, there are instances where the radiative forces become larger than the gravitational forces ($f_g > f_{rad}$) causing the source luminosity to exceed the Eddington luminosity for short periods of time. When this occurs it is referred to as “flaring” .

Relativistic jets

In special cases like blazars, excess energy is ejected out of the galaxy along the poles of the rotation axis, towards the observers line of sight, in the form of one or two highly collimated polarized jets (Blandford & Konigl, 1979; Tammi & Oksman, 2013). The jets are believed to be the main sources of the highly energetic and variable emission observed throughout the EM spectrum. Energy liberated in blazars can vary on very short time scales from a few days to a few hours or less (Marscher & Jorstad, 2010; Gupta et al., 2012), to longer timescales of a few months to

years (Hovatta et al., 2008; Nieppola et al., 2009; Pushkarev et al., 2010). Believed to form at a distance between roughly 10 and 10^3 Schwarzschild radii from the SMBH (Böttcher et al., 2012), relativistic jets are remarkable structures to behold. The physics behind the jet formation however is still very complex and remains one of the current hot topics in blazar astronomy, mainly due to the fact that a decision cannot be made on the exact particle content of the jet structures, among other things.

One of the models that is extensively used to give a basic analysis of the jet physics is the magneto-hydrodynamics (MHD) acceleration model (Lovelace, 1976; Blandford & Znajek, 1977). According to current understanding, particle acceleration of relativistically moving particles is believed to be the most likely triggering mechanism for jet creation. Once the jets are created they require a large injection of energy to sustain the bulk acceleration of the relativistically moving particles. Excess energy can then be extracted from the rotating accretion disk (Blandford & Payne, 1982; Meier & Koide, 2000) or a possibly spinning black hole (Blandford & Znajek, 1977) and fed into the jet. The jet which is a plasma flow of high energy particles propagates the relativistically moving particles along well defined paths of highly magnetic collimated streams that flow along the rotation axis and get twisted along the jet direction by the ergosphere of the rotating black hole forming helical field lines. Figure 2.4 shows an artists impression a quasar's jet structure.

Relativistically moving particles accelerated perpendicular to magnetic field lines emit synchrotron radiation (§2.2.3). At low frequencies, the radiated emission however appears optically thick as highly variable magnetic fields at the base of the jet cause turbulent activity in the plasma which results in the electrons becoming opaque to their own synchrotron radiation in a process called synchrotron self absorption. As particles move downstream further along the jet, the magnetic field contribution decreases in strength as it converts to kinetic energy, and the jet becomes optically thin to radio emission which we observe as a standing shock or radio core (figure 2.4).

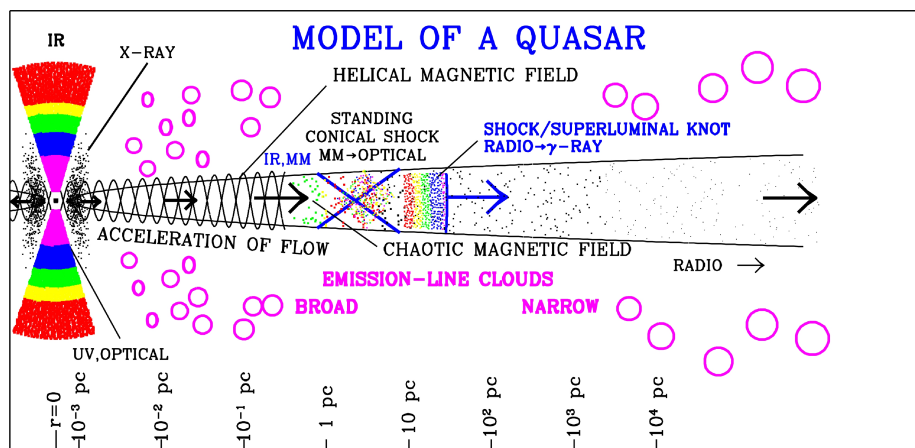


Figure 2.4: The figure shows the shock propagation along a collimated jet stream. During a flaring event, initial flaring is believed to occur closer to the end of the collimation zone region, with the second occurring within the millimeter-wave core. The distances from the black hole are shown in parsecs. *Image credit: Boston university blazar group web notes.*³

³ <https://www.bu.edu/blazars/Images/quasaremiscol5.jpg>

Shocks in radio jets are believed to be created when there is a significant disturbance in the steady jet flow (Marscher, 1990). The disturbance, formed at points where there are steep pressure gradients propagates down the jet at superluminal speeds. As particles get accelerated and reflected at the shock front by fermi processes (Fermi, 1954) they gain energy until they the energy gained is high enough to accelerate the particles across the shock front. When particles cross a shock they are boosted to higher energies and the shock expands adiabatically (van der Laan, 1966; Kellermann & Pauliny-Toth, 1968) as it propagates down the jet. The variable behavior we observe in the source emission is believed to form as a result of instabilities in the flow and shocks. Particles move with a bulk motion considered to be highly relativistic expressed in terms of the bulk Lorentz factor Γ as

$$\Gamma \equiv \frac{1}{\sqrt{1 - \beta_\Gamma^2}} \quad (2.4)$$

where $\beta_\Gamma = v_j/c$ is the jet plasma velocity and v_j is the jet bulk velocity.

In AGNs; like blazars, when the jet plasma velocity approaches the speed of light, c , the bulk Lorentz factor Γ reaches values ~ 10 to 30 . Plasma jets pointing towards the observer sometimes appear to have velocities much larger than the speed of light, i.e. $v_{\text{apparent}} > c$, and when this occurs it is referred to as Superluminal motion. For a relativistically expanding source with a bulk Lorentz factor Γ , the plasma is strongly Doppler boosted by the Doppler factor

$$\delta = \frac{1}{\Gamma(1 - \beta_\Gamma \cos \theta)} \quad (2.5)$$

where θ is the angle between the jet axis and the observers line of sight. Along the direction of the relativistic motion this δ is boosted by a factor $\approx 2\Gamma$, causing the light traveling towards the observer to get relativistically beamed into a cone of opening angle $\theta = 1/\Gamma$, normally ~ 20 degrees or less. The jets in some cases have been known to show some precession (Smith, 2012), which sometimes causes variations in the observed flux density. This has opened up suggestions of possible binary SMBH systems which can in some cases cause periodicity in observed light curves (Rieger, 2005).

2.2.3 Radio emission processes

The radio emission from AGN jets is non-thermal, being synchrotron, radiation produced by relativistic electrons moving in the magnetic field. A relativistic electron with energy $E = \gamma m_e c^2$ accelerated in the presence of a magnetic field B , emits radiation at a characteristic frequency (ν_c) which peaks at about $\nu_{\text{peak}} = 0.29\nu_c$

$$\nu_c = \frac{3\gamma^2 e B}{4\pi m_e c} \quad (2.6)$$

where B = magnetic field strength, e = electron charge, m_e = mass of electron ($511 \text{ keV}/c^2$), c = speed of light, and γ = the Lorentz factor

$$\gamma = \frac{1}{\sqrt{1 - (v/c)^2}} \quad (2.7)$$

An electron radiating with a frequency $\nu \sim 10$ GHz in a magnetic field $\sim 10^{-4}$ G would need a minimum Lorentz factor of $\sim 10^5$ meaning the electrons have to be highly relativistic. Given an electron relativistically moving in a magnetic field, it will generate on average a total radiated power of

$$P_{sy} = \frac{4}{3} \sigma_T c \beta^2 \gamma^2 U_B \quad (2.8)$$

dependent on the and the energy density $U_B = B^2/8\pi$ of the magnetic field for an isotropic distribution of electron velocities (Rybicki & Lightman, 1979), where σ_T is the Thompson cross-section. As the electron radiates it will loose energy, cooling down at a rate

$$\frac{dE}{dt} = P_{sy} \propto \gamma^2 U_B \quad (2.9)$$

At this rate we can estimate the electron lifetimes as the ratio between the total energy and the instantaneous power to give

$$\tau_{sy} = \frac{E}{dE/dt} \propto \frac{1}{\gamma^2 U_B} \quad (2.10)$$

At low frequencies, the emitted synchrotron radiation observed from electrons some time after they were accelerated will be from electrons that have lifetimes $\tau_{sy} \sim 10^8$ yrs. The energy radiated in the frequency range ν to $\nu + d\nu$ for an electron distribution with energies between E and $E+dE$ with an electron number density, $N(E) = KE^{-p}$, can often be described in terms of a power-law of the form

$$F_\nu \propto \nu^{-\alpha} \quad (2.11)$$

where F_ν is the flux density of the source, and α is the radio spectral index of the synchrotron emission spectrum. The radio spectral index is related to the particle distribution index p which is the slope of the log-log representation of $N(E)$ through the equation

$$\alpha = \frac{(p-1)}{2} \quad (2.12)$$

As electrons spiral around a magnetic field they emit energy over a broad range of frequencies depending on the speed of the electron. The distribution of this emitted radiation results in a power-law energy spectrum with the maximum energy of the electron peaking at the critical frequency (eq. 2.6) of the emitting electron. By super-positioning the spectrum of each contributing electron we get a characteristic spectrum described by a steady decline in flux density with increasing frequency which also follows a power-law described by eq. 2.11. The spectrum, as shown in figure 2.5, describes the spectral shape of the synchrotron emission emitted over a broad range of frequencies with ν_1 (turnover frequency) as the frequency at which the flux density reaches a maximum. For frequencies lower than ν_1 ($\nu \ll \nu_1$), the source becomes optically thick to synchrotron radiation, and the spectrum takes on the characteristic shape described by the relation $F_\nu \propto \nu^{5/2}$, a characteristic of self-absorbed ($\tau \sim 1$) opaque synchrotron sources. However, for frequencies higher than ν_1

($\nu \gg \nu_1$), the source becomes optically thin to synchrotron radiation with a characteristic shape described by the relation $F_\nu \propto \nu^{-(p-1)/2}$. Cosmic rays in our galaxy for example, have a characteristic spectral index $\alpha \sim 0.7$ with an electron distribution $N(E) \propto E^{-2.4}$.

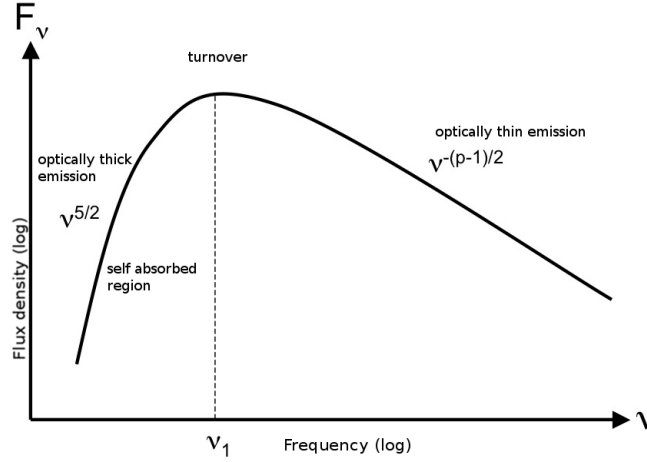


Figure 2.5: The synchrotron emission spectrum from a power-law distribution of electrons. *Image credit: Synchrotron radiation web notes.*⁴

2.2.4 Gamma-ray emission processes

Gamma-ray emission is characterized by short wavelengths and with typical frequencies in the range $10^{16}\text{Hz} < \nu < 10^{26}\text{Hz}$ with energies well above the MeV range. Energy emitted in this range must exist or emanate from a region very close to the jet base within a radius of 1 pc from the source core in the BLR. However, where exactly in the 1 pc region the gamma-rays are formed is still an open question. The same applies to the actual particle content responsible for the gamma-ray emission observed. Currently, there are two models for the origin of the high energy component of blazar jets. The models, (i) leptonic and (ii) hadronic, reproduce gamma-ray emission mechanisms with two different particle contents in mind with equally different emission methods.

Leptonic model

In the Leptonic model the dominant particles are assumed to be leptons (i.e. electrons and positrons). The model describes gamma-ray emission as a byproduct of ideally the same electron content as that responsible for the synchrotron radiation. The electrons produce gamma-ray emission created when a low energy radio photon gains energy by colliding with an accelerated relativistic electron. During the collision the electron loses energy by transferring it to the radio photon thus up-scaling/boosting the photon energy, by a factor of $\sim \gamma^2$ in the observers frame, to higher energies (gamma-ray photon) in a process called inverse Compton (IC) scattering, for an electron with energy $E \sim \gamma m_e c^2$.

IC scattering can be described in one of two forms based on the origin of the seed photons that are scattered. If the seed photons originate from the same population of relativistic electrons

⁴<http://www.ifa.hawaii.edu/~jpjw/classes/ast622.spring2008/handouts/synchrotron.html>

responsible for synchrotron emission within the jet, it is described as synchrotron self Compton (SSC, Marscher & Gear (1985)). However, if the origin of the seed photons is external, e.g. originating from the BLR (Sikora et al., 1994), accretion disk (Dermer & Schlickeiser, 1993) or cosmic rays it is described as, external Compton (EC). For the purpose of this study we are only going to focus on the SSC as it involves the radio synchrotron emission that forms part of the basis of this thesis. The total power emitted by relativistically boosted photons in an isotropic distribution of electrons due to IC scattering takes the form

$$P_{IC} = \frac{4}{3} \sigma_T c \beta^2 \gamma^2 U_{ph} \quad (2.13)$$

where U_{ph} is the radiation energy density of the photons before scattering. IC losses have the same energy dependence as the synchrotron losses, with the exception of the energy density being attributed to the photons rather than the magnetic field (eq. 2.8). Both equations (eq. 2.8 and eq. 2.13) describe the interaction of an electron with an EM field. Electrons accelerated across a shock front loose energy downstream of the jet, which makes it difficult to produce synchrotron radiation at higher frequencies because they cannot radiate much above the critical frequency (eq. 2.6). Lifetimes of IC electrons are $\sim 10^4 \text{ yrs}$. To sustain these electrons, it becomes apparent that a continuous injection of relativistic particles would have to occur continuously throughout the jet and not only be confined to the base of the jet where the radio emission is thought to be generated. The ratio of the inverse Compton to synchrotron losses

$$\eta = \frac{P_{IC}}{P_{sy}} = \frac{U_{ph}}{U_B} \quad (2.14)$$

provides a very important result. Electrons in a region that has both photon and magnetic energy will emit both synchrotron and inverse Compton radiation. There are however limitations to this result. If the photon energy density becomes larger than the magnetic energy density an IC catastrophe will occur (Kellermann & Pauliny-Toth, 1969). This results in the high energy electrons loosing more energy more quickly because more energy is now required to scatter the X-rays to gamma-rays. Similar to synchrotron emission, if the energy spectrum of the particles is a power-law, the radiation spectrum is also a power-law. The radiation produced by IC scattering has a power-law spectrum.

The leptonic model has been widely accepted as a model that can accurately model the SEDs of all blazar classes. For typical magnetic fields of $\sim 1 \text{ G}$, we get radiative cooling times $\sim 1 \text{ d}$ and $\lesssim 1 \text{ hr}$ in optical and x-rays respectively, compatible with observed intraday variability. However, the leptonic model is not the only one that has been suggested for describing the high energy emission regions (Dermer & Lott, 2012; Ojha, 2012; Böttcher et al., 2013).

Hadronic model

An alternative model known as the hadronic model suggests instead that the dominant particles are relativistic protons, with the high energy emission explained through the creation of gamma-rays from secondary particles. The Hadronic model assumes that synchrotron emission still dominate the

low frequency regime, however the high energy emission is a product of the relativistically accelerated protons. Because of the mass of the proton ($m_p = 1836 m_e$) a lot more energy is required to accelerate the protons. Accelerated protons produce neutral and charged pions that decay into electrons and positrons, which then ultimately produce the radiated gamma-ray photons and neutrinos. To produce γ -rays with energies ($E > 100$ MeV) scattering of photons from the following processes, π^0 decay (" π^0 cascade"), electrons from $\pi^\pm \rightarrow \mu^\pm \rightarrow e^\pm$ decay (" $\pi^\pm$ cascade"), p -synchrotron photons (" p -synchrotron cascade"), and μ^- , π^- and K^- -synchrotron photons (" $\mu^\pm$ -synchrotron cascade") can produce the required protons needed for relativistic proton acceleration (for a full breakdown of the hadronic processes please refer to Böttcher, 2010; Böttcher et al., 2013).

The Hadronic model however has not been as widely accepted due to its complicated energy dependencies of involved cross-sections. In some extreme cases when the SEDs of blazars cannot be explained using the leptonic model (for example 3C 279), the Hadronic model generally works well as shown by Böttcher et al. (2009).

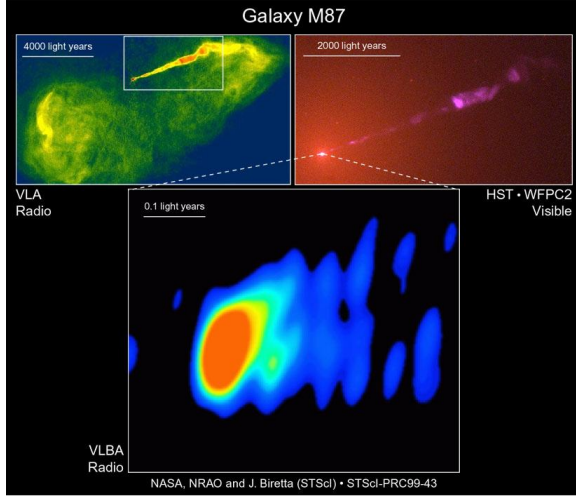
2.3 Blazar variability and multi-wavelength studies

Although both emission models seem to describe the blazar emission behavior well, to date no standard model providing a concrete solution to origin of the emission mechanisms has been found (Costamante, 2012; Ojha, 2012; Dondi & Ghisellini, 1995). Studies on radio jets in blazar sources however strongly suggest that these objects hold the key to unlocking the secrets to high energy phenomena. Throughout these parsec-scale structures relativistically moving particles undergo shocks that create variability in the emission of these sources. It has also been suggested that a direct correlation between the radio and gamma-ray emission can also be observed from these sources (Kovalev et al., 2009).

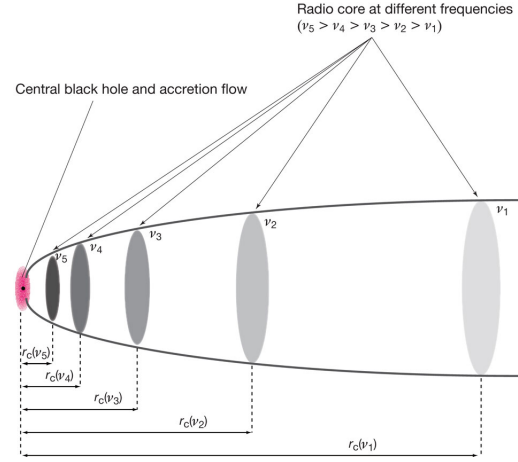
When observed on VLBI or milliarcsecond scales (figure 2.6a), the frequency dependent core shift can also be measured, where the radio core position shifts as a function of frequency (core shift is more pronounced at lower frequencies) due to SSC (figure 2.6b, Sokolovsky et al., 2011). The core shift also gives a measure of the time delay between light curves at different frequencies.

Following the assumption that the particle content is exclusively made up of electrons, we attempt to explain the jet feature using the popular model developed by Marscher & Gear (1985) called the Shock-in-jet or internal shocks model. It is important to note that other more complex models do exist, involving shock/jet recollimation (Cohen et al., 2014a; Perucho, 2013), magnetic reconnections (Giannios, 2013) and binary SMBH (Rieger, 2005) for example. During flaring the physical conditions of the jet get drastically altered. These changes in the jet form shocks in the expanding jet, which accelerate the electrons to higher energies producing optically thin radio synchrotron and gamma-ray emission.

During the ejection of a new jet component, some particles gain more energy, while others lose energy, causing the variations in flux density that we observe. In some cases, we can observe more than one flaring event. The flares are thought to be caused by inhomogeneities in the jet region or a shock due to a slowly propagating previous flare.



(a) VLBI image of the galaxy M87 *Image credit: Junor et al. (1999)*



(b) Schematic impression of the radio VLBI core shift. *Image credit: Hada et al. (2011).*

Figure 2.6: Figure (a) shows VLBI images of the galaxy M87. The images show the jet structure on mas scales, and (b) illustrates the radio VLBI core at different frequencies.

The shocks produced in blazar jets give rise to emission spread across the EM spectrum, this is why it is important that these sources are observed at multiple wavelengths, to study the variability and possible connections between different frequencies. Blazar light curves can also tell us about the creation and evolution of synchrotron emission.

The year 2008 provided a breakthrough in probing these objects with the launch of the Fermi Gamma-ray Space Telescope (FERMI-GST)⁵ whose mission, was to detect and image gamma-rays from a low Earth orbit. Commissioned for detecting gamma-rays with energies between 20 MeV (Mega electron-volts) and 300 GeV (Giga electron-volts) this meant that galaxies could now be probed through the most violent of events occurring very close to the black hole, providing a gateway to studying the inner workings of these sources. Given the nature of these structures it is very difficult to draw conclusions about their behavior by using only single frequency observations. Thus a multi-wavelength analysis is required to establish the true nature, location and effect of the emitted radiation.

2.4 Overview of target source PKS 1424-418

At a red-shift (z) of 1.522, PKS 1424-418, also known as, J1427-4206 is a very bright FSRQ blazar source (White et al., 1988). Over the years it has become one of the most interesting Southern Hemisphere sources, showing flaring behavior spanning over decades in frequencies. PKS 1424-418 is a highly variable source and shows strong optical and radio polarization (Impey & Tapia, 1988). Emitting high energy gamma-rays with energies $E > 100$ MeV, PKS 1424-418 is one of the sources most regularly monitored by Fermi Large Area Telescope (FERMI-LAT) group. On milliarcsecond scales, PKS 1424-418 is a compact source (figure 2.7) making it an ideal candidate for reference frame

⁵<http://www-glast.stanford.edu/>

sources. Due to its highly compact structure coupled with good positional stability, PKS 1424-418 forms part of the International Celestial Reference Frame (ICRF) defining sources⁶, used for determining the positions of geodetic VLBI antennas and Earth's orientation in space, among other things. Because of its southern declination, PKS 1424-418 is also a regularly monitored source of the TANAMI (Tracking Active Galactic Nuclei with Austral Milliarcsecond Interferometry) group, who monitor blazar sources in the Southern Hemisphere.

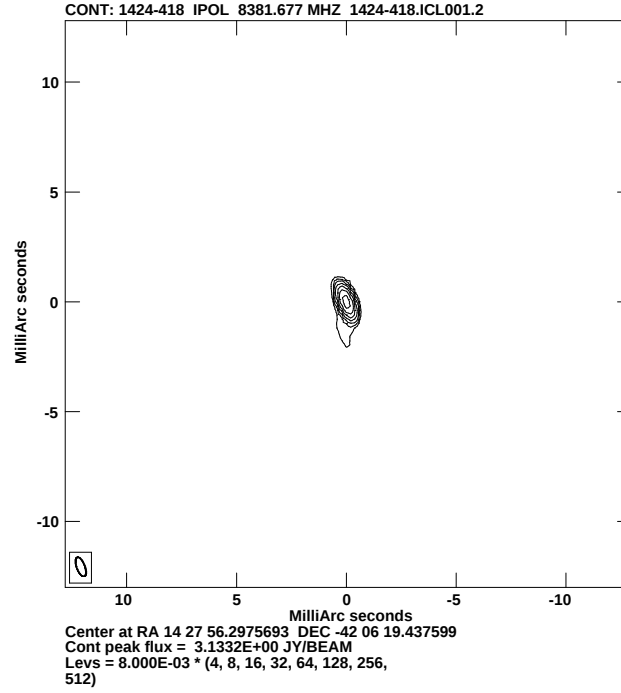
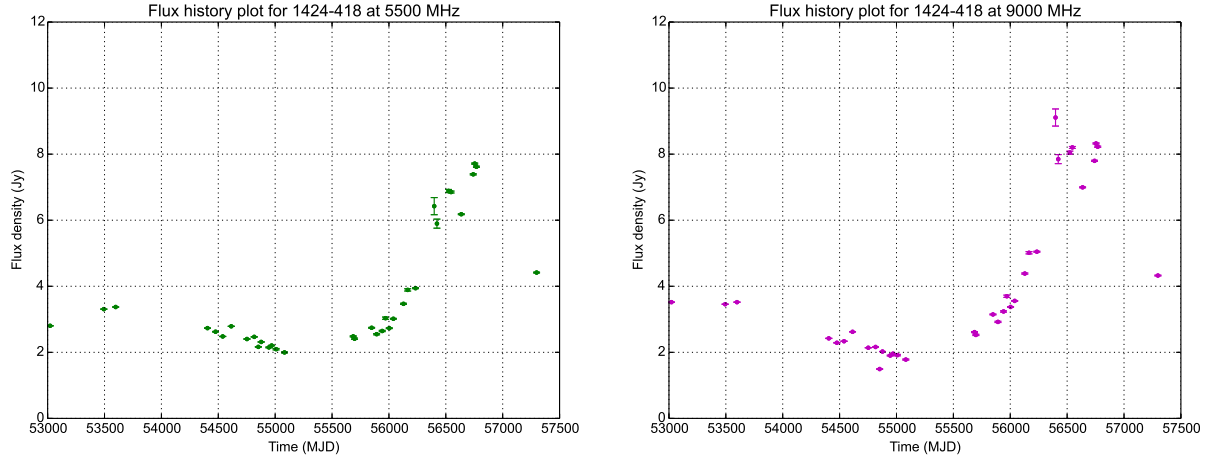


Figure 2.7: Recent 8.4-GHz image of PKS 1424-418 from the IVS data taken in February 2014. *Image credit: Sayan Basu (HartRAO).*

Since FERMI-LAT began monitoring it, PKS 1424-418 has become increasingly bright through the entire EM spectrum from gamma rays to radio waves. In radio, the Australian Telescope Compact Array (ATCA), recorded steadily increasing trends in both the 5500-MHz time-series with a mean flux density of 6.869 ± 0.007 Jy, and the 9000-MHz time-series with a mean flux density of 8.2 ± 0.01 Jy, as shown in figures 2.8a and 2.8b respectively. These slow changes in flux over time are very useful in AGN research, as they provide a platform for developing constraints on the physical processes responsible for the high energy radiation emitted by AGN sources.

⁶hpiers.obspm.fr/icrs-pc/icrf/icrf.html



(a) PKS 1424-418 at 5500 MHz.

(b) PKS 1424-418 at 9000 MHz.

Figure 2.8: Monitoring of PKS 1424-418 using ATCA from July 2009 to July 2013. Figure 2.8a shows PKS 1424-418 at 5500 MHz and figure 2.8b shows PKS 1424-418 at 9000 MHz. Image credit: Data from ATCA⁷

2.5 Motivation of this study

Blandford & Konigl (1979) presented one of the earliest models that attempted to explain the mechanisms responsible for the phenomenon we observe in Blazars, focusing on the internal motions of the particles producing the detected emission. Of particular interest are the radio and gamma-rays (lowest and highest radiation emission respectively) that we observe from these objects. Recent studies that focused on long term monitoring of these objects (Stevens et al., 2012; Hovatta et al., 2008; Raiteri et al., 2006) have shown that studying the multi-wavelength variability of the AGN jet region might lead to a better understanding of the processes at work in these objects, making the AGN core a vital key in achieving this. Studies conducted by Ghirlanda et al. (2011) and Max-Moerbeck et al. (2010) produced correlation coefficients of 0.42 and 0.56 respectively, between radio and gamma-ray flux density variations. The results propose a possible significant connection between the two energy regimes. A study of gamma-ray emitting blazars by Dondi & Ghisellini (1995) suggested that radio and gamma-rays are closely linked, as did the recent discovery by Collaboration et al. (2012) that the radio luminosity of the blazar PKS 2155-304 increased after a peak in the very high energy (VHE) activity of the blazar, indicating a strong probability of some correlation between the radio and gamma-rays. Buson et al. (2014) also studied the multiwavelength correlation between gamma-rays and optical emission in PKS 1424-418, and most recently Tavecchio et al. (2013) studied the multiwavelength IR to gamma-ray variability during the 2013 outburst.

It is therefore very important that we understand the connection between the high and low energy systems, and continued multi-frequency studies of these AGN sources affords us the ability to do so. Since the launch of Fermi-LAT there has been a lot of interest in conducting more detailed studies of

⁷http://www.narrabri.atnf.csiro.au/calibrators/calibrator_database_viewcal?source=1424-418

blazars to further refine our understanding of these structures, more importantly what causes them to behave the way they do.

2.6 Objectives of the research

In this dissertation, I aim to try to determine whether there is a correlated variation between the gamma-ray and radio frequencies in the blazar PKS 1424-418, and the time-delay ranges that are factored in as a result of the observed variability following a gamma-ray flare event, using quasi-simultaneously observed data. A radio to gamma-ray time delay was observed by Pushkarev et al. (2010) in their study of a large sample of 183 FERMI-LAT-detected AGN's. Pushkarev et al. (2010) found that the most probable delay was of 1.2 months. Other studies have shown shorter time delays within days of a flaring event.

To get a broad view of the relationship between the radio and gamma-ray emission of PKS 1424-418, I conducted radio observations over a period of 11 months following a gamma-ray flare detected by FERMI-LAT (Ojha, 2012). We reported some of the early radio results in Nemenashi et al. (2013). I obtained quasi-simultaneous radio observations at 2.3, 4.8, 8.4 and 12.2 GHz and the results obtained are recorded and analyzed in Chapter 5. The high energy data used for the correlation analysis was obtained from the FERMI-LAT archive and, together with the radio data, were used to study the connection between the radio and the gamma-ray behavior of the source.

TECHNICAL ASPECTS & OBSERVATIONS

Flaring blazar sources, like PKS 1424-418, require high cadence observing at multiple frequencies in order to adequately detail the source activity. The ability of radio telescopes to monitor both rapid and slow changes in source flux density over time makes them very useful tools in blazar research. Radio telescopes are able to monitor the activity of low energy radio waves along the jet of the blazar source. High energy photons, on the other hand, allow us to peer into regions close to the black hole where the energy production in AGN is assumed to take place. Gamma-ray instruments allow us to monitor the most energetic events from these extreme conditions.

This chapter provides details of the two telescopes, the Hartebeesthoek Radio Astronomy Observatory (HartRAO) 26 m radio telescope and the FERMI-LAT, and the observing techniques that were used for data collection.

3.1 Telescope layout and signal detection

3.1.1 The HartRAO 26 m radio telescope

All the radio data was obtained using the HartRAO 26 m telescope (see Figure 3.1), hereafter referred to as the Hart26m. The telescope is located in the Southern Hemisphere in an isolated valley 65 km North-West of Johannesburg, with coordinates 25.9 degrees South and 27.7 degrees East, and was built by a US company, Blaw Knox, in 1961 as part of the National Aeronautics and Space Administration (NASA) Deep Space Network¹.

¹<http://www.hartrao.ac.za/summary/sumeng.html>



Figure 3.1: The Hart26m radio telescope in the foreground with the HartRAO 15 m telescope in the background. *Image credit: Carolina Odman Govender.*²

The Hart26m has an equatorial mount geometry with a Cassegrain optical configuration based on a design that was originally developed for the Michigan 26 m radio telescope located at Peach Mountain Observatory³. The Hart26m telescope is utilized for both single dish and VLBI observing, and is an important instrument that services both local and international astronomers observing the southern skies. It is limited to an absolute declination of $+45^\circ$.

Regular maintenance on the Hart26m ensures that it is continuously upgraded to modern research standards and continues to provide a wealth of data on galactic and extra-galactic high energy sources. Table 3.1 gives a short version of the basic specifications of the Hart26m telescope.

Latitude	25.887°
Longitude	27.685°
Radio telescope mount	offset equatorial (polar) mount
Diameter of main reflector	25.914 m
Focal length of main reflector (f)	10.886 m
Focal Ratio (f/D)	0.420
Optical configuration	Cassegrain
Diameter of secondary reflector (D_S)	2.438 m
Focal length of Cassegrain system (f_C)	4.807 m
Focal Ratio (f_C/D_S)	1.97
Surface error of main reflector (rms)	0.5 mm
Short wavelength limit	1.3 cm
Pointing Resolution	0.001°
Repeatability	0.004°
Slew Rate on each axis	$0.5^\circ s^{-1}$

Table 3.1: The Hart26m telescope specifications⁴.

²https://c1.staticflickr.com/5/4133/5083909662_dd2acb8b0b_z.jpg

³<http://www.umich.edu/~lowbrows/history/peach-mountain.html>

⁴http://www.hartrao.ac.za/hh26m_factsfile.html

At the cassegrain focus of the Hart26m dish are a set of microwave receivers which can work quasi-simultaneously to collect radio emission from a target source at different frequencies. The Hart26m telescope currently has seven receivers that operate at 1.7 GHz (18 cm), 2.3 GHz (13 cm), 4.8 GHz (6 cm), 6.7 GHz (4.5 cm), 8.4 GHz (3.5 cm), 12.2 GHz (2.5 cm) and 22 GHz (1.3 cm). These very sensitive instruments are required to detect and extract weak radio signals that are normally embedded within the noise from the background radiation and the noise generated by the receiver itself (see §4.1 for more details on noise contributing factors). All receivers, apart from the 12.2-GHz receiver, are cryogenically cooled to minimize the thermal noise generated by components suffering from ohmic losses. For the purpose of this study we used the 2.3, 4.8, 8.4 and 12.2-GHz receivers. Table 3.2 shows a list of the basic properties of the receiver components used in this study. The Hart26m telescope receivers are all dual polarization systems. All receivers operate in total power mode with the exception of the 4.8-GHz and 8.4-GHz receivers that have two feeds aligned East-West to allow Dicke-switched radiometry. The radio signal going through the receivers can be used unfiltered, or passed through 4, 8, 16 or 32-MHz bandwidth filters to exclude interference from external signals at some observing frequencies.

Band	13 cm	6 cm	3.5 cm	2.5 cm
Feed horns	1 x circular	2 x circular	2 x circular	1 x rectangular
Polarization	LCP & RCP	LCP & RCP	LCP & RCP	LCP & RCP
Amplifier	cryogenic HEMT	cryogenic HEMT	cryogenic HEMT	uncooled PHEMT
Central frequency (GHz)	2.3	4.8	8.3	12.2
Beam-width: full width at half max (degrees)	0.332	0.160	0.092	0.059
Beam-width: between first nulls (degrees)	0.80	0.36	0.23	0.16
Minimum system temperature at Zenith (K)	36	55	50	100
Point Source Sensitivity per polarization (Jy/K/Pol)	4.8	6.0	6.1	5.8

Table 3.2: The Hart26m telescope microwave receiver specifications⁵, where LCP and RCP are the Left and Right Circular Polarizations respectively. HEMT (High Electron Mobility Transistor) and PHEMT (Pseudomorphic High Electron Mobility Transistors)⁶ are models of amplifiers used on the Hart26m telescope.

3.1.2 The Hart26m receiver layout and signal chain

Figure 3.2 shows the basic layout of the Hart26m telescope receivers for both the single- and dual-beam systems. When the Hart26m points at a radio source in the sky, the radiation is reflected towards the sub-reflector located in front of the focus of the main reflector. The radiation then gets focused onto the receivers located in the telescope cone at the focus of the sub-reflector. All incoming signals are split into Left circular polarization (LCP) and right circular polarization (RCP)

⁵http://www.hartrao.ac.za/hh26m_factsfile.html

⁶<http://www.radio-electronics.com/info/data/semicond/fet-field-effect-transistor/hemt-phemt-transistor.php>

by a hybrid wave-guide polarization splitter (POL) at the base of each feed horn, feeding LCP to one receiver chain and RCP to the other, except for 12.2 GHz which has a $\frac{1}{4}$ wave plate polarization converter ahead of the feed and dual linear polarization outputs. To calibrate the system a high-stability noise diode (ND) injects a known noise signal which is split equally by a power divider (PW DIV) between the LCP and RCP receiver chains. Each noise signal is then coupled to the incoming signal by a directional coupler (CPR). Radio signals are very weak and as such require amplification to a detectable level through a low-noise amplifier (LN AMP). Because the internal noise in the amplifiers is generally much larger than the signal, specially designed amplifiers that are cryogenically cooled are used to maximize sensitivity.

The Hart26m receivers are based on the superheterodyne receiver design in which the amplified radio frequency (RF) signal is down converted to a lower frequency in order to minimize signal losses in the passive components (e.g. wave-guide and coaxial cable). The mixer (MXR) then multiplies the RF signal with a locally generated signal from the local oscillator (LO) to produce an output signal that is the difference frequency component (RF - LO) of the product which is called the intermediate frequency (IF). To get the final output the IF signal is amplified, this time using an IF Amplifier (IF AMP). The signal is then detected in the radiometer by a Square-Law detector (S/L DET) which converts the IF signal into an output DC voltage proportional to the input power. The voltage to frequency converter (V/F CON) then converts the signal to a square wave train, where the amplitude remains constant but the frequency is proportional to the DC voltage input. These oscillations are then measured with a counter (CTR), such that the count rate (in units of Hertz) is then proportional to the original IF signal's power. From here the signals are loaded onto the Hart26m server in FITS (Flexible Image Transport System) format with the universal time, object name and observer name use to identify the fits files. At this stage the data is ready for display and processing.

Total power receivers

Total power receivers (see Figure 3.2) measure the total, time-averaged power of the input noise from the radio telescope over some well defined radio frequency band. A Square-Law detector converts noise voltage into noise power proportional to the square of the input voltage

$$\langle P \rangle = \int_{t-\tau/2}^{t+\tau/2} p_d(t) dt \propto \int_{t-\tau/2}^{t+\tau/2} [v_o(t)]^2 dt \quad (3.1)$$

where P = output power, τ = averaging time, $p_d(t)$ = instantaneous power measured by the detector and $v_o(t)$ = output amplitude. The system design assumes that gains in the receiver remain constant over the duration of a typical scan. However, random fluctuations in ambient temperature or bending of radio frequency (RF) cables as the telescope moves around, for example, can cause the receiver gains to randomly change, ultimately affecting the output power of the receiver system. This causes drastic reductions in the receiver sensitivity which degrades the quality of the data observed. To combat these variations in gain a noise diode is activated prior to each scan.

The noise diode generates a constant signal with a known noise temperature that is used to calibrate the system gain. For more details on antenna calibration see §4.1.

Dicke-switch receivers

Dicke-switching as the name implies, is a method of switching rapidly between two identical feed horns (A & B) that are installed next to each other on the telescope (see Figure 3.2). If feed A is pointing at the source, and the angular size of the source is smaller than the separation of the beams from the two feeds, then feed B will point off-source but measure nearly the same sample of atmosphere in the near field. Because the output of the receiver is multiplied by +1 when the receiver is connected to feed A and by -1 when it is connected to feed B, any fluctuations in atmospheric emission and drifts due to changes in receiver gain are canceled for frequencies below the switching rate. This method is particularly useful for frequencies higher than ~ 5 GHz where atmospheric contributions from water vapor become a problem. At HartRAO, the Hart26m telescope switches between the beams at a switching rate of 50 Hz.

3.1.3 The Fermi Gamma-ray Space Telescope

The Fermi Gamma-ray Space Telescope (Fermi-GST) was developed to detect and monitor high energy radiation from above the Earth's atmosphere (Atwood et al., 2009; Ciprini et al., 2013), and was launched into orbit in June 2008. The Fermi-GST design was based on the operation of two main scientific instruments; the Fermi Large Area Telescope (FERMI-LAT) and the Fermi Gamma-ray Burst Monitor (FERMI-GBM). The FERMI-LAT is the primary detector used to observe high-energy gamma rays between 20 MeV and over 300 GeV while the Fermi-GBM observes X-rays and gamma rays between 8 KeV and 30 MeV. Every three hours the FERMI-LAT instrument scans the entire sky for high-energy events, observing 20% of the sky at each glance (Grove & Johnson, 2009). Table 3.4 provides a list of the main specifications for the FERMI-LAT instrument.

To date, FERMI-LAT is the most sensitive gamma-ray telescope used in all-sky surveys. It is a 100 times more sensitive than it's predecessor EGRET (Energetic Gamma-Ray Experiment Telescope) whose design only covered 20 MeV to 30 GeV gamma-ray detections. With a field-of-view (FOV) four times that of EGRET (Thompson, 1993) and a resolution ~ 1 arcminute, FERMI-LAT affords the opportunity to perform high cadence observations of the universe's most energetic objects. The high-energy flux time-series, known as light curves, produced from these monitoring observations show flaring activity with unprecedented detail, making the FERMI-LAT a preferred instrument for blazar monitoring. Figure 3.3 shows a sky map from a 5 year survey, in all-sky monitoring mode, observed by the FERMI-LAT instrument.

3.1.4 FERMI-LAT signal detection

The FERMI-LAT is comprised of four main components (Figure 3.4), the anticoincidence shield (ACD), particle tracker/detector, Calorimeter and a data acquisition system (DAQ)

Parameter	Requirement	Goal
Lifetime (> 20% degradation)	> 5 yrs	> 10 yrs
Telemetry Downlink:		
Orbit Average	> 300 kbps	> 1 Mbps
Realtime	> 1 kbps	> 2 kbps
Telemetry Uplink - Realtime	> 1 kbpsr	> 2 kbps
Time to Respond to TOO's on Ground	> 6 hours	> 4 hours
Spacecraft Repointing	> 10 min	> 5 min
Times for Autonomous Slews		
GRB Notification Time to Ground by Spacecraft	> 5 sec	> 2 sec
Pointing Accuracy (Absolute)	> 2°	> 0.5°
Pointing Knowledge	> 5 arcsec	> 2 arcsec
Observing Modes	- Rocking zenith pointing - Pointed mode ⁷	
Targeting	No restrictions on pointing of axis normal to LAT	
Uniformity of Sky Coverage during Scanning	> ± 20%	> ± 10%
Observatory Absolute Time Accuracy	> 10 μsec	> 3 μsec
Observatory Absolute Position Accuracy	< 3.3 km	> 1 km
Observing Efficiency	> 90%	> 95%
Data Loss	< 2%	< 1%
Data Corruption	< 10 ⁻¹⁰	< 3 × 10 ⁻¹¹

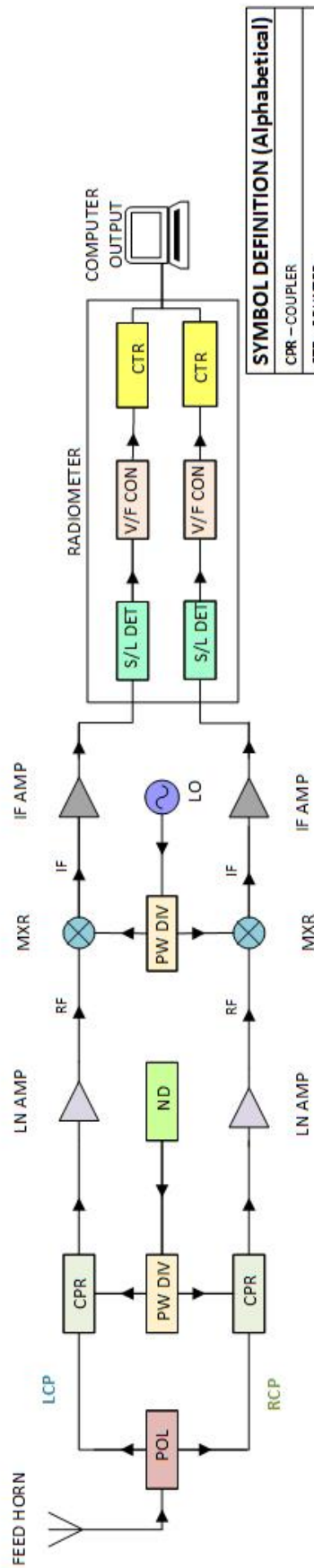
Table 3.3: A list of some of the main Fermi-GST mission objectives.. For a full explanation of terms please refer to the FERMI-LAT website⁷.

When the FERMI-LAT observes a target, the ACD works as a cosmic-ray filter. A gamma-ray will pass through the ACD, while a charged cosmic ray will produce a signal in the ACD that will tell the DAQ to reject the signal. The gamma-ray that passed through the ACD will then interact with specially designed conversion foils made from a high-Z material (e.g. Tungsten) and this interaction will convert the gamma-ray into an electron and a positron through particle pair-production. Silicon-strip detectors in the tracker then measure the paths of the electron and positron to determine the direction of the original gamma ray. The Calorimeter then measures the energy of the electron and the positron and thus the energy of the original gamma ray. Information collected from all pre-processes (ACD, Tracker and Calorimeter) is then analyzed by the data acquisition system to distinguish between unwanted signals from cosmic rays and the gamma ray signals the LAT needs to collect. The on board analysis is performed by a set of specialized electronics and microprocessors before it is sent to the ground based station.

Because high-energy gamma-rays cannot be measured directly, the detection of the high energy radiation requires a particle physics approach. The simplest way to achieve gamma-ray

⁷<http://fermi.gsfc.nasa.gov/science/parameters.html>

TOTAL POWER RECEIVER (SINGLE BEAM).



SYMBOL DEFINITION (Alphabetical)

CPR – COUPLER
CTR – COUNTER
D/S – DICKE SWITCH
IF AMP – INTERMEDIATE FREQUENCY AMPLIFIER
LCP – LEFT CIRCULAR POLARIZATION
LN AMP – LOW NOISE AMPLIFIER
LO – LOCAL OSCILLATOR
MXR – MIXER
ND – NOISE DIODE
POL – POLARIZER
PW DIV – POWER DIVIDER
RCP – RIGHT CIRCULAR POLARIZATION
S/L DET – SQUARE LAW DETECTOR
V/F CON – VOLTAGE/FREQUENCY CONVERTER

DICKE SWITCHED RECEIVER (DUAL BEAMS).

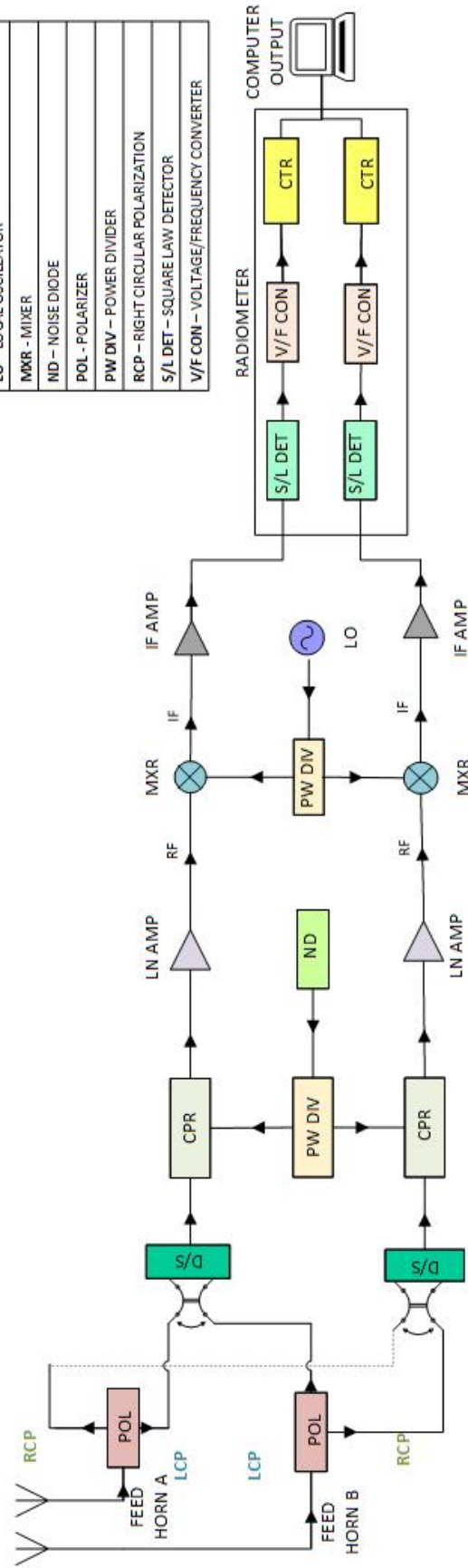


Figure 3.2: The Hart26m telescope receiver layout and signal chain

photon detections is through particle pair-production. Particle pair-production occurs when energy gets converted to mass creating an elementary particle and its antiparticle (e.g. e^- , e^+). The FERMI-LAT tracker component takes advantage of this principle by monitoring particle pairs created by incoming gamma-rays.

The e^-e^+ particle pairs then form an electromagnetic shower that gets collected by an on-board calorimeter component, which then measures the energy of the particles as well as their trajectory and arrival times. Energy profiles of all e^-e^+ pairs are then utilized to infer the original gamma ray. Information collected from all pre-processes (ACD, Tracker and Calorimeter) is then analyzed by the data acquisition system to distinguish between unwanted signals from cosmic rays and the gamma-ray signals the LAT needs to collect. The on board analysis is performed by a set of specialized electronics and microprocessors before it is sent to the ground based station.

Quantity	Specification
Energy range	20 MeV - >300 GeV
Peak Effective Area	>8000 cm ² at normal incidence
Field of View (FOV)	> 2.4 sr
Angular resolution	< 3.5°, on axis, 68% space angle containment for (E = 100 MeV) < 0.15°, on axis, 68% space angle containment radius for (E>10 GeV)
Energy Resolution	< 15 % at energies > 100 MeV
Dead-time per event	< 100 μ s
Source location determination	< 0.5' for high-latitude sources
Point source sensitivity	< 6 $\times 10^{-9}$ cm ⁻² s ⁻¹ (E > 100MeV) with 5 σ detection after 1 year sky survey
Time Accuracy	< 10 μ s, relative to spacecraft time
Background rejection (after analysis)	<10% residual contamination of high latitude diffuse sample for E = 100 MeV - 300 GeV

Table 3.4: FERMI-LAT specifications and performance outline⁸.

3.2 Multi-wavelength observations of PKS 1424-418

Over the years, the blazar PKS 1424-418 has been showing evidence of high activity in gamma-ray wavelengths. Since 2009 astronomers have monitored flaring behavior from PKS 1424-418 which in turn triggered a host of multi-wavelength campaigns (see Table 5.1). Long term monitoring of PKS 1424-418 at multiple radio wavelengths using the Hart26m telescope began in October 2012 after an increased gamma-ray activity detected by the FERMI-LAT team (see Ojha & Dutka, 2012).

⁸http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone_Introduction/LAT_overview.html

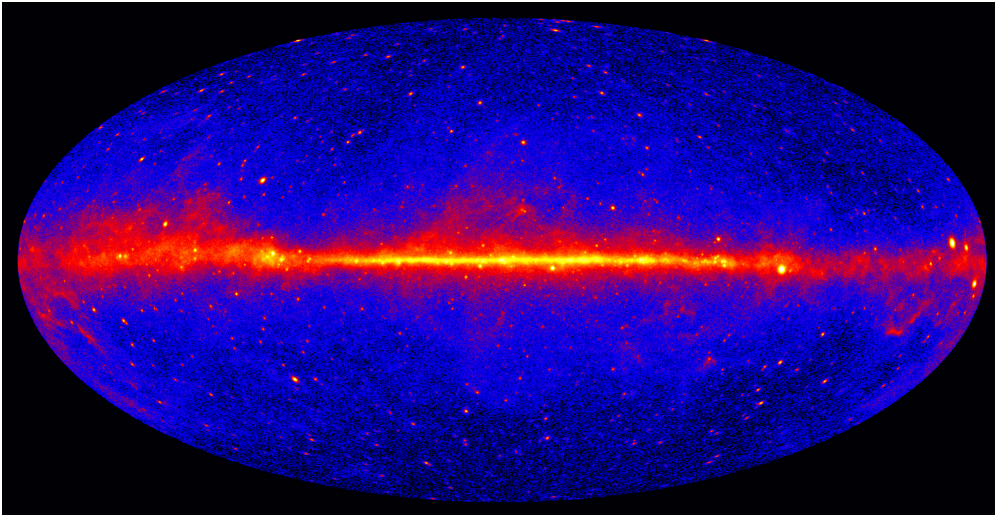


Figure 3.3: An all-sky map of the gamma-ray sky from data obtained over 5 years by the FERMI-LAT for $E > 1$ GeV sources. The image shows the most energetic sources as the bright points in the figure, with the galactic center being the brightest region *Image credit: NASA/DOE/Fermi LAT Collaboration*⁹.

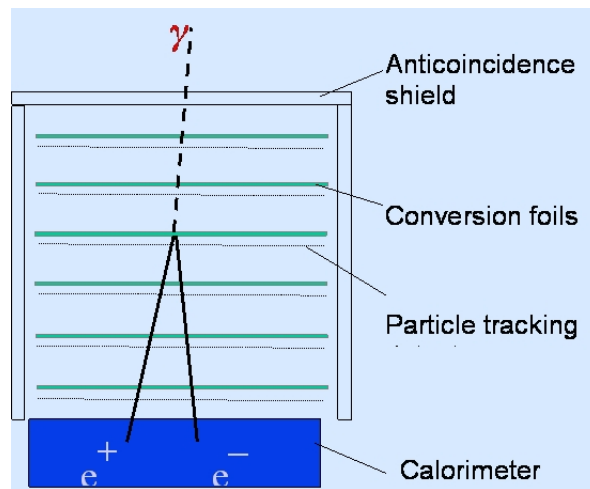


Figure 3.4: Schematic of the FERMI-LAT instrument layout *Image credit: NASA/Fermi LAT Collaboration*¹⁰.

3.2.1 Observations of PKS 1424-418 with the HartRAO 26-m telescope

Observations using the Hart26m telescope were conducted at multiple frequencies using drift scans. This method is used to observe target sources without having to track the moving target across the sky. Drift scans are obtained by using the rotation of the Earth to scan the telescope main beam across the source at a sidereal rate (Briggs et al., 1997; Leto et al., 2006). The signal from the source is sampled as the Earth rotates and the source “drifts” through the beam of the telescope. The output of the radiometer will be the convolution of the antenna beam pattern with

⁹http://fermi.gsfc.nasa.gov/ssc/Fermi_5_year.jpg

¹⁰http://fermi.gsfc.nasa.gov/ssc/data/analysis/documentation/Cicerone/Cicerone.Introduction/LAT_concept.gif.

the brightness distribution of the source.

This observing method is very useful in observing objects with an angular size much smaller than the angular size of the telescope beam, as the output of the radiometer will then effectively be an east-west cross-section of the beam of the telescope. The apparent hour-angle, full width at half maximum (FWHM) of the telescope main beam depends on the frequency of observation and the diameter of the dish (where the $\text{FWHM} \sim 1.2 \lambda/D$), and therefore the FWHM of the telescope main beam will decrease with increasing frequency. However, the width of the scan pattern is the FWHM of the telescope main beam divided by the cosine of the declination of the source at the epoch of observation, as scans in Right Ascension are broadened by the secant of the declination of the source. On a spherical surface, lines of longitude converge towards the poles. The distance of a degree of longitude is at its greatest at the equator and decreases to zero at the poles.

Figures 3.5a and 3.5b show typical outputs of the single-beam drift scans. The dual-beam receivers used for 4.8-GHz and 8.4-GHz observations contain two separate feed horns placed next to each other, with the “A” horn on the North/South axis and the “B” horn just west of the “A” horn, with beam separations of $+0.288$ and $+0.254$ decimal degrees respectively. In the case of a dual-beam system the second feed-horn will follow the path of the first feed-horn to produce an output as shown in Figures 3.5c and 3.5d.

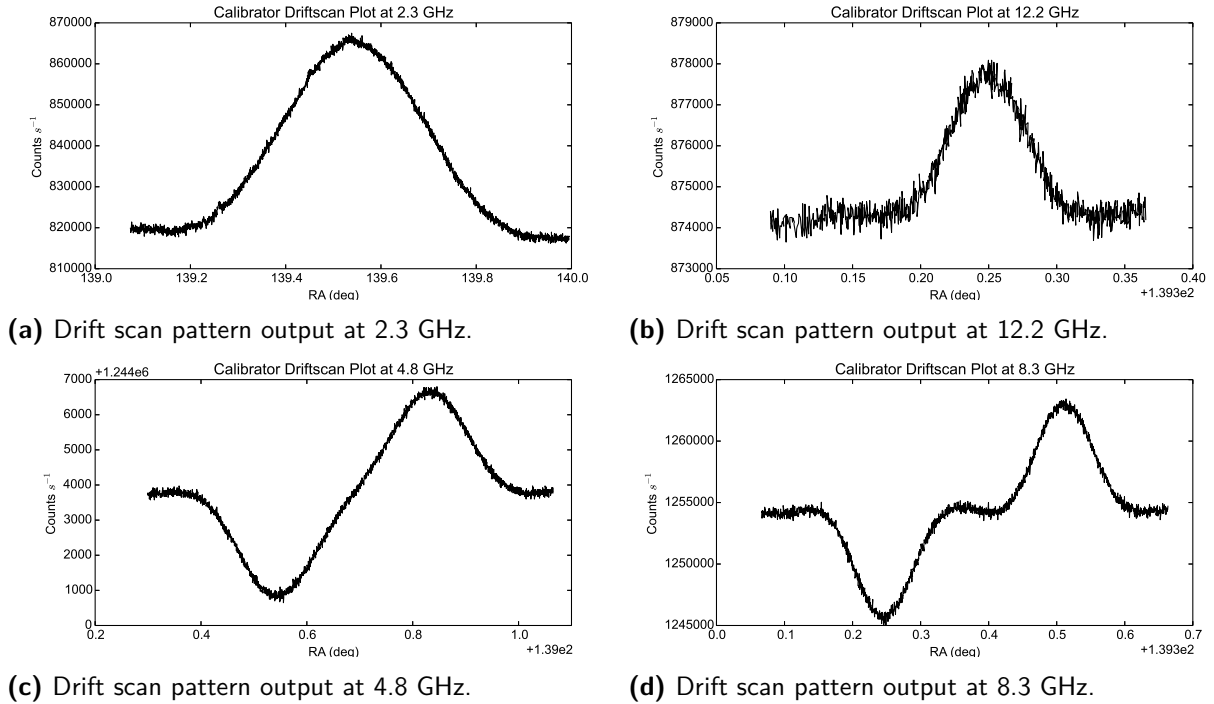


Figure 3.5: Figures (a) and (b) show the single-beam drift scan pattern at 2.3 and 12.2 GHz respectively. Figures (c) and (d) show the dual-beam drift scan pattern at 4.8 and 8.4 GHz. The x-axis is the Right Ascension in degrees, and the y-axis is the count-rate measurement (counts s^{-1}) of the source amplitude in units of Hertz (as previously discussed in §3.1.2).

The source PKS 1424-418 was observed in both LCP and RCP to preserve as much information as possible in the weak radio signals before any processing could be applied to them. Most of the observations were done using triple drift scans, where the first scan is made at the nominal

declination of the target (hereafter ON), and then the other two at the half power beam width (HPBW) North (hereafter HPN) and South (hereafter HPS) of the target, to allow compensation of pointing errors (see §4.2 for more details).

The 4.8-GHz and 8.4-GHz observations were done in Dicke-switched mode. At 2.3 GHz the bandwidth was filtered to 16 MHz to avoid radio frequency interference (RFI). At higher frequencies, 4.8 GHz, 8.3 GHz and 12.2 GHz, two separate observations were done directly after each other and averaged in order to reduce the noise in the data set. On days when the weather was not suitable for observing, observations went up to four per day, but those were not common and only occurred at 8.3 GHz and 12.2 GHz.

For calibration purposes, the radio galaxy 3C218, also known as HYDRA A or PKS 0915-11 (Lane et al., 2004) was used. HYDRA A is a powerful radio source located at a red-shift $z=0.054$ in the center of the X-ray galaxy cluster Abell 780 (Abell 1958) (Taylor et al., 1990; Hamer et al., 2013). The source is known to be a very bright compact source that shows only small variations in the total flux density on large scales, over the time-scale of a decade. Ott et al. (1994) presented new flux densities for the radio sources in the calibrator list of Baars et al. (1977). Compared to earlier measurements, Hydra A appears to be fainter by 0.4 - 4.7% (between 1.4 and 23 GHz), but still lie within the error range of the Baars et al. (1977) flux densities.. The flux density of HYDRA A is well known at certain frequencies and can be calculated for other radio frequencies using the interpolation equation and coefficients from Ott et al. (1994);

$$\log S[Jy] = a + b \times \log \nu[MHz] + c \times \log^2 \nu[MHz] \quad (3.2)$$

where $a = 4.729$, $b = -1.025$ and $c = 0.0130$. Table 3.5 lists the flux densities of Hydra A, calculated from eqn. 3.2, at the frequencies used in the radio observations of this study.

Freq [GHz]	2.3	4.8	8.3	12.2
S [Jy]	27.146	13.549	8.177	5.714

Table 3.5: Flux densities of Hydra A using the equation and coefficients from Ott et al. (1994)

The calibrator source is required to estimate the flux density of the target source (see §4.3.1 for more details). Radio observations of both the target source and the calibrator source have been conducted daily since October 2012, (apart from days when the telescope was required for VLBI observing or days when one, or more, of the receivers required maintenance or servicing) using the same observing technique and at the same frequencies. All data obtained by the dish was captured in FITS file format using the CONTINUUM program written by Dr Jonathan Quick at HartRAO.

3.2.2 Observations of PKS 1424-418 with the FERMI-LAT

The FERMI-LAT telescope has four different observing modes; All-Sky Survey, Pointed Observing, Target of Opportunity (ToO) observing and Modified Observing Strategy. The Pointed Observing and Modified Observing modes focus on maximizing exposure towards the galactic center, while the Target of Opportunity mode focuses on user requested observations. The primary observing mode

of the FERMI-LAT telescope is the All-Sky Survey mode. For a full breakdown of each method, the reader can visit the FERMI-LAT observations page¹¹.

In All-Sky Survey mode, the telescope alternates between the Southern and Northern Hemisphere, observing a particular area of the sky within its large FOV (~ 2.4 sr) for approximately 30 minutes. At this rate FERMI-LAT observes the entire sky in three hours. This observing mode is optimized for multiple-source observations and for capturing transients and flaring events as they spontaneously occur. The All-Sky Survey mode was used to collect data on our target source PKS 1424-418.

FERMI-LAT monitors bright sources with flaring activity or flux values above a minimum limit of $10^{-6} \text{cm}^{-2} \text{s}^{-1}$. This is done on daily and weekly epochs, and every week an update on the source activity is made available on the FERMI-LAT Flare Advocate Blog page¹². All data obtained by FERMI-LAT on PKS 1424-418 is available to the public¹³. FERMI-LAT has been observing PKS 1424-418 since it began observations in 2008. During that time PKS 1424-418 has flared on five different occasions each of which triggered an ATel (Astronomer's Telegram). The FERMI-LAT gamma-ray data used in this study was reduced by Roopesh Ojha from the NASA Goddard Space Flight Center and details of the data reduction process are available on the FERMI-LAT webpage¹⁴. The following chapter provides details on the methods used in reducing the Hart26m radio data from observations of PKS 1424-418 and HYDRA A.

¹¹<http://fermi.gsfc.nasa.gov/ssc/observations/types/>

¹²<http://fermisky.blogspot.com/>

¹³http://fermi.gsfc.nasa.gov/ssc/data/access/lat/msl_lc/

¹⁴<http://fermi.gsfc.nasa.gov/ssc/data/analysis/>

DATA REDUCTION AND ANALYSIS METHODS

The data reduction for observations with the Hart26m telescope consisted of three main phases, antenna calibration, data fitting and flux density calibration. First, the signal's unit from the output of the counter had to be converted into units of antenna temperature (T_A) in Kelvins (K). Secondly, beam pattern fitting was required to estimate the maximum amplitude (T_A) for each of the component scans. Lastly the calculation of the telescope point source sensitivity (PSS) was required in order to estimate the total flux density of the target source, PKS 1424-418. After calibration the radio and gamma-ray data were examined for variability and cross-correlations between different frequencies.

4.1 Calibration

The data reduction program called LINES was used to analyze the data obtained with the Hart26m for both the target source and the calibrator source. LINES is a program originally developed for spectral analysis of data stored in multi-column ASCII format from the Hart26m telescope. It is based on FORTRAN 77 and was written by the late Dr Micheal Gaylard from HartRAO. The program contains data plotting and fitting functions that were used to reduce the data obtained from observations of PKS 1424-418 and HYDRA A.

File conversion

The raw output from the telescope is saved in FITS format and as a first step had to be converted into comma separated value (CSV) format required for processing with LINES. A number of scripts are available to open and extract data from the FITS files and write out the files in CSV format

that can be read by LINES. Part of an example output file in CSV format is shown in figure 4.1. Important housekeeping information, for instance the system temperature, scan coordinates and date and time of the observation is extracted and stored in the header or top part of the output CSV file.

34	Tbatmos_22.23GHz	15.093683	K	Meeks	
35	Tbatmos_25GHz	8.535417	K	SKA	
36	Tbatmos_35GHz	12.304429	K	Meeks	
37					
38	Calibration Data - scan data are scaled from high level noise diode Hz/K				
39	Tcallo_LCP	3.7	K	Tcallo_RCP	4.1 K
40	Tcalhi_LCP	16.3	K	Tcalhi_RCP	15.2 K
41	Hzperk1lo	16678.123952	K	Hzperk2lo	18895.896773 K
42	Hzkerr1lo	4.307631	K	Hzkerr2lo	3.364136 K
43	Hzperk1hi	19140.042197	K	Hzperk2hi	18384.193186 K
44	Hzkerr1hi	78.301536	K	Hzkerr2hi	83.988464 K
45	Tsys1hi	38.967554	K		
46	Tsys2hi	40.531181	K		
47	Tsyserr1	0.165298	K		
48	Tsyserr2	0.188992	K		
49	MJD_centre taken from centr of on source scan is	56828.507423			
50	Zenith Angle of on source scan is	23.85901	deg		
51	Dec J2000 2nd scan	-12.095115	deg		
52	Hour Angle of 2nd scan	-20.720842	deg		
53					
54	RA_J2000_deg	Ta_ON_LCP_K	Ta_ON_RCP_K		
55	139.074159	0	0		
56	139.07518	0.018294	-0.030609		
57	139.075515	0.037241	0.104071		
58	139.075849	-0.016987	0.044213		
59	139.076182	-0.037894	0.049655		
60	139.07583	-0.058147	0.044213		
61	139.076851	0.037241	-0.031289		
62	139.077186	0.012414	0.024487		
63	139.07752	0.039854	0.023807		
64	139.077854	-0.03332	-0.031289		

Figure 4.1: An example of a CSV output data file

Antenna calibration

The antenna needs to be calibrated to convert the signal amplitude in units of counts s^{-1} (Hz) to units of antenna temperature in Kelvins (K), as it is the standard physically meaningful scale used with most radio analysis techniques. The antenna temperature, T_A , is the increase in noise temperature (receiver output), taking into account noise contributions from all sources that can significantly affect the quality of the signal detected, when the antenna is pointed at a radio source. The system temperature, T_{sys} , is the noise temperature equivalent to the receiver output power from all noise contributing sources, including the radio source being observed. The system temperature is generally expressed as

$$T_{sys} = T_{sky} + T_A + T_{at} + T_g + T_R \quad [K] \quad (4.1)$$

where T_{sky} is the contribution from the background sky brightness. At centimeter wavelengths T_{sky} is the contribution from the cosmic microwave background (CMB), but at lower frequencies the radio emission from the Milky Way becomes increasingly stronger. The antenna temperature, T_A , is the contribution from the radio source, T_{at} is the contribution from the dry atmosphere and above ~ 10 GHz, also from water vapour in the atmosphere. The noise contribution from the ground is given by T_g and T_R is the electronic receiver noise temperature from components such as the

amplifiers.

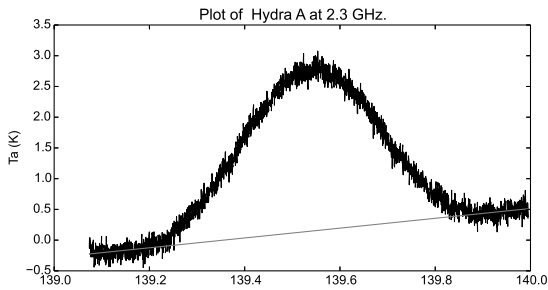
Prior to each drift scan, the noise diode injects a noise signal with a known noise temperature and this is used to calibrate the receiver's system temperature scale. By comparing the noise diode's noise temperature to its count rate, one can derive a conversion factor (K/Hz) to convert from count s^{-1} (Hz) to antenna temperature (K). This conversion factor can then be used to convert the amplitude of the actual drift scan signal of the source to units of Kelvin (K). When all the data units have been converted accordingly and the required CSV files have been written, the data reduction with the LINES program can begin. It should be noted that each step in the analysis is done independently for LCP and RCP data until after the final flux density calibration is done.

4.2 Data fitting

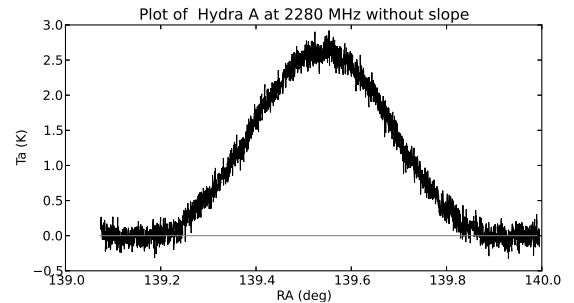
After the antenna calibration, the data is plotted in LINES for further analysis. The data is plotted in two dimensions with the right ascension (RA, deg) on the x-axis and the antenna temperature (T_A , K) on the y-axis, to show a bell shaped drift scan pattern that mimics the antenna main beam pattern because the source is point-like. Due to external factors that affect astronomical radio signals detected by the telescope (e.g. changes in atmospheric conditions or faulty equipment), a series of corrections and checks is needed before final calibration can be done.

Beam fitting: Baseline removal

In order to get reasonable estimates of the antenna temperature, T_A (K), any slope found in the drift scan pattern needs to be removed from the data. A low order polynomial fitted along the sections in the data that mainly consisted of background noise (e.g. the outer edges of the drift scan or the first nulls of the main gaussian), was used to remove this effect. Figure 4.2a, as an example, shows a slow drift in the signal level that could be due to changing atmospheric conditions or a change in the gain of the receiver system. Figure 4.2b shows the result after the slope in the baseline was removed.



(a) Hydra A drift scan before any baseline fitting. The grey line indicates the slope in the data.



(b) Hydra A drift scan after the slope was removed.

Figure 4.2: Example of a drift scan pattern for the calibrator source Hydra A at 2.3 GHz. Figure (a) shows the data before data processing and Figure (b) shows the data after processing. The x-axis is the Right Ascension in degrees, and the y-axis is the antenna temperature in Kelvins.

Beam fitting: Polynomial fitting

After any slopes in the baseline had been removed from the data, the resulting drift scan can then be modeled by a mathematical function that best represents the underlying signal that you want to detect. Under good conditions, the drift scan pattern resembles that of a bell shaped curve that is not necessarily symmetric about the center. It was found that the best estimate of the maximum antenna temperature was derived by fitting a second order polynomial ideally to the top twenty percent of the data (see Figure 4.3). Depending on the quality of the drift scan, the fit criteria varied between fitting 20-50% of the drift scan peak.

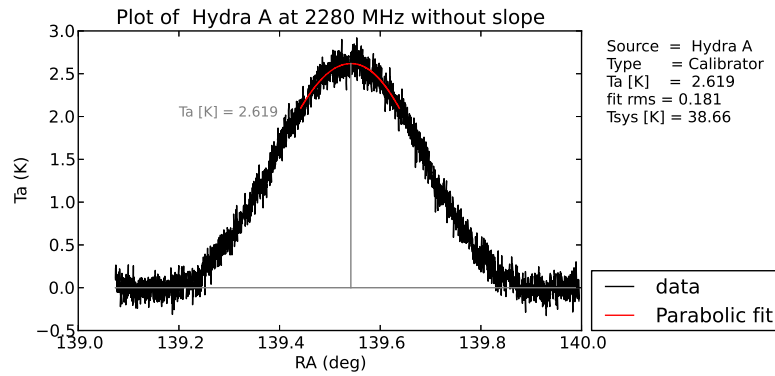


Figure 4.3: Example of a drift scan pattern fitted with a second order polynomial, to estimate the maximum antenna temperature of the scan. The x-axis is the Right Ascension in degrees, and the y-axis is the antenna temperature in Kelvins.

Pointing corrections

For the 4.8-GHz, 8.3-GHz and 12.2-GHz observations we did triple drift scans, one scan ON source, and the other two scans at the HPN and HPS points. Figure 4.4 shows an example of a drift scan pattern with each of the three component scans (ON, HPN, HPS) overlayed on top of each other.

The purpose of the triple drift scans is to correct for any pointing errors. This error occurs when the source does not pass directly through the center of the beam pattern resulting in the measured amplitude of the signal being lower than the actual signal amplitude. Comparing the amplitudes of the three component drift scans will reveal any errors in the pointing and allows for its correction. For correction of the pointing errors we use eq. 4.2, 4.3 and 4.4 from Gaylard 2005¹, where T_{cor} is the resulting corrected temperature in Kelvins and T_{Aon} , $T_{Ahp\bar{n}}$ and $T_{Ahp\bar{s}}$ are the antenna temperature values for the ON, HPS and HPN observations. Eq. 4.2, 4.3 and 4.4 assume a Gaussian main beam profile. It should be noted that baseline removal and polynomial fitting, to estimate the maximum antenna temperature, was done separately for each of the three component scans before correcting for pointing errors.

Depending on the quality of the data obtained, different pointing corrections had to be applied to the data to improve the accuracy of the result as much as possible. For observations when all

¹Gaylard, M. J. (2005), Practical Radio Astronomy a hi-math introduction, HartRAO

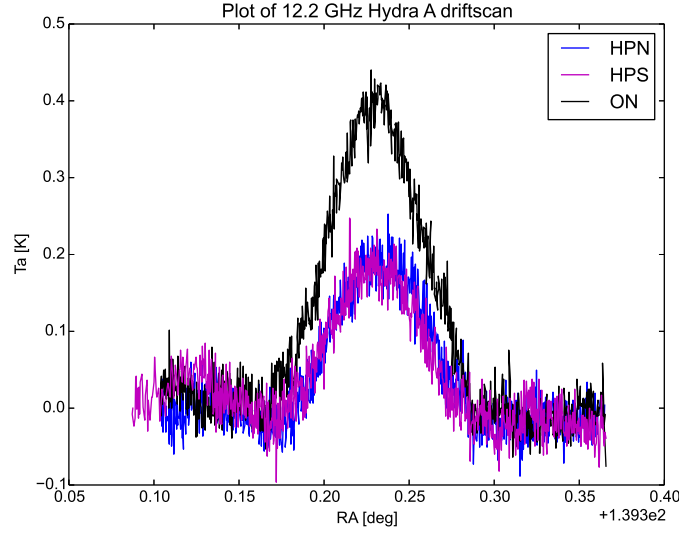


Figure 4.4: Example of a triple drift scan at 12.2 GHz, with ON, HPN and HPS components overlaid on top of each other. The x-axis is the Right Ascension in degrees, and the y-axis is the antenna temperature in Kelvins.

data was present for both polarizations, and the HPN and HPS scans were of good quality, we used equation 4.2. During some observations either the HPN or HPS scans were of low quality due to external factors such as the weather for example. When the HPN data was unusable we made use of equation 4.3, and for cases when the HPS data was unusable we used equation 4.4. In cases where the ON scans were of bad quality the data were discarded.

$$T_{cor} = T_{Aon} \times \exp \left[\frac{(\ln(T_{Ahps}) - \ln(T_{Ahp}))^2}{16 \ln(2)} \right] \quad (4.2)$$

$$T_{cor} = T_{Aon} \times \exp \left[\frac{(\ln(T_{Ahps}) - \ln(T_{Aon}) + \ln(2))^2}{4 \ln(2)} \right] \quad (4.3)$$

$$T_{cor} = T_{Aon} \times \exp \left[\frac{(\ln(T_{Aon}) - \ln(T_{Ahp}))^2}{4 \ln(2)} \right] \quad (4.4)$$

4.3 Flux density determination

4.3.1 Point Source Sensitivity estimation

The aim of the thesis is to determine the flux density of the target source PKS 1424-418, measured in Janskys (Jy). The method used to find the unknown flux density of a target source is by comparing the amplitude of the signal of the target source with that of a calibrator source with a known flux density. For this purpose the point source sensitivity (PSS) for the telescope, obtained from observations of the calibrator source, is used. The PSS provides a conversion factor at a specified frequency that can then also be used to convert the amplitude of the signal of the target source

from units of antenna temperature (K) to units of flux density (Jy) in each polarization (Jy K⁻¹ per pol) using the equations

$$PSS_{lcp}[Jy/K] = \frac{S/2}{K_s T_{A_{lcp}}}, \quad PSS_{rcp}[Jy/K] = \frac{S/2}{K_s T_{A_{rcp}}} \quad (4.5)$$

where S is the total known flux density of the calibrator source (where for an unpolarized source, half the total flux density $S/2$ is received in each polarization) and $T_{A_{lcp}}$ and $T_{A_{rcp}}$ are the antenna temperatures per polarization (or the corrected antenna temperature, T_{cor}). For sources much smaller than the telescope beam size, i.e. point sources as in our case, the source correction factor K_s is regarded as equal to 1. A list of the nominal PSS values for the Hart26m telescope at different frequencies is given in Table 3.2.

Since we did not have calibrator observations or reliable PSS values for every single observation of our target source, we used an average PSS value to estimate the total flux density for each observation of the target source. In order to monitor and track the PSS during the observing period, PSS time series plots were constructed for each polarization and at each of our observing frequencies. These plots are shown in Figures 4.5a, b, c, d, e and f. During the study, a number of hardware related changes caused variations in the PSS time-series, resulting in step changes, more prominently seen in the PSS plots at higher frequencies (8.4 and 12.2 GHz). For this reason an average PSS value in LCP (PSS_{avelcp}) and an average PSS value in RCP (PSS_{avercp}) for each block of observations was calculated to estimate the total flux density of the target source within the same given time block. Also, PSS values above or below 2.7σ of the average PSS in each block were considered as outliers and removed from the data set.

The step change recorded from day 56299 (January 7, 2013) came as the result of a telescope surface panel reset. A few years prior to the start of observations a random set of surface test panels had been selected and deliberately offset by 3 mm and 6 mm for the calibration of a microwave holography experiment conducted in 2008 (Klein, 2008). Since then the panels had been left unchanged until 2013. The effect of the panel offset was immediately detected at the highest frequencies, 8.3 GHz (see Figures 4.5e and 4.5f) and 12.2 GHz (see Figure 4.5b). The step change can also be seen in the lower frequencies at 2.3 GHz (see Figure 4.5a) and at 4.8 GHz (see Figures 4.5c and 4.5d), but it is not as prominent.

From day 56466 (23 June 2013) to day 56486 (12 July 2013) the 4.8-GHz receiver was removed from the Hart26m for repairs of the low noise amplifiers (LNA), and the 8.3-GHz removed from day 56431 (19 May 2013) to day 56455 (12 June 2013) for repairs on the receiver. The removal of the two receivers resulted in the light curves at these frequencies showing gaps in the data shown here in figures 4.5c, 4.5d, 4.5f and 4.5e. At closer inspection the 8.3-GHz data also showed a second step change immediately after the receiver was replaced. The change was found to be due to the fact that the 8.3-GHz receiver was not firmly secured or clamped down when it was fitted back on the telescope. The effect was unfortunately only noticed a week after the receiver was replaced.

We discovered that the PSS measurements after the panel reset showed a significant improvement in the overall antenna efficiency. Table 4.1 shows the total improvements at each of the radio frequencies. The improvement was much higher than expected, especially at the higher frequencies,

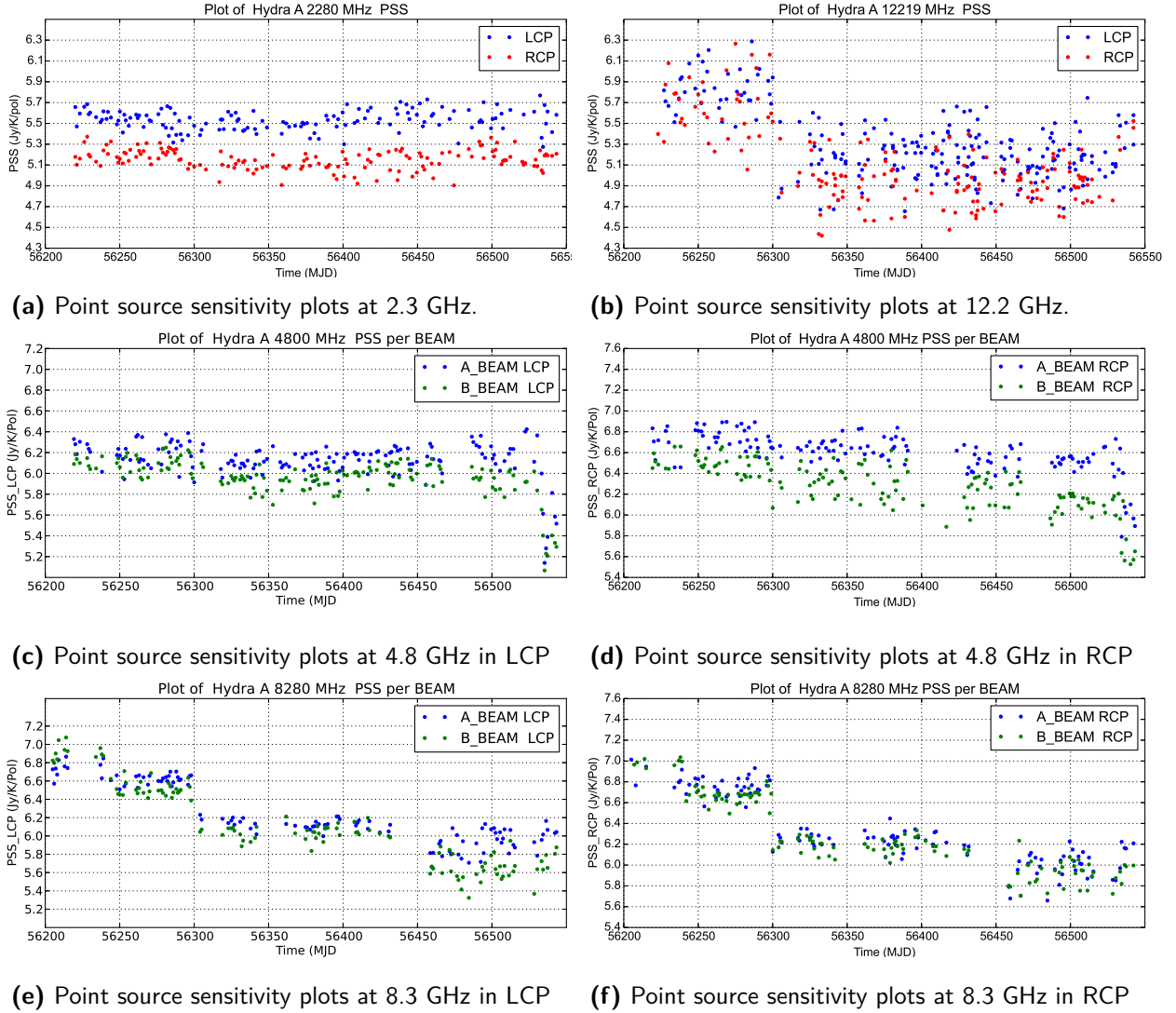


Figure 4.5: PSS time-series plots with the x-axis as time in MJD and the y-axis as PSS in Jy K^{-1} per polarization.

implying that the panel offset had significantly degraded the antenna efficiency.

Table 4.1: The Hart26m telescope PSS improvement table after the panel reset on 2013-01-07.

Source	Frequency (GHz)	PSS Before panel reset	PSS After panel reset	Overall avg improvement (%)	Error in improvement (%)
Hydra A	2.3	5.367	5.301	1.3	0.3
Hydra A	4.8	6.383	6.245	2.2	0.3
Hydra A	8.3	6.874	6.634	2.0	0.2
Hydra A	12.2	5.754	5.059	13.8	1.5

Shortly after the antenna panels were reset, the 8.3-GHz receiver was removed for repairs as mentioned previously. After the 8.3-GHz receiver was repaired and replaced on the telescope the efficiency improved to an average of $8 \pm 0.3\%$. Table 4.2 shows the total improvement at 8.3 GHz.

Table 4.2: Hart26m telescope PSS improvement table after receiver repairs for 8.3 GHz.

Source	Frequency (GHz)	PSS Before repairs	PSS After repairs	Overall avg improvement (%)	Error in improvement (%)
Hydra A	8.3	6.634	6.141	8.0	0.3

4.3.2 Source flux density estimation

The flux density of the target source PKS 1424-418 was obtained using a simple conversion from Kelvin to Jansky using the block averaged PSS values calculated from the calibrator source for both LCP and RCP

$$S_{\nu_{lcp}}[Jy] = T_{A_{lcp}} \times PSS_{avelcp}, \quad S_{\nu_{rcp}}[Jy] = T_{A_{rcp}} \times PSS_{avercp} \quad (4.6)$$

where $S_{\nu_{lcp}}$ and $S_{\nu_{rcp}}$ is the flux density and $T_{A_{lcp}}$ and $T_{A_{rcp}}$ the antenna temperature of the target source in LCP and RCP respectively. The flux density was calculated for each frequency and each drift scan throughout the observing period. For each observation, a total flux density estimate was calculated by averaging the flux densities obtained from both LCP and RCP polarizations and multiplying the result by a factor of 2 to account for the separate polarizations.

$$S_{\nu_{tot}}[Jy] = \left(\frac{S_{\nu_{lcp}} + S_{\nu_{rcp}}}{N} \right) \times 2 \quad (4.7)$$

where N is total number of flux density contributions. The data obtained was used to create a flux density time-series plot, referred to as a light curve, to follow any changes in the radio flux density of the target source over time. The results of which are shown in Figure 5.2 in the following chapter.

4.4 Uncertainties and quality assessment

Data quality is an important factor in any measurement and needs to be estimated to assess the reliability of the final result. To estimate the quality of the model fitted to the data, we used the root-mean-square rms error between the drift scan pattern and the fitted model. The rms error gives a measure of the statistical error between a measured value (the drift scan points) and a model (the parabolic fit).

$$rms = \sqrt{\frac{\sum_{i=1}^n (X_{obs,i} - X_{model,i})^2}{n}} \quad (4.8)$$

where $X_{obs,i}$ is the observed values, $X_{model,i}$ is the model values and n is the number of observations.

From this we then calculated the errors in the total flux density using the propagation of errors method found in Bevington & Robinson (2003). To eliminate bias selections in the results, all drift scans were individually inspected for symptoms of detrimental radio frequency interference in the data which could affect the final result. Outliers were identified by eye and manually flagged for exclusion from further analysis. Only data where the rms error from the model fit were within 2.7 sigma of the average were considered for the final sample. Outliers are observations that contain extreme values

that show large deviations from other values observed under the same conditions. These deviations can include influences from the weather (clouds, water vapor etc.), RFI from appliances, electrical devices, transiting satellites and low-level instrumental issues.

4.5 Source variability

The ultimate goal of studying high-energy sources is to try and understand the core energy production systems responsible for the bright emissions we observe. Blazar sources are very powerful objects which show strong variability across the electromagnetic spectrum, and it is this variability property that serves as the main key to unlocking the underlying physical mechanisms. For many years studies have shown that spectral and time variability serve as important tools for putting constraints on the emission regions of active sources (Chiang & Bottcher, 2002), and these tools were applied here.

4.5.1 Periodic variation

Over the observing period, the gamma-ray light curve showed sinusoidal variations over time scales of a few months. To confirm the existence or lack of possible periodicity within the sinusoidal nature of the gamma-ray light curve, we applied a periodogram analysis to the data using the Lomb-Scargle method, designed for period searches in unevenly sampled data, together with a period significance test using the false alarm probability method (Lomb, 1976; Scargle, 1982). The results of the test are shown in the following chapter.

4.5.2 Spectral index variation

The radio spectral index, in particular, is closely related to the shock development and dissipation within the radio jets we observe in blazar sources (as discussed in §2.2.3). The choice of spectral index notation employed is based on the user's preference and the science they want to get out of it. For the purpose of this dissertation we have opted to follow a negative alpha ($-\alpha$) notation. The radio spectral index was calculated using the two-point spectral index which is the slope of the flux density against frequency in log-log space

$$\alpha = \frac{\log(S_1/S_2)}{\log(\nu_1/\nu_2)} \quad (4.9)$$

where ν_1 and ν_2 are two distinct frequencies, and S_1 and S_2 are the respective flux densities at those frequencies. We estimated the spectral index for days in which we had flux density estimates at all frequencies and also separately for only days just before and after the individual flaring events. The results are shown in the following chapter.

4.6 Data cross-correlation

One of the main aims of this dissertation was to determine whether any correlation existed between the radio and gamma-ray data obtained from observations of PKS 1424-418. This evaluation was

carried out using the Discrete Correlation Function (DCF, Edelson & Krolik, 1988) method. The DCF method is a technique that was developed for the estimation of time-lags/shifts between two unevenly sampled time-series.

Estimating cross-correlations between astronomical data sets is a challenge for a number of reasons, the most important of which is the difficulty to continuously observe any single source at multiple wavelengths, or simultaneously for that matter. Problems with instrumentation and weather can also cause temporary delays in the observations, creating gaps in the light curve data, which was the case with some of the Hart26m radio observations. As a remedy to this Blandford & Konigl (1979) proposed a solution that slightly modified the Cross-Correlation Function (CCF) given by

$$CCF(\tau) = \frac{E[(x(t) - \bar{x})(y(t + \tau) - \bar{y})]}{\sigma_x \sigma_y} \quad (4.10)$$

with $E(f)$ as the expectation value of the function f , $\bar{x}$ and $\bar{y}$ as their means, τ as the constant spacing, and σ_x and σ_y as their standard deviations. The CCF method relies on the assumption that the data to be correlated needs to be continuous and evenly spaced, which is unrealistic for naturally spontaneous events like those we observe in blazar objects like our target source PKS 1424-418. So for this method to work, one or both of the light curves would have to be interpolated prior to being cross-correlated which is not ideal. This meant that if Edelson & Krolik were to address this problem they had to take into account that the light curves would need to be unaltered, meaning that they would have to make no prior assumptions about the data and employ the use of the light curves in their original state. The solution to this problem was realized in the adaptation of the CCF through the DCF. The DCF eliminates the need for interpolation of time-series by creating an Unbinned cross-correlation function (UDCF) for all measured discrete pair points (x_i, y_j) within the time-series

$$UDCF_{ij} = \frac{(x_i - \bar{x})(y_j - \bar{y})}{\sqrt{\sigma_x \sigma_y}} \quad (4.11)$$

with $\sigma_x \sigma_y = (\sigma_x^2 - e_x^2)(\sigma_y^2 - e_y^2)$, where $(\bar{x}, \bar{y})$ are the mean values, (σ_x, σ_y) are the standard deviations, and (e_x, e_y) are the corresponding errors of the respective time-series.

The method estimates the DCF by averaging the correlation coefficients ($UDCF_{ij}$) over the pairwise lag $\Delta t_{ij} = t_j - t_i$ within the range $\tau - \Delta\tau/2 < \Delta t_{ij} < \tau + \Delta\tau/2$ where τ is the time-lag and $\Delta\tau$ is the chosen bin width as shown in equation 4.12

$$DCF(\tau) = \frac{1}{N} \sum UDCF_{ij} \quad (4.12)$$

with N being the number of UDCF entries. Error estimations in the resulting DCF are then easily extracted as the scatter in the $UDCF_{ij}(\tau)$ terms. For the purpose of this study, we only require the lag obtained from the correlation and not the correlation itself. The lag in the data was estimated by fitting a simple Gaussian over the dominant peak in the correlation. Each correlation obtained was evaluated using different bin widths mainly led by eye. The aim here was to find the best peak that exhibited a profile closest to the Gaussian profile. This however does not assume the data to

be perfectly symmetric but rather assumes the profile of the correlation follows it closely. Results of the DCF estimations are shown in the following chapter.

As a separate test to estimate the time-lags and correlations in the time-series we also created cross-correlations using another method called the Z-Transformed Discrete Cross-Correlation Function (ZDCF, Alexander, 1997). The ZDCF differs from the DCF in a sense that it bins over equal populations rather than equal bin widths, using the Fisher (1921) z-transform matrix. These results are shown in Appendix A.

RESULTS

The objective of this thesis was to study the activity of source PKS 1424-418 to try and establish the nature of the relationship between the radio waves and the gamma-rays. To approach this problem we focused on answering four main questions.

- Did the gamma-ray flares produce an equivalent radio event?
- Is there any correlation between the radio and gamma-rays?
- What were the time-delays?
- Is there any periodicity associated with the gamma-ray events?
- and how did the radio spectral index vary over time?

Not all blazars that flare in gamma-rays produce an equivalent radio flare, as was the case with the 2008 flare of the blazar 3C 279 (Abdo et al., 2010). In fact, in most cases, gamma-ray flares from blazars seem to be highly correlated with optical flaring counterparts instead (Wagner, 1996; Abdo et al., 2011; Patiño-Álvarez et al., 2013; Cohen et al., 2014b). Although there are those who believe that the possibility of a correlation existing between radio and gamma-rays can not be proven (Mucke et al., 1997), there are others that have provided evidence of a possible correlation (Fuhrmann et al., 2014; Max-Moerbeck et al., 2014). It is important to bear in mind that in order to prove the existence or lack of a significant correlation relies heavily on the number of data points (observations). Current research suggests that the radio and gamma-rays might share the same primary particles (as discussed in §2.2.4), which implies a possible connection between the two. This theory, however, still lacks any conclusive evidence. The results stated here present a detailed view of the source activity during the observing period 19 October 2012 to 9 October 2013, in both the radio and gamma rays.

5.1 Light curves

Regular monitoring of the source PKS 1424-418 during the observing period provided us with a set of well sampled light curves that we could use for a detailed analysis of the source variation and flaring state. From data obtained, using the methods discussed in §3.2, we present the radio and gamma-ray light curves of the source.

5.1.1 Gamma-ray light curve

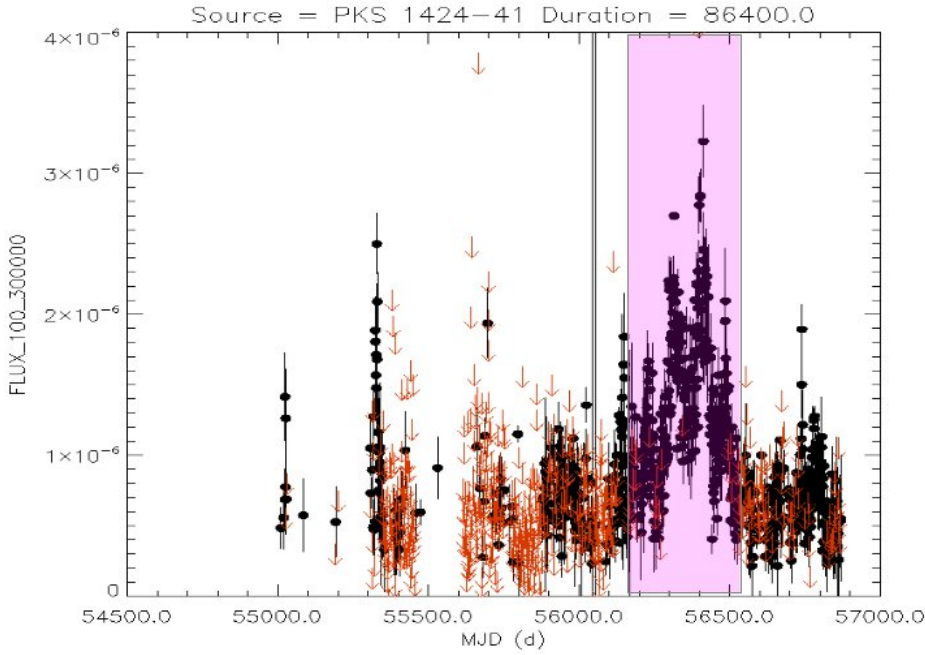
PKS 1424-418 has been a continuously monitored target of the FERMI-LAT science team since FERMI-LAT began operations in June 2008. During this time the source has flared multiple times in the gamma-rays and at radio wavelengths. The regular flaring events that have occurred almost every year since the beginning of FERMI-LAT observations (see Table 5.1) show the source in constant activity, becoming brighter with each event (Longo et al., 2009; Donato, 2010; Szostek, 2011; Ojha & Dutka, 2012; D’Ammando et al., 2013).

Table 5.1: FERMI-LAT ATel sightings obtained from the ASI Science Data Center (ASDC) website¹. Max Flux, is the maximum flux density detected by FERMI-LAT during the observing periods stated in the table, corresponding to the respective ATels.

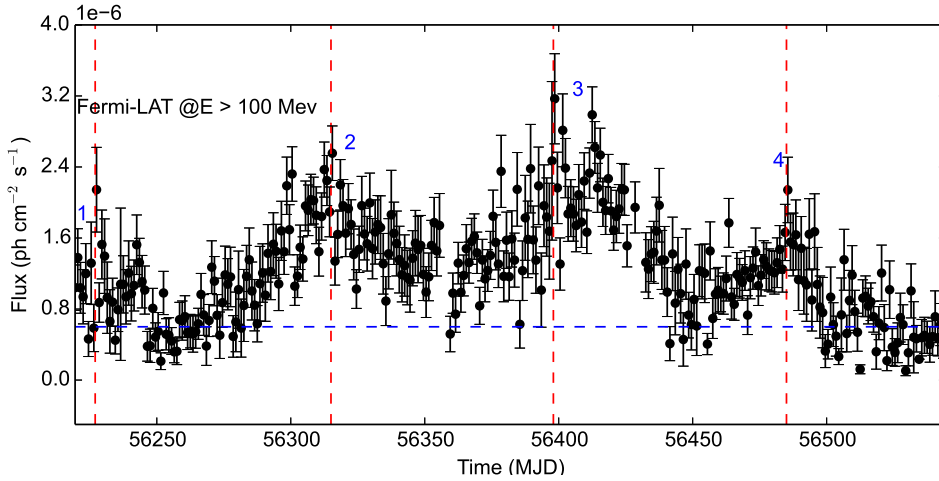
Date of flare event	Max flux ($10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}$)	FERMI-LAT ATel Number	X-ray ATel Number	Optical ATel Number	Radio ATel Number
30 June 2009	0.6	ATel #2104	-	ATel #2103	-
21 April 2010	1.0	ATel #2583	-	ATel #2613	-
5 May 2011	1.1	ATel #3329	-	ATel #3337	-
15 October 2012	1.4	ATel #4494	-	-	-
6 January 2013	2.3	ATel #4714	ATel #4714	ATel #4714	ATel #4714

Between June 2009 and January 2013 the source intensity increased from $0.6 \pm 0.2 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}$ (Longo et al., 2009) to $2.3 \pm 0.4 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}$ (D’Ammando et al., 2013), a 26% increase in intensity. By April 2013, PKS 1424-418 exhibited a new flaring event, this time reaching $3 \times 10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}$ (Tavecchio et al., 2013), the brightest gamma-ray flaring event recorded to date for PKS 1424-418. Remnants of these flaring events, in some cases, were also observed at other wavelengths such as radio, optical and even X-rays (see Table 5.1). Figures 5.1a and 5.1b show the gamma-ray light curve in the energy range 100 MeV to 300 GeV constructed from the FERMI-LAT data. The figures show the gamma-ray light curve on two unique scales detailing the activity of the target source PKS 1424-418. Figure 5.1a includes all data obtained from the first FERMI-LAT observation up until July 2014. Figure 5.1b includes only data obtained during the radio monitoring period at HartRAO, as highlighted in Figure 5.1a (i.e. 19 October 2012 to 9 October 2013). A full update on the current state of the source is available on the FERMI-LAT website.

¹ <http://www.asdc.asi.it/feratel/>



(a) Average daily gamma-ray flux for PKS 1424-418 for the period from June 2009 until July 2014. The red arrows indicate times at which the blazar was not detected. The data is binned on one day intervals. The highlighted section corresponds to the period from 19 October 2012 to 9 October 2013, when the source was also monitored in the radio with the Hart26m telescope. *Image credit: Fermi-LAT monitored source list*².



(b) Average daily gamma-ray flux for PKS 1424-418 for the period 19 October 2012 to 9 October 2013. The blue dashed line running across the data indicates the average flux of the quiescent source. The red dashed lines indicate the position of the peak flux for each of the flaring events (numbered 1 to 4), that occurred during this observing period. *Image credit: Roopesh Ojha*³.

Figure 5.1: FERMI-LAT gamma-ray light curves in the energy range 100 MeV - 300 GeV, for the source PKS 1424-418. The x-axis is the time in MJD and the y-axis is the gamma-ray flux in $\text{ph cm}^{-2} \text{s}^{-1}$.

²http://fermi.gsfc.nasa.gov/FTP/glast/data/lat/catalogs/asp/current/lightcurves/PKS1424-41_86400.png

³NASA Goddard Space Center

The FERMI-LAT data, as seen in figure 5.1b (for the time period 19 October 2012 to 9 October 2013), shows four separate, distinct flaring events (numbered 1 to 4), occurring on scales of a few months. The gamma-ray flux shows large variations between the first and last flare during this observing period; with flares increasing in intensity from the first to the third gamma-ray flare and thereafter steadily decreasing with time. A "flare" is considered as the sudden rise and fall of the source flux where the maximum turnover flux must be at least twice that of half the average flux. The flaring period for each flare from beginning to end or the flare event cycle is considered as the time between two successive local minima. Details of the flaring period and peak flux for each of the gamma-ray flares, for the source PKS 1424-418, for the period 19 October 2012 to 9 October 2013 are listed in table 5.4.

Table 5.2: Flaring period and peak flux for each of the observed gamma-ray flares of the source PKS 1424-418.

Flare no.	Flaring period (MJD)	Peak flux ($10^{-6} \text{ ph cm}^{-2} \text{ s}^{-1}$)	Date of peak flux (MJD)
1	56180 - 56250	2.14 ± 0.5	56227
2	56250 - 56350	2.56 ± 0.3	56315
3	56350 - 56450	3.17 ± 0.5	56398
4	56450 - 56544	2.14 ± 0.4	56485

5.1.2 Radio light curves

To complement the gamma-ray observations, a monitoring campaign to observe PKS 1424-418 at multiple radio frequencies was initiated and started on 19 October 2012. At the time, radio light curves from the Australian Telescope Compact Array (ATCA) monitoring campaign PKS 1424-418, shown in figure 5.3, indicated that the source was not in a quiescent state and that it was above the detection limit of the Hart26m telescope.

Test observations of the source PKS 1424-418 showed that it was bright enough in the radio to be detected with the Hart26m at 2.3, 4.8, 8.4 and 12.2 GHz. Results of the radio observations, for all of the above mentioned frequencies, for the period 19 October 2012 to 9 October 2013, are shown in Figure 5.2.

The light curves from the Hart26m telescope radio observations, for PKS 1424-418, show a noticeable increase in the flux density almost immediately after the radio monitoring began and just after the peak of the first gamma-ray flare. The flux density then seems to increase gradually over the observing period. At the higher frequencies, there appear to be a sharp decrease in the radio flux density, almost coincident with the peak of the second gamma-ray flare and another more gradual decrease in the radio flux density which appears to be some time after the third gamma-ray flare. The radio flux density then seems to increase again shortly after the peak of the fourth gamma-ray flare. These trends are seen more prominently in the higher frequency, 4.8, 8.4 and 12.2 GHz, light curves. However, more data than that covered for this dissertation is required in order to establish the complete trend of the source at radio wavelengths. Light curves from the ATCA monitoring program of PKS 1424-418, at 5.5, 9 and 17 GHz (figure 5.3), show similar behaviour as that seen in

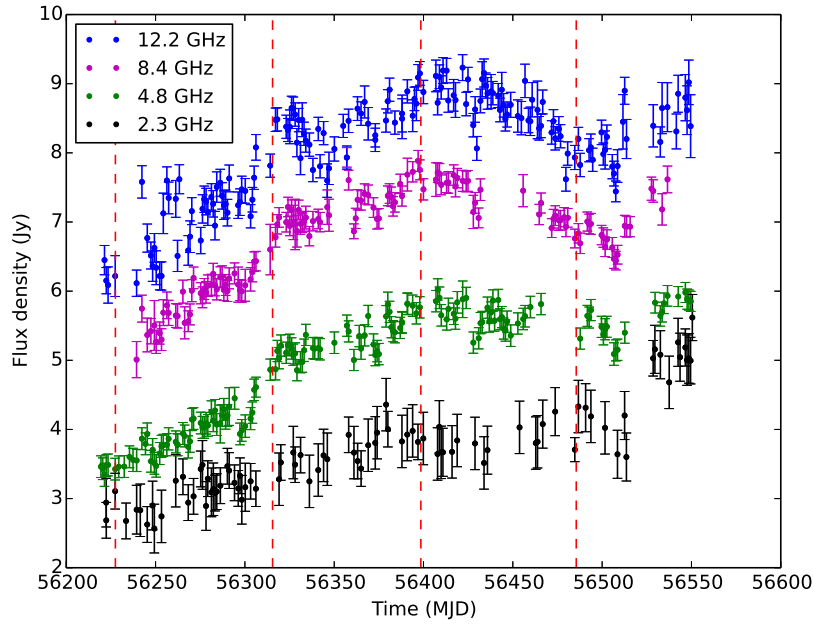


Figure 5.2: Hart26m data obtained between 17 October of 2012 and 9 October 2013 for the source PKS1424-418. The light curves increase in frequency from 2.3 GHz at the bottom to 12.2 GHz at the top. The red dashed lines indicate the dates at which the gamma-rays reached a maximum during a flaring cycle. The flare maximums are numbered and shown in Figure 5.1b. The x-axis is the time in MJD and the y-axis is the radio flux density in Jy.

the Hart26m data. The ATCA data shown in figure 5.3 extends past the observing period considered in this study and shows yet another increase in the radio flux density before it declines again.

Error bars were also included for each data point in figure 5.2, to establish the significance of the flux density variations. The errors were estimated using the propagation of errors method (see §4.4). Errors were estimated from the polynomial fits to the individual drift scans of the target source. Errors from the polynomial fits to the calibrator data were propagated through the PSS calculation when we converted the amplitude of the signal of the target source from units of antenna temperature (K) to units of flux density (Jy). On average, the errors in the radio flux density ranged from ± 0.2 Jy to ± 0.4 Jy at 2.3 GHz, ± 0.1 Jy to ± 0.3 Jy at 4.8 GHz, ± 0.1 Jy to ± 0.4 Jy at 8.4 GHz and ± 0.2 Jy to ± 0.5 Jy at 12.2 GHz as shown in table 5.3.

Table 5.3: Min and max flux density and error values of PKS 1424-418 radio observations.

Frequency (GHz)	Min Flux density (Jy)	Max Flux density (Jy)	Min error (Jy)	Max error (Jy)
2.3	2.57	5.62	± 0.2	± 0.4
4.8	3.34	6.02	± 0.1	± 0.3
8.4	5.01	7.93	± 0.1	± 0.4
12.2	6.09	9.23	± 0.2	± 0.5

The following section gives a detailed description of the Hart26m light curve results.

5.2 Flux density variation

In order to examine the overall trend of the flux density variation on both shorter and longer time-scales, a running average was applied to all the radio light curves using several time bin periods.

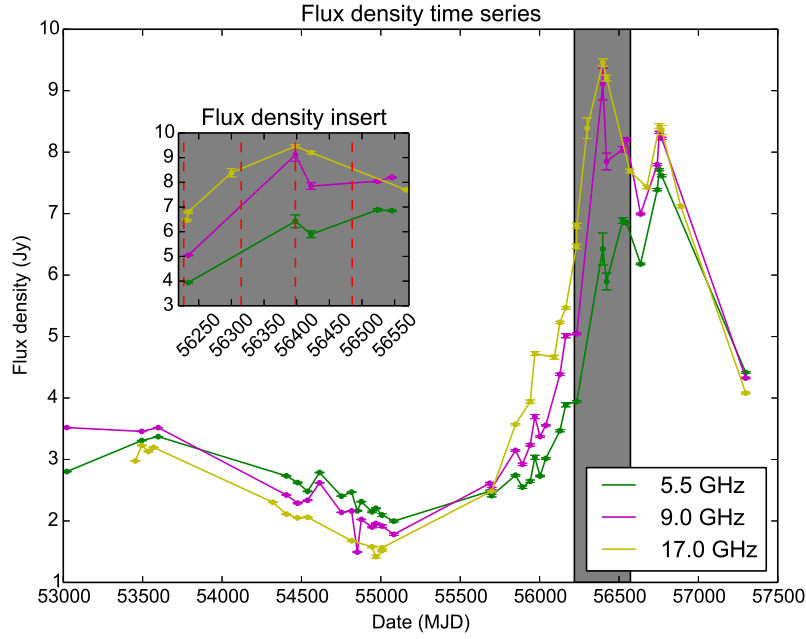


Figure 5.3: Flux density light curve of ATCA observations at 5.5 GHz, 9 GHz and 17 GHz for the source PKS 1424-418. The x-axis is the time in MJD and the y-axis is the radio flux density in Janskys (Jy). The flux density insert shows ATCA data for the same period as the HartRAO observations. Gamma-ray flaring activity for each of the four flaring periods is indicated by the red dashed lines in the figure. *Image credit: The ATCA calibrator database*⁴.

For this study, a weekly binning period was chosen because it best represented the data at hand and the results of the binned light curves are shown in figure 5.4.

From the figures, the source appears to be showing considerable flux variability at the highest frequencies. After the first hundred days of observations, the 4.8, 8.4 and 12.2 GHz light curves show rapid increases in flux density, ~ 1 Jy, over a 20 day period. Thereafter, the data shows a steep rapid decline just after the second gamma-ray flare before returning to the long term flux evolution trend also seen at 12.2 GHz, but less prominent at 8.4 GHz and 4.8 GHz. At 2.3 GHz, this trend is also observed, only delayed with respect to the higher frequencies as expected. It takes the source 200 days from start of observations at 2.3 GHz frequency to reach a ~ 1 Jy flux density increase. The data also further indicates a decrease in flux density after the third gamma-ray flare with yet another sudden upturn after the fourth gamma-ray flare, also appearing again as a feature in 12.2 GHz, 8.4 GHz and 4.8 GHz light curves. The 2.3 GHz light curve however does not show this trend yet due to time-delays.

⁴http://www.narrabri.atnf.csiro.au/calibrators/calibrator_database_viewcal?source=1424-418&detailed=true

Light curve running mean

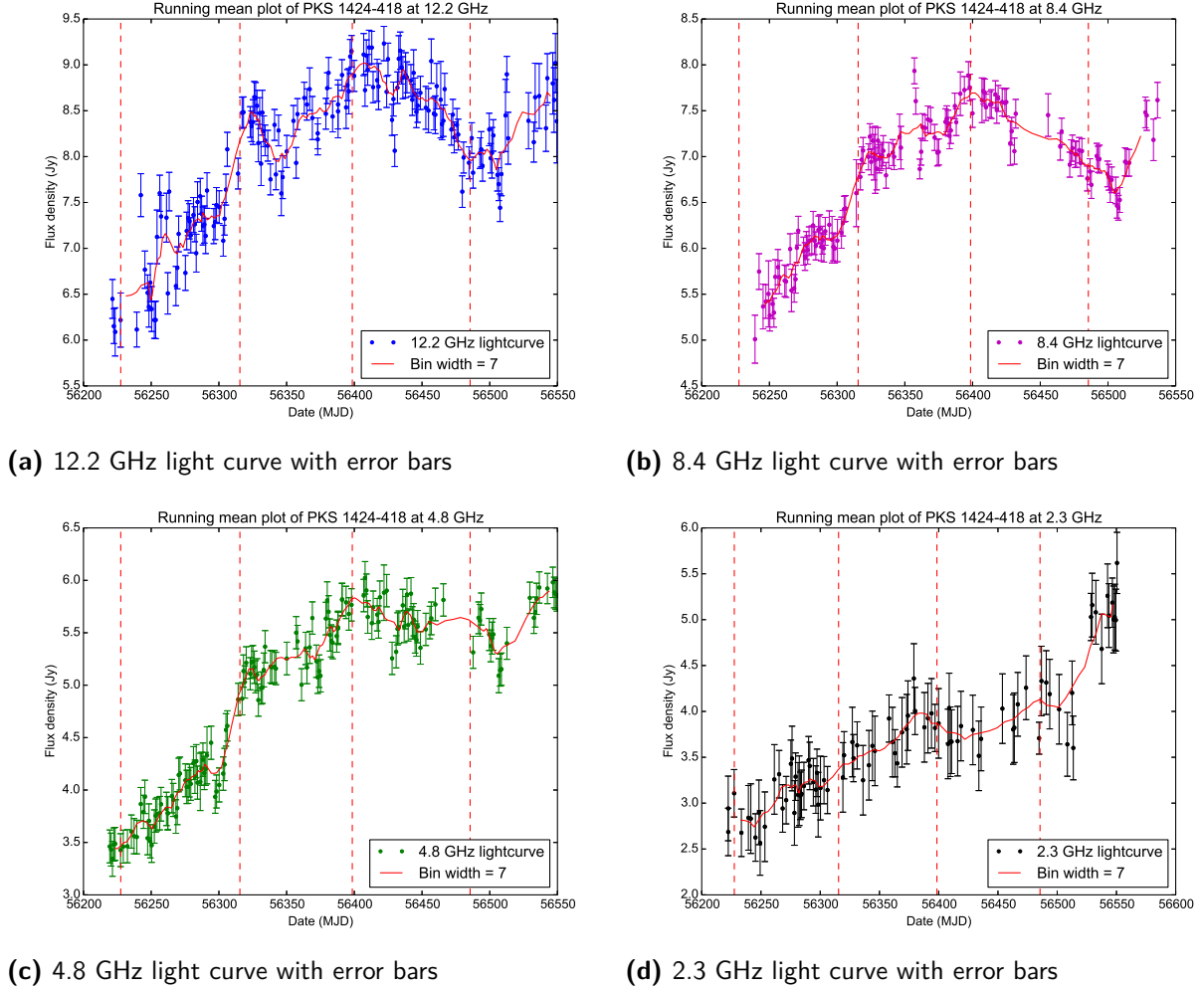


Figure 5.4: Running mean light curves at 12.2, 8.4, 4.8 and 2.3 GHz. The x-axis is the time in MJD and the y-axis is the radio flux density in Jy. The red dashed lines indicate the days on which gamma-ray flares were detected.

5.3 Spectral energy distribution (SED)

This part of the study was done to evaluate the spectral energy distribution (§2.2.1) of the source. Here, we present results of the SED at a range of selected epochs. We were particularly interested in the radio SED of all radio observations for days closest to the date when we observed the peak flux of each gamma-ray flare event. But, because of changes in the weather and possible RFI interference, we could not get a perfect data sample with observations for each day during the study. For the purposes of this dissertation we chose to calculate the SED for the days before and after each flare when all radio frequencies had at least 1 good observation. There was however one exception, because observations at the 8.4 GHz only began after the first flaring event had occurred and there was no SED calculated at this frequency prior the first gamma-ray flare.

The dates used in the study are listed in table 5.4.

Table 5.4: Dates selected before and after each gamma-ray flare maximum flux.

Gamma-ray flare #	MJD peak flux	MJD before flare	MJD after flare
1	56221	56227	56239
2	56315	56306	56327
3	56398	56394	56408
4	56485	56410	56494

Figures 5.5a to 5.5d show the SED variation on the dates used in the study, with errorbars estimated using the propagated error method.

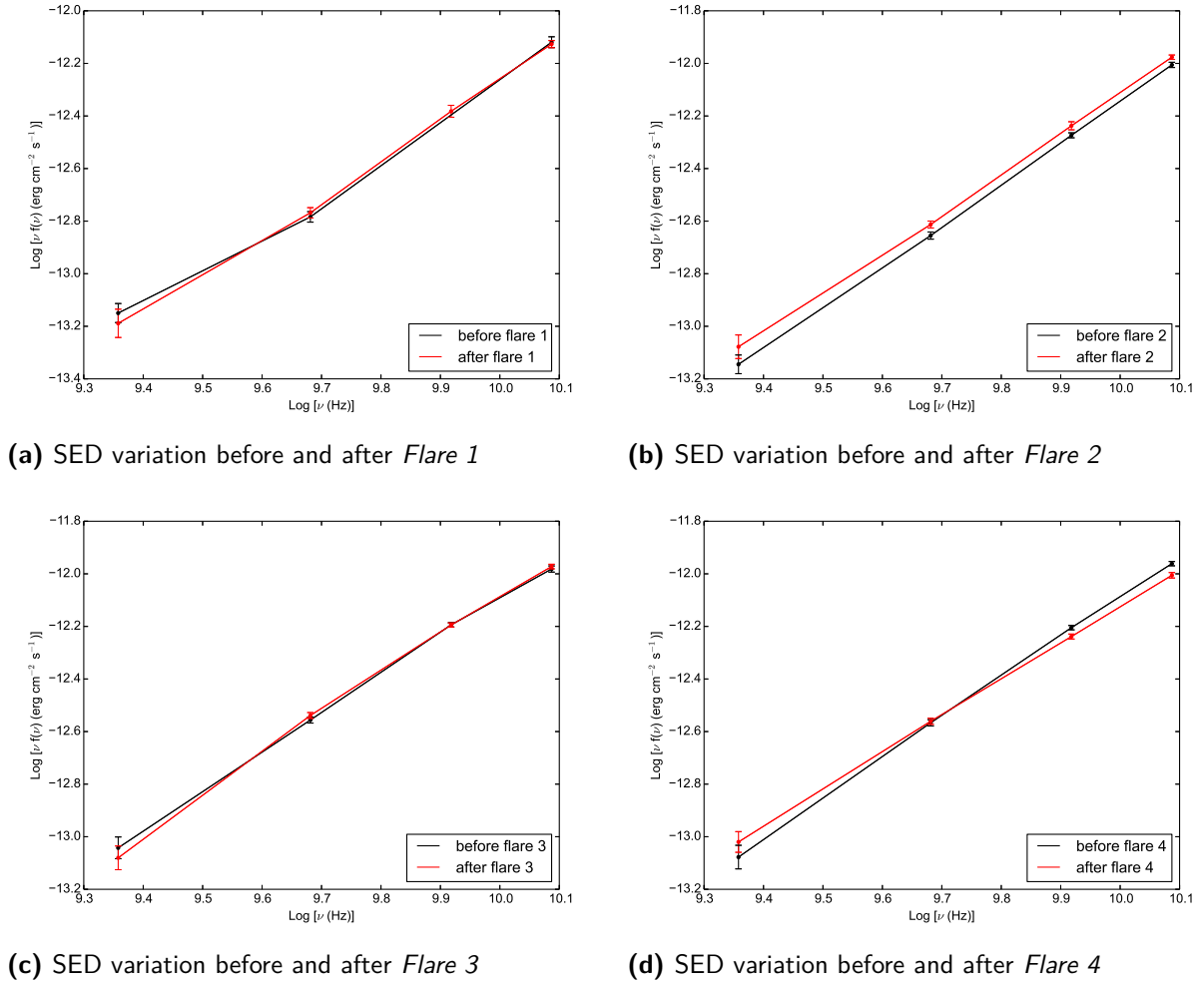


Figure 5.5: The log-log SED variability for PKS 1424-418 before and after each peak gamma-ray flare. The spectral energy in each frequency is indicated in red for days before each gamma-ray peak flare MJD and in black for days after each gamma-ray peak flare MJD. The x-axis is the log of the frequency in Hz and the y-axis is the log of the energy in $\text{erg cm}^{-2} \text{s}^{-1}$.

The error contribution was mainly from the flux density as the frequency is assumed to be error free. Results show the source almost non varying in energy around the time of the first gamma-ray flare (Figure 5.5a). By the second gamma-ray flare (figure 5.5b), the source appears to show a

noticeable difference in energy before and after this flare. There is an increase in energy which also only happens to occur after the second gamma-ray flare. When the third gamma-ray flare (figure 5.5c) occurs, the source energy decreases and continues to decrease by the fourth gamma-ray flare (figure 5.5d).

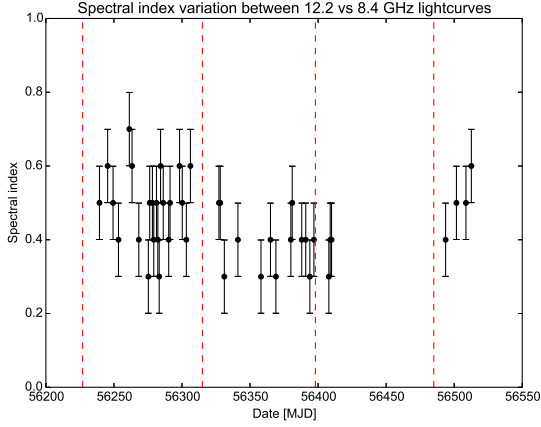
5.4 Spectral index variation

The spectral index of a flaring source can change in a variety of ways over the flaring period. Results of the spectral index shown here trace the radio behavior of the target source over the observing period (as discussed in §4.5). These results are based on observations made only on days when there was at least one good observation at all the frequencies. Figure 5.6 shows the spectral index results for all radio observations. For the error analysis we used the propagated error of the radio fluxes. The gaps in the data indicate days which were excluded due to the fact that not all of the frequencies had a good observation. The radio spectral index gives a measure of the dependence of flux on frequency in log-log space and also tells us about the particle behavior within the source on a longer time span from start to end of observing period.

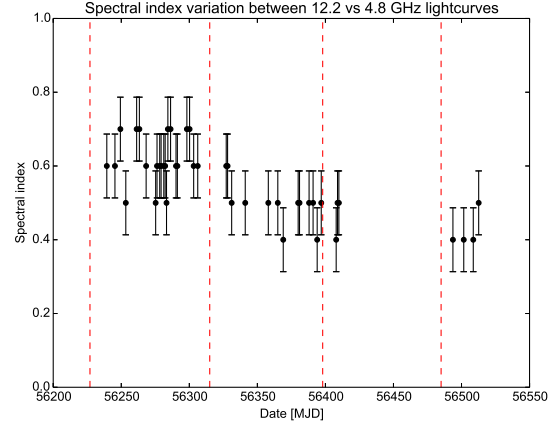
Figures 5.6a to 5.6f show the spectral index variability of PKS 1424-418 over time. From the results, the radio spectral index between the higher frequencies shown in figures 5.6a, 5.6b and 5.6d appear to get flatter between the first and third gamma-ray flares before becoming steeper after flare 4. The radio spectral index between the higher and lower frequencies shown in figures 5.6c, 5.6e and 5.6f however appear to be relatively flat throughout the observing period. All frequencies also show a positive spectral index throughout the entire observing period and table ?? lists the spectral indices of each observation.

5.5 Correlation results

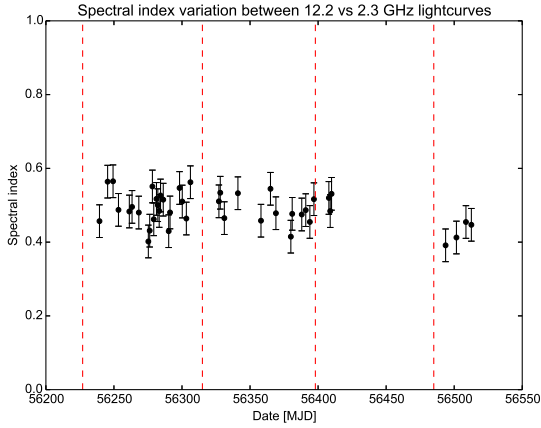
The PKS 1424-418 light curves contain valuable information on the activity of the source. Although the light curves obtained at HartRAO (Figure 5.2) and FERMI-LAT (Figure 5.1b) show some evolutionary differences, conducting a correlation analysis works as a good indication of whether there is a real connection between the radio and gamma-ray data. This connection is believed to be observed when one light curve is delayed relative to the other, showing a clear peak indicating the time delay between the two light curves in the DCF. The rapid rise in the gamma-ray flux over the observing period coincides with more than one rise in the radio flux density as we have seen. To test whether the variations in the HartRAO radio data are related to the variations in the FERMI-LAT gamma-ray data, a series of cross-correlation analysis tests using the DCF and the ZDCF were conducted on both light curves (as discussed in §4.6). Cross-correlations were tested between the radio and gamma-rays and also between corresponding radio frequencies. All cross-correlations were fitted with a simple Gaussian profile in order to determine the time-lag between the correlated light curves. The DCF and the ZDCF were in close agreement within the errors. This chapter will therefore only show the results from the DCF while results from the ZDCF are listed in Appendix A.



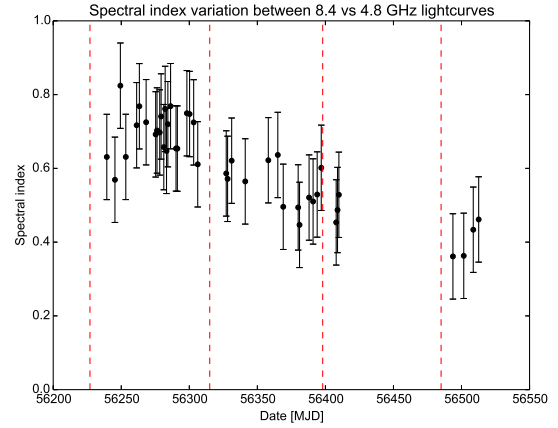
(a) Spectral index variation between 12.2 GHz and 8.4 GHz.



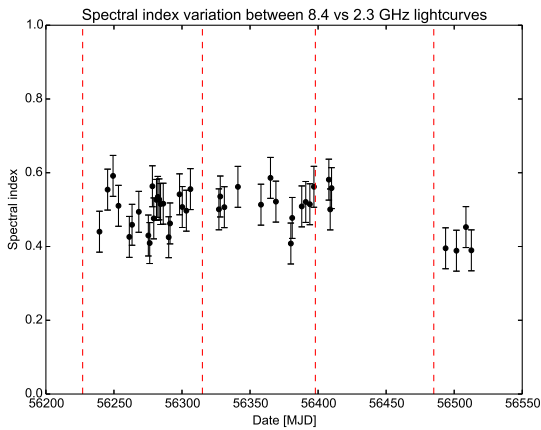
(b) Spectral index variation between 12.2 GHz and 4.8 GHz.



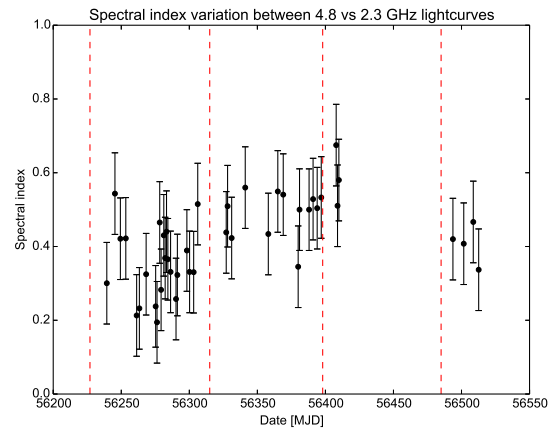
(c) Spectral index variation between 12.2 GHz and 2.3 GHz.



(d) Spectral index variation between 8.4 GHz and 4.8 GHz.



(e) Spectral index variation between 8.4 GHz and 2.3 GHz.

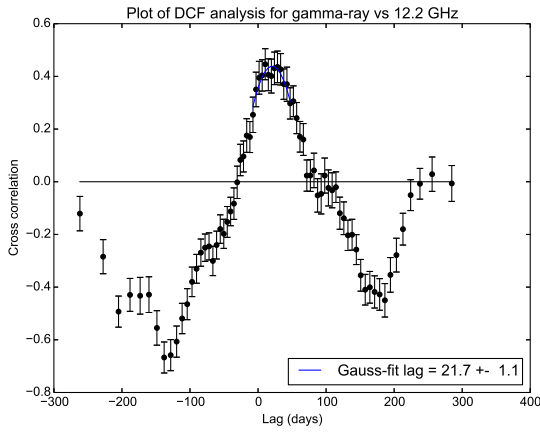


(f) Spectral index variation between 4.8 GHz and 2.3 GHz.

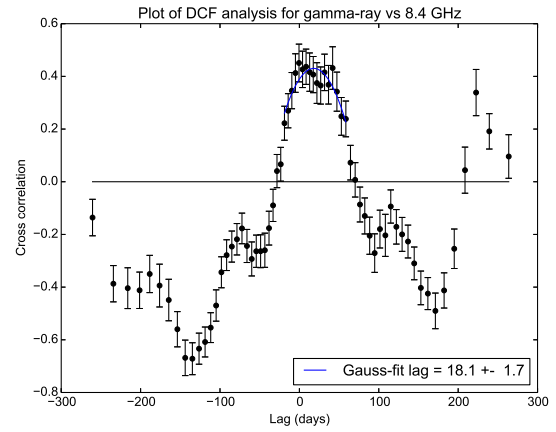
Figure 5.6: Spectral index variability plots between different observed frequencies. The x-axis is time in MJD and the y-axis is the spectral index. The red dashed line indicate the days in which the gamma-ray flaring was at maximum for each individual flare.

5.6 Gamma-ray to radio correlation

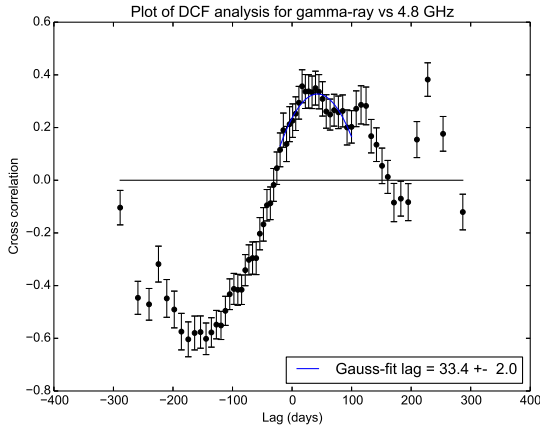
Gamma-ray to radio correlations were conducted for the HartRAO radio frequencies at 2.3 GHz, 4.8 GHz, 8.4 GHz and 12.2 GHz, in order to estimate the time-lags between the frequencies. The Cross-correlation analysis on the light curves was conducted from the beginning to the end of the observing period. The following results are plots of the gamma-ray to radio correlations for all the different light curve combinations.



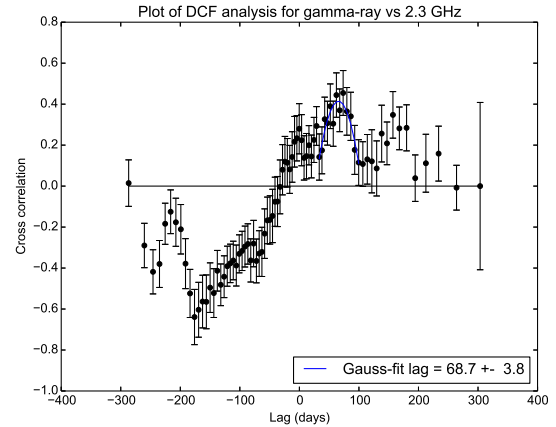
(a) Gamma-ray vs 12.2-GHz DCF correlation.



(b) Gamma-ray vs 8.4-GHz DCF correlation.



(c) Gamma-ray vs 4.8-GHz DCF correlation.



(d) Gamma-ray vs 2.3-GHz DCF correlation.

Figure 5.7: Figure 5.7a, 5.7b, 5.7c and 5.7d show cross-correlation results of the gamma-rays vs radio data. The x-axis is the lag in days and the y-axis is the cross correlation. The horizontal line in the DCF plots indicates the region where the DCF = 0.

Results from the gamma-ray vs radio cross-correlations in figure 5.7 show the gamma-rays leading the radio waves with all time-lags > 0 . The results also show a number of smaller DCF peaks below and above a DCF = 0. These peaks may be due to the rapid short term variability in the gamma-ray light curve that has occurred due to flaring. Figure 5.7d appears to show the most variation of all the cross correlations and the largest delay which lasts over 2 months. This variable behavior however makes it very challenging to clearly access the delay in the correlation of the light curves,

in these cases we opt for the peak closest to the zero lag as the time-delay between the two light curves. With the higher frequencies at 12.2 GHz (figure 5.7a) and 8.4 GHz (figure 5.7b) a more well defined peak gives a clear correlation between the two light curves. These two frequencies also have the shortest delays averaging around 20 days. A list of the time delays is given in table 5.5. Looking at the delay between the two light curves shows an increase in the time-delay as you move to lower radio frequencies. Which is what we expect.

Table 5.5: Results for γ -rays/radio DCF correlations

Light curve 1	Light curve 2	Time-lag (days)
γ -rays	12.2 GHz	21.7 ± 1.1
γ -rays	8.4 GHz	18.1 ± 1.7
γ -rays	4.8 GHz	33.4 ± 2.0
γ -rays	2.3 GHz	68.7 ± 3.8

5.7 Radio to radio correlation

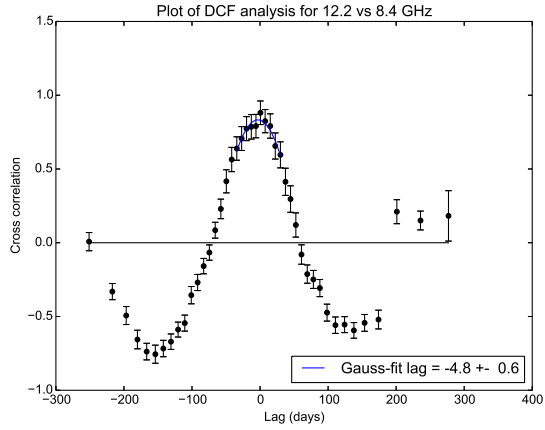
Radio to radio correlations were also conducted for the HartRAO radio frequencies at 2.3 GHz, 4.8 GHz, 8.4 GHz and 12.2 GHz.

A cross-correlation analysis was applied on the light curves from the beginning to the end of the observing period only on days where there were observations for both frequencies to be analyzed. The following results are plots of the radio to radio correlations for all the different frequency combinations. Results from the radio vs radio cross-correlations show the higher frequency radio waves leading the lower frequency radio waves. There are exceptions to this trend observed in figures 5.8a which show the lower frequencies leading the higher ones. The time delays of the results of all the cross-correlations are listed in Table 5.6.

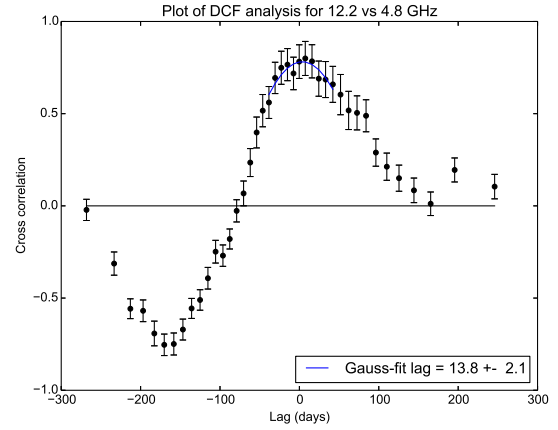
Table 5.6: Results for radio/radio DCF correlations

Light curve 1	Light curve 2	Time-lag (days)
12.2 GHz	8.4 GHz	-4.8 ± 0.6
12.2 GHz	4.8 GHz	13.8 ± 2.1
12.2 GHz	2.3 GHz	11.9 ± 2.7
8.4 GHz	4.8 GHz	15.8 ± 1.8
8.4 GHz	2.3 GHz	22.8 ± 2.3
4.8 GHz	2.3 GHz	4.92 ± 2.4

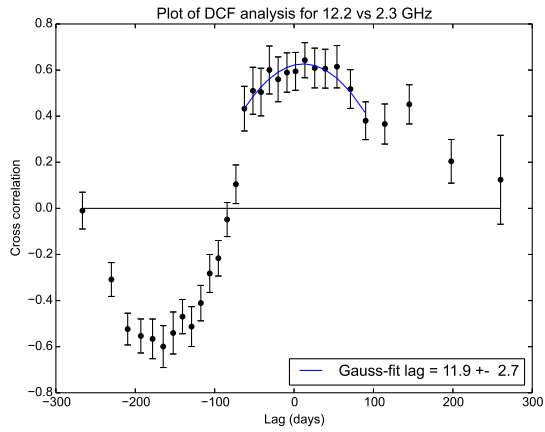
From table 5.6, the time-lags between the radio light curves are considerably shorter compared to the gamma-ray radio delays discussed in §5.6. The shortest delay was found to be 4.8 ± 0.6 days between the 12.2 and 8.4 GHz light curves, this also happens to be the correlation with the most well defined peak profile (figure 5.8a). The longest was found to be shorter than a month at 22.8 ± 2.3 days between the 8.4 and 2.3 GHz light curves (figure 5.8e). Although all the radio correlations also show single peak profiles (figures 5.8a - 5.8f), they also show some variation in the DCF correlation as with the gamma-ray radio correlations. With more data than that presented in



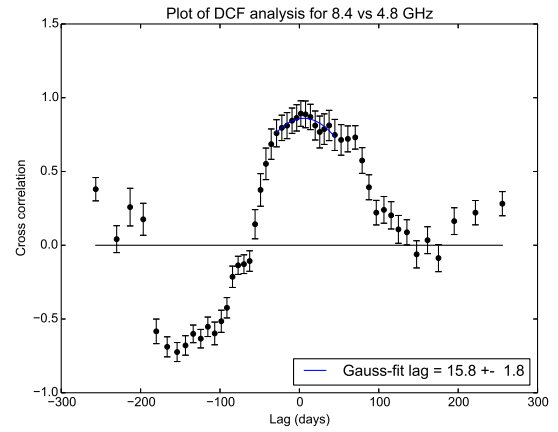
(a) 12.2 GHz vs 8.4 GHz DCF correlation.



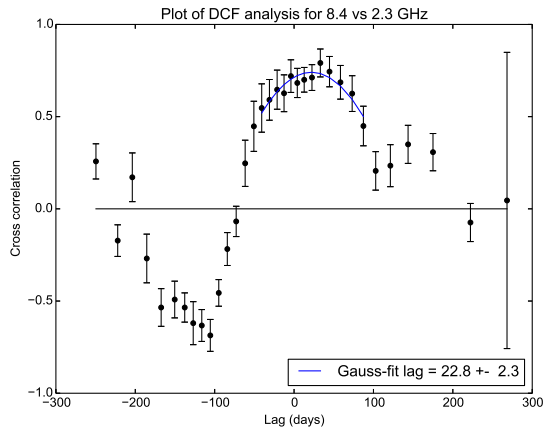
(b) 12.2 GHz vs 4.8 GHz DCF correlation.



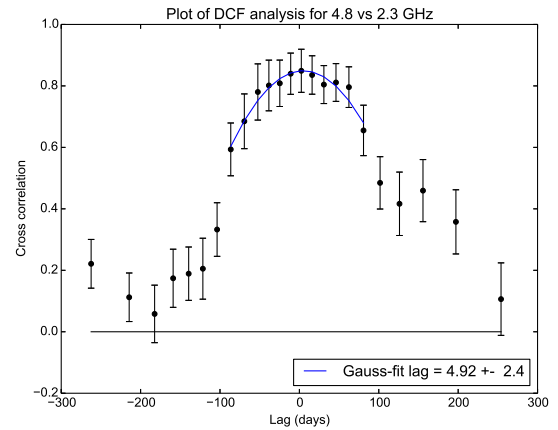
(c) 12.2 GHz vs 2.3 GHz DCF correlation.



(d) 8.4 GHz vs 4.8 GHz DCF correlation.



(e) 8.4 GHz vs 2.3 GHz DCF correlation.



(f) 4.8 GHz vs 2.3 GHz DCF correlation.

Figure 5.8: Figures 5.8a - 5.8f show cross-correlation results of the radio data. The x-axis is the lag in days and the y-axis is the cross correlation. The horizontal line in the DCF plots indicates the region where the DCF = 0.

this thesis these effects could be minimized to produce better correlations.

5.8 Periodic variation

The FERMI-LAT gamma-ray flares shown in Figure 5.1b suggest a 100 day periodicity. For our purposes we defined a flaring event cycle as the time between two successive local minima. Periodic variations in gamma-ray blazars have only rarely been studied, as the size of the data set greatly influences the interpretation of the source behavior of the source variability. It is not always easy to obtain observing time to monitor sources on a daily basis, especially on multiple frequencies and on different instruments over the same period. Results from the periodogram analysis (as discussed in section §4.5) show a possible periodicity exists in the gamma-ray data. The data shows a well defined peak at a period of 86 ± 10 days for the individual flaring events which is shown in Figure 5.9.

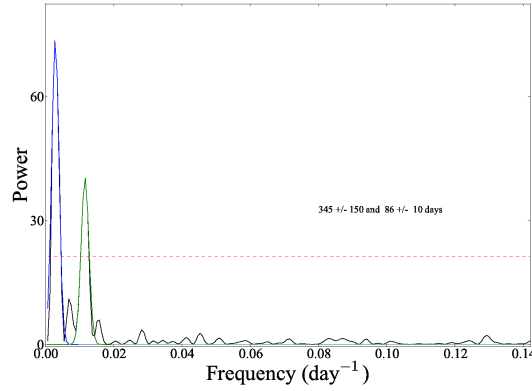


Figure 5.9: PKS 1424-418 Periodogram analysis. The horizontal line represents the false detection limit with a 3 sigma probability. The highest peak corresponds to a 345 ± 150 day period for the long term variation over the observing period, and the second highest peak to an 86 ± 10 day period for short term variations. the x-axis is the frequency in day^{-1} and the y-axis is the power.

The following and final chapter provides a more detailed discussion of the results presented in this chapter, as well as a brief discussion on future work.

DISCUSSION & CONCLUSION

Understanding the nature of the underlying physics in blazar sources is a very complex subject to tackle. When ISM accretes onto a SMBH, the process gives rise to the formation of an accretion disc around the SMBH, due to the angular momentum of the accreting particles. Furthermore, electromagnetic fields are generated and thought to power the highly collimated jets we observe in blazar sources. The process from matter accretion to matter ejection is one that borrows from many fields in physics, some far beyond the scope of this dissertation. This chapter discusses all the results presented in the previous chapter and provide possible conclusions about the behavior of PKS 1424-418 based on those results.

Results obtained from this study show the evolution of the flux of PKS 1424-418 in radio (2.3-GHz, 4.8-GHz, 8.4-GHz, 12.2-GHz) and gamma-ray ($E > 100$ MeV) wavelengths over the observing period. Four distinct flaring events were detected in the gamma-ray data, with energies well above the FERMI-LAT monitoring threshold of $10^{-6} \text{ cm}^{-2} \text{ s}^{-1}$ (see Figure 5.1a).

Soon after the first gamma-ray flaring event, the radio light curves show an almost immediate increase in flux at all radio wavelengths. This behavior is believed to be a direct response to the gamma-ray flaring event, as radio data prior to the start of the Hart26m observations show the source in a quiescent state (see Figure 5.3). As expected, the radio flares also appear delayed relative to the gamma-rays, with the delay increasing with decreasing frequency.

6.1 Isolating the gamma-ray data

When isolating the gamma-ray data, each individual flare appears to be occurring on average every $\sim 86 \pm 10$ days (Figure 5.9). Between the first flare and the second flare we observe the steepest ascent between any two flaring events, and between the third flare and the fourth flare we observe the steepest descent between any two flaring events, the decent also appears to take the longest time.

6.2 Isolating the radio data

When isolating the radio data, the individual light curves show a long term general increase from the start of the observing period to the end (see figure 5.2). As discussed in §2.2.2 and §2.3, disturbances in the jet are time-delayed at different frequencies depending on the location of the shock. As one goes to higher frequencies, shorter time scale variations become more evident in the light curves, being most prominent at the highest frequency at 12.2 GHz (figure 5.4a).

It can be seen that the data also show a somewhat complex behavior at least 1 month after the start of the observing period (figure 5.2). Observations depict a sharp drop in radio flux density just after MJD 56300 at higher radio frequencies (hereafter *dipping effect*). This is particularly interesting behavior because (1) according to the data the dipping effect in flux density is only observed once, (2) the event appears to not affect the overall long term general trend, and (3) the event appears to only be obvious at 12.2 GHz. However, we suspect that 8.4 GHz might have the same effect but to a much lesser extent. As you go down to lower frequencies the effect seems to fade out as expected.

Towards the end of the observing period, around MJD 56500, the radio light curves show another sudden change in flux density. This time a sudden upturn. Given that the effect is occurring near the end of the observing period, it could be that (1) the effect observed before is occurring again, or (2) the radio flux density is on an increasing trend, yet again showing the long term delay expected from synchrotron radio emission. Either one of these possible explanations clearly indicates that there is a need for longer term observations of the radio frequencies during flaring events, in order to thoroughly explain the radio variability behavior.

The radio light curves were also examined using the running mean with weekly bins (figure 5.4) to monitor the short-to-long term radio variations. The data revealed that the dipping effect observed at 12.2 GHz can also be seen for 1 week averages. The data also shows the same effect occurring in the 8.4-GHz (figure 5.4b) and the 4.8-GHz (figure 5.4c) light curves. On average a ~ 1 Jy flux density increase in the binned data was observed just before MJD 56300 within a period of 20 days, from the 8th of January 2013 to the 28th of January 2013, in all higher frequency radio light curves. This increase was also noted in the unbinned light curves at 8.4 GHz and with a significant steep increase from $\sim 6.1 \pm 0.1$ Jy to $\sim 7.0 \pm 0.1$ Jy by Nemenashi et al. (2013). The trend, however, does not appear to be present at the lower 2.3 GHz frequency. Increasing the bin widths from 2 - 4 weeks smoothed out most of the small scale variations as expected, and only shows the gradual long term increasing trend already noted.

6.3 Combining the radio and gamma-ray

Looking at all the data one can see that the long term trend in the radio light curves is a direct response to the initial gamma-ray activity (see figure 5.2). However, when we look at the short scale variability, the variations appear to be a consequence of subsequent gamma-ray flaring events (figure 5.4). The first flare in the gamma-rays seems to be the driving the long term steady increase in the radio at all the observed frequencies. By the time the second flare erupts, the radio data

at higher frequencies reacts to the event by causing a sharp drop in frequency over a very short-lived period (for ~ 1 month after the second flare at 12.2 GHz), compared to the long term steady increase in the radio. We assume that this sudden dipping in radio flux density can be explained by two possible scenarios. (1) The dip is a direct response to the first flare but has been delayed by ~ 86 days, or (2) the dip is a direct response to the eruption of the second flare. If we assume the first case to be true, it would imply that delays between the radio and gamma-ray frequencies are roughly ~ 86 days. However, from the cross-correlation analysis between the gamma rays and 12.2 GHz we get a 21.7 ± 1.1 day (see Figure 5.7a) delay. This is a factor of ~ 5 less than what we observe, which makes this scenario highly unlikely. This opens up the possibility that the delay might be due to some geometrical effect in the jet structure. Taking scenario (2) into consideration brings us to consider the effects discussed in §2.2.2.

In the simplest case the behavior of these flares could be explained by the basic shock-in-jet model by Marscher & Gear (1985). Looking at the results from sections 5.3, under the assumption that the SSC model holds (Sokolov et al., 2004), the increase in radio flux density between the first flare and the second flare could be assumed to be due to an injection of energy into the jet particle content through shocks causing a redistribution of the electron population constrained by the ratio of the energy densities U_B/U_{rad} . This is consistent with examinations of previous flaring episodes in PKS 1424-418 by Buson et al. (2014).

When the first flare occurs, the particle content in the jet is boosted to higher energies, but the energy injected can be assumed to be little because the effect of the boosting observed shows very little variation from the average flux density in gamma-rays. By the second flare the particle content is more energized by perhaps a second injection, and appears a lot steeper than before, one can now see the source flux density as two separate components before and after the flare (Figure 5.5b). From that point the particles do not receive any more external energy injections, so they begin suffering energy losses as one moves from the second flare to the third flare. By the time one reaches the fourth flare, one can see the obvious effect more prominently at the higher frequencies, as the flux density becomes flatter over time, because of adiabatic expansion.

Results obtained from the spectral index calculations also show a similar particle injection trend which is more visible at the higher frequencies (Figures 5.6a, 5.6b, 5.6d). The spectral indices show a general trend moving from steep to flat just after the second flare, while the rest remain almost flat throughout the observing period. At close inspection, the spectral index estimations shown in §5.4 appear to be sensitive to changes in the radio light curves. According to Shabala et al. (2014), when variability in both light curves occurs in phase and similar amplitude the spectral index remains constant, however the spectral index begins to vary as soon as a time-lag appears. For the radio light curves, the results show a clear consistency with this theory. When the time lags are short we observe small changes in the spectral index variability.

In the discussion, the radio and gamma-ray data were interpreted both together and separately so that a holistic picture of what could be happening in the flaring blazar PKS 1424-418 could be created. The behavior of the flux density distribution before and after each flare was looked at, and the relationship between the radio and the gamma-rays was examined over the entire observing

period. The possibly periodic nature of the gamma-ray flaring events and the relationship between the radio light curves using the radio spectral index was also investigated.

The results show some evidence that the gamma-ray flaring events did produce equivalent radio events, with the radio wavelengths delayed relative to the gamma-rays §5.6. The radio to radio correlations also show the higher frequencies leading the lower frequencies, with the exception of the 12 vs 2 GHz and 12 vs 8 GHz correlations having the lower frequencies leading the higher ones, possibly indicating that at those frequencies the lower frequencies were possibly boosted with more energy than the higher frequency photons. The delays range from a few days to a few months, increasing with increasing wavelength.

Results also show the possibility of an 86 ± 10 day period for the individual flaring events in the gamma-rays and a spectral hardening with each flaring event. This period is based on the observed cycles and for this reason we need more data to confirm whether source periodicity is truly inherent.

Blazar sources still pose a lot of unanswered questions, and studies into their variability appears to be one way we can get a step closer to finding plausible solutions to these problems.

6.4 Future work

PKS 1424-418 is a continuously monitored source at the Hartebeesthoek Radio Astronomy Observatory. As a further study, we plan to continue reducing the radio data obtained after the end of the thesis observing period and also refine and automated the data reduction program in order to make data processing more efficient. The additional data obtained will provide further insight into the radio behavior of the source with respect to the gamma-ray flaring events. We would also like to thoroughly investigate the relationship between the gamma-ray radiation and the radio core through VLBI observations, it would be interesting to examine the structural changes on milliarcsecond scales as during flaring events. There are also plans to evaluate each gamma-ray flare individually, as each one has its own characteristic time-lag that can change drastically between flaring events and should be split accordingly (Shabala et al., 2014) As an added measure we would also like to include more Southern Hemisphere sources to compare the behavior amongst different sources. Further more, HartRAO has plans to build a 15 GHz receiver. At almost twice the frequency of the 8.4 GHz receiver we expect to observe the radio sources in better detail, especially the short term variations of the flaring events. A new cooled 22-GHz receiver was recently installed and observations of PKS 1424-418 have already started. This will provide us with better resolution, and insight to the particle behavior and the process that occur during flaring events.

Appendices

APPENDIX

A

CROSS-CORRELATIONS

A.1 Z-Transformed Discrete Cross-Correlation Function (ZDCF)

Developed by Alexander (1997) the Z-Transformed Discrete Cross-Correlation Function (ZDCF) estimates the cross-correlation between two time-series. This method employs the same binning analogy as the previous DCF method, the only difference being that the ZDCF bins over equal populations rather than equal bin widths ($\Delta\tau$). Designed to work on unevenly sampled data, the method uses the Fisher (1921) z-transform

$$z = \frac{1}{2} \log \left(\frac{1+r}{1-r} \right) \quad (\text{A.1})$$

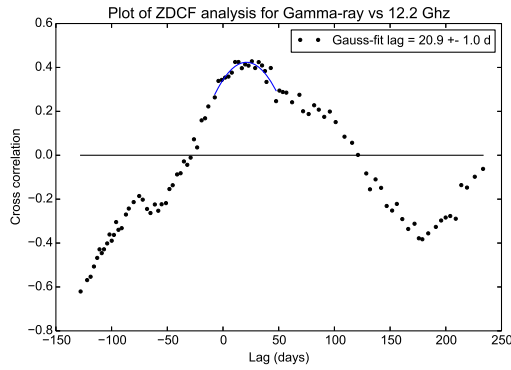
with $r = \tanh z$ as the observed correlation coefficient, resulting in a normalized distribution of the coefficients with mean and standard deviation $\bar{z}(r)$ and $\sqrt{s_z^2(r)}$ respectively. The ZDCF is then estimated using the equation

$$ZDCF(\tau) = r \pm \delta r \quad (\text{A.2})$$

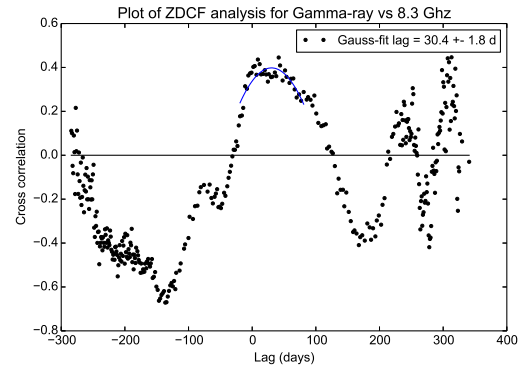
where $\delta r = |\tanh(\bar{z}(r) \pm s_z(r)) - r|$. From this result, the uncertainties can be thus estimated using Monte Carlo simulations of random errors averaged over the ZDCF coefficients of the light curves. The ZDCF method suffers from a single drawback that requires the minimum number of points per bin (n_{min}) to be no less than 11 in order to converge to a solution. The result obtained however is a great improvement from that obtained by the CCF as it also avoids interpolation of data points.

A.2 ZDCF correlations

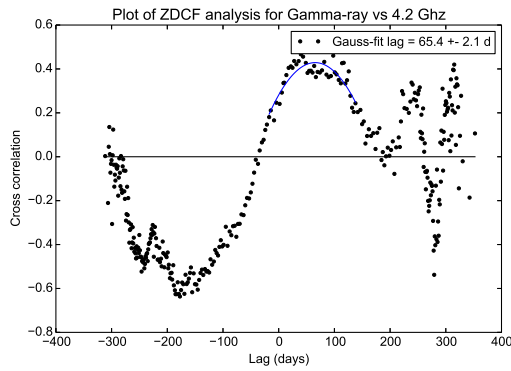
A.2.1 Gamma-ray to Radio



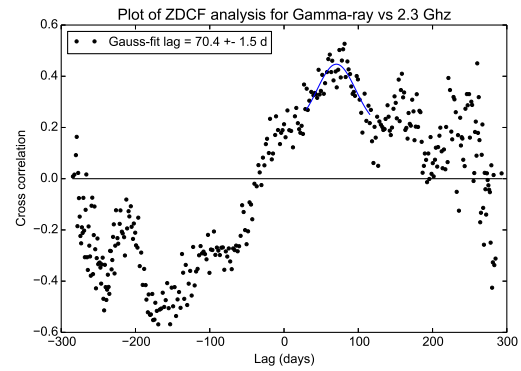
(a) Gamma-ray vs 12.2-GHz ZDCF correlation.



(b) Gamma-ray vs 8.4-GHz ZDCF correlation.



(c) Gamma-ray vs 4.8-GHz ZDCF correlation.



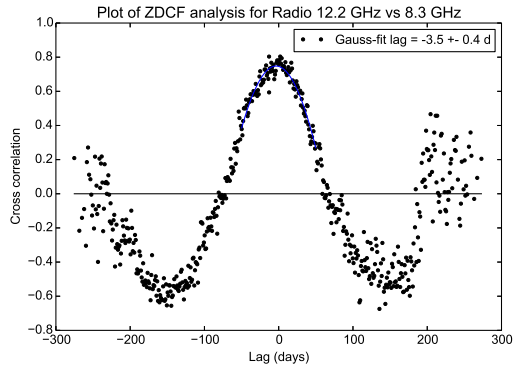
(d) Gamma-ray vs 2.3-GHz ZDCF correlation.

Figure A.1: Figure A.1a, A.1b, A.1c and A.1d show ZDCF cross-correlation results of the gamma-rays vs radio data. The x-axis is the lag in days and the y-axis is the cross correlation. The horizontal line in the ZDCF plots indicates the region where the ZDCF = 0.

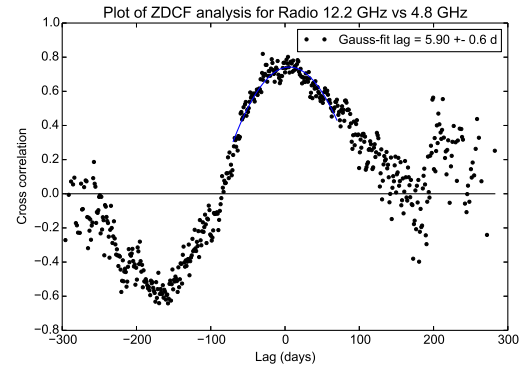
Table A.1: Results for γ -rays/radio ZDCF correlations

Light curve 1	Light curve 2	Time-lag (days)
γ -rays	12.2 GHz	20.9 ± 1.0
γ -rays	8.4 GHz	30.4 ± 1.8
γ -rays	4.8 GHz	65.4 ± 2.1
γ -rays	2.3 GHz	70.4 ± 1.5

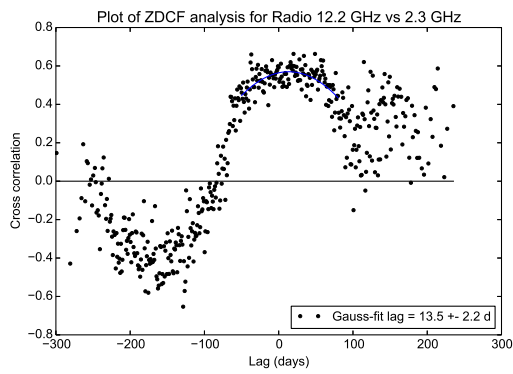
A.2.2 Radio to Radio correlation



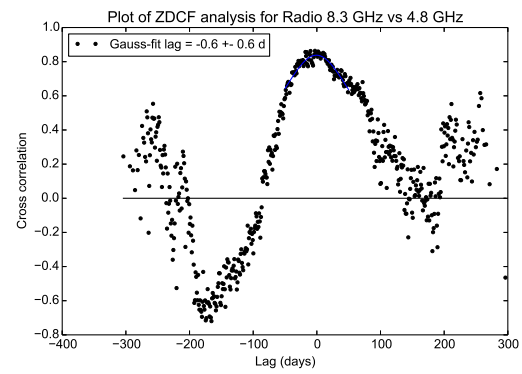
(a) 12.2 GHz vs 8.4 GHz ZDCF correlation.



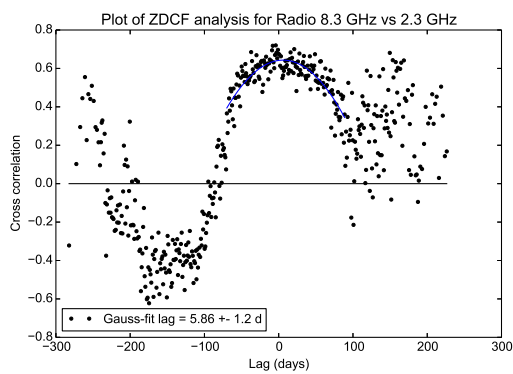
(b) 12.2 GHz vs 4.8 GHz ZDCF correlation.



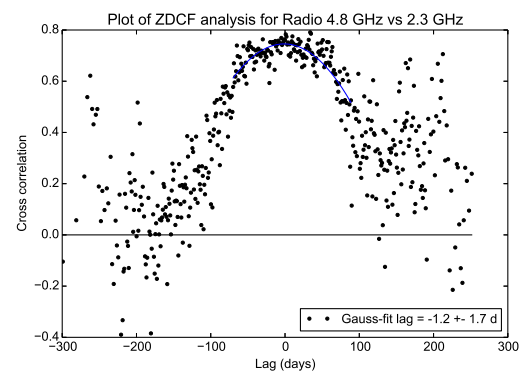
(c) 12.2 GHz vs 2.3 GHz ZDCF correlation.



(d) 8.4 GHz vs 4.8 GHz ZDCF correlation.



(e) 8.4 GHz vs 2.3 GHz ZDCF correlation.



(f) 4.8 GHz vs 2.3 GHz ZDCF correlation.

Figure A.2: Figures A.2a - A.2f show ZDCF results of the radio data. The x-axis is the lag in days and the y-axis is the cross correlation. The horizontal line in the ZDCF plots indicates the region where the ZDCF = 0.

Table A.2: Results for radio/radio ZDCF correlations

Light curve 1	Light curve 2	Time-lag (days)
12.2 GHz	8.4 GHz	-3.5 ± 0.4
12.2 GHz	4.8 GHz	5.90 ± 0.6
12.2 GHz	2.3 GHz	13.5 ± 2.2
8.4 GHz	4.8 GHz	-0.6 ± 0.6
8.4 GHz	2.3 GHz	5.86 ± 1.2
4.8 GHz	2.3 GHz	-1.2 ± 1.7

REFERENCES

- Abdo, A., A., Ackermann, M., Ajello, A., et al. 2011, A&A, 526, 43
- Abdo, A., A., Ackermann, M., Ajello, M., et al. 2010, Nature, 463, 919
- Alexander, T. 1997, Astronomical Time Series, 218, 163
- Atwood, W., B., Abdo, A., A., Ackermann, M., et al. 2009, ApJ, 697, 1071
- Baars, J., W. M., Genzel, R., Pauliny-Toth, I., I. K., & Witzel, A. 1977, A&A, 61, 99
- Beckmann, V. & Shrader, C., R. 2012, in Proceedings of "An INTEGRAL view of the high-energy sky (the first 10 years)" - 9th INTEGRAL Workshop and celebration of the 10th anniversary of the launch (INTEGRAL 2012), 69
- Bevington, P., R. & Robinson, D., K. 2003, Data reduction and Error analysis for the physical sciences, 3rd edn. (Mc Graw Hill)
- Blanchard, J., M., Lovell, J., E. J., Dickey, J., et al. 2012, ArXiv e-prints
- Blandford, R., D. 2002, in Lighthouses of the Universe: The Most Luminous Celestial Objects and Their Use for Cosmology, ed. M. Gilfanov, R. Sunyeav, & E. Churazov, 381
- Blandford, R., D. & Konigl, A. 1979, ApJ, 232, 34
- Blandford, R., D. & Payne, D., G. 1982, MNRAS, 199, 883
- Blandford, R., D. & Znajek, R., L. 1977, MNRAS, 179, 433
- Błażejowski, M., Blaylock, G., Bond, I., H., et al. 2005, ApJ, 630, 130
- Böttcher, M. 2010, in Fermi Meets Jansky - AGN at Radio and Gamma-Rays, ed. T. Savolainen, E. Ros, W. Porcas, R., & A. Zensus, J., 41
- Böttcher, M., Harris, D., E., & Krawczynski, H. 2012, Relativistic jets from active galactic nuclei (WILEY-VCH)
- Böttcher, M., Reimer, A., & Marscher, A., P. 2009, ApJ, 703, 1168
- Böttcher, M., Reimer, A., Sweeny, K., & Prakash, A. 2013, ApJ, 768, 54

- Briggs, F., H., Sorar, E., Kraan-Korteweg, R., C., & van Driel, W. 1997, *PASA*, 14, 37
- Buson, S., Longo, F., Larsson, S., et al. 2014, *A&A*, 569, A40
- Chiang, J. & Bottcher, M. 2002, *ApJ*, 564, 92
- Ciprini, S., Thompson, D., J., & on behalf of the Fermi LAT collaboration. 2013, *ArXiv e-prints*
- Cohen, M., H., Meier, D., L., Arshakian, T., G., et al. 2014a, *ApJ*, 787, 151
- Cohen, D., P., Romani, R., W., Filippenko, A., V., et al. 2014b, *ApJ*, 797, 137
- Collaboration, H., Abramowski, A., Acero, F., et al. 2012, *A&A*, 539, A149
- Collmar, W., Reimer, O., Bennett, K., et al. 2000, *A&A*, 354, 513
- Costamante, L. 2012, *Mem. S. A. It*, 83, 138
- D'Ammando, F., Orienti, M., Longo, F., et al. 2013, *ATel* #4714
- Dermer, C. & Lott, B. 2012, in *International workshop on beamed and unbeamed gamma-rays from galaxies*, 355 (IOP Publishing)
- Dermer, C. & Schlickeiser, R. 1993, *ApJ*, 416, 458
- Donato, D. 2010, *ATel* #2583
- Dondi, L. & Ghisellini, G. 1995, *MNRAS*, 273, 583
- Donnarumma, I. 2012, *Journal of Physics: Conference series*, 355
- DuPuy, D., Schmitt, J., McClure, R., van den Berg, S., & Racine, R. 1969, *ApJ*, 156, L135
- Edelson, R., A. & Krolik, J., H. 1988, *ApJ*, 333, 646
- Fabian, A., C. 1999, in *Proc Natl. Acad. Sci., USA*, 4749–4751
- Fermi, E. 1954, *ApJ*, 119, 1
- Fisher, R., A. 1921, *Metron*, 1, 3
- Fuhrmann, L., Larsson, S., Chiang, J., et al. 2014, *MNRAS*, 441, 1899
- Ghirlanda, G., Ghisellini, G., Tavecchio, F., & Bonnoli, G. 2011, *MNRAS*, 413, 852
- Giannios, D. 2013, *MNRAS*, 431, 355
- Grove, J., E. & Johnson, W., N. 2009, *U.S. Naval Research Laboratory Review*
- Gupta, A., C., Krichbaum, T., P., Wiita, P., J., et al. 2012, *MNRAS*, 425, 1357
- Hada, K., Doi, A., Kino, M., et al. 2011, *Nature*, 477, 185
- Hamer, S., L., Edge, A., C., Swinbank, A., M., et al. 2013, *MNRAS*, 437, 862
- Hoffmeister, C. 1929, *Astron. Nachr.*, 236, 233
- Hovatta, T., Nieppola, E., Tornikoski, M., et al. 2008, *A&A*, 485, 51
- Impey, C., D. & Tapia, S. 1988, *ApJ*, 333, 666

- Junor, W., Biretta, J., A., & Livio, M. 1999, *Nature*, 401, 891
- Kellermann, K., I. & Pauliny-Toth, I., I. K. 1968, *Annual Review of Astronomy and Astrophysics*, 6, 417
- Kellermann, K., I. & Pauliny-Toth, I., I. K. 1969, *ApJ*, 155, L71
- Kellermann, K., I., Sramek, R., Schmidt, M., Sha er, D., B., & Green, R. 1989, *ApJ*, 98, 1195
- Klein, B. 2008, Msc thesis, University of the Witwatersrand Faculty of Engineering and the Built Environment, Johannesburg
- Kovalev, Y., Y., Aller, H., D., Aller, M., F., et al. 2009, *ApJ*, 696, L17
- Krawczynski, H., Hughes, S., B., Horan, D., et al. 2004, *ApJ*, 601, 151
- Lainela, M., Takalo, L., O., Sillanpaa, A., et al. 1999, *A&A*, 521, 561
- Lane, W., M., Clarke, T., E., Taylor, G., B., Perley, R., A., & Kassim, N., E. 2004, 127, 48
- Leto, P., Buemi, C., S., Trigilio, C., et al. 2006, *Mem. S.A.It. Suppl.*, 10
- Lomb, N., R. 1976, *Ap&SS*, 39
- Longo, F., Iafrate, G., Hays, E., & Marelli, M. 2009, *ATel* #2104
- Lovelace, R., V. E. 1976, *Nature*
- Marscher, A., P. 1990, in *Parsec-scale radio jets*, ed. A. Zensus, J. & J. Pearson, T., 236
- Marscher, A., P. & Gear, W., K. 1985, *ApJ*, 298, 114
- Marscher, A., P. & Jorstad, S., G. 2010, in *Fermi meets Jansky - AGN at Radio and Gamma-rays*, ed. T. Savolainen, E. Ros, W. Porcas, R., & A. Zensus, J., Bonn, Germany
- Max-Moerbeck, W., Hovatta, T., Richards, J., L., et al. 2014, *MNRAS*, 445, 428
- Max-Moerbeck, W., Richards, J., L., Pavlidou, V., et al. 2010, in *Fermi meets jansky - AGN at radio and gamma-rays*, ed. T. Savolainen, E. Ros, W. Porcas, R., & A. Zensus, J., Bonn, Germany
- Meier, D., L. & Koide, S. 2000, in *Astrophysical Phenomena Revealed by Space VLBI*, ed. H. Hirabayashi, G. Edwards, P., & W. Murphy, D., 31–38
- Mucke, A., Pohl, M., Reich, P., et al. 1997, *A&A*, 320, 33
- Nemenashi, P., Gaylard, M., J., & Ojha, R. 2013, *ATel* #4819
- Nieppola, E., Hovatta, T., Tornikoski, M., et al. 2009, *ApJ*, 137, 5022
- Nishikawa, D., Hayashi, S., Chamoto, N., et al. 1999, in *26th International Cosmic Ray Conference*, ed. L. Dingus, B., B. Kieda, D., & H. Salamon, M., AIP Conference Proceedings (American Institute of Physics; 2000 edition), 424
- Ojha, R. 2012, in *J. Phys. Conf. Ser.*, Vol. 355, *International Workshop on Beamed and Unbeamed Gamma-Rays from Galaxies*, Muonio Finland
- Ojha, R. & Dutka, M. 2012, *ATel* #4494
- Ott, M., Witzel, A., Quirrenbach, A., et al. 1994, *A&A*, 284, 331
- Patiño-Álvarez, V., Carramiñana, A., Carrasco, L., & Chavushyan, V. 2013, *ArXiv e-prints*

- Perucho, M. 2013, in European Physical Journal Web of Conferences, Vol. 61
- Pushkarev, A., B., Kovalev, Y., Y., & Lister, M., L. 2010, ApJL, L7
- Raiteri, C., M., Villata, M., Kadler, M., et al. 2006, A&A, 459, 731
- Rieger, F., M. 2004, American Institute of Physics, 615, L5
- Rieger, F., M. 2005, in American Institute of Physics Conference Series, Vol. 745, High Energy Gamma-Ray Astronomy, ed. A. Aharonian, F., J. Völk, H., & D. Horns, 487–492
- Rybicki, G., B. & Lightman, A., P. 1979, Radiative processes in Astrophysics (Wiley-VCH)
- Scargle, J., D. 1982, ApJ, 263, 835
- Schmidt, M. 1963, Nature, 197, 1040
- Seyfert, C., K. 1943, ApJ, 97, 28
- Shabala, S., S., Rogers, J., G., McCallum, J., N., et al. 2014, Journal of Geodesy, 88, 575
- Sikora, M., Begelman, M., C., & Rees, M., J. 1994, ApJ, 421, 153
- Smith, M., D. 2012, Astrophysical Jets and Beams (Cambridge Astrophysics Series; 49), 71
- Smitt, J., L. 1968, Nature, 218, 663
- Sokolov, A., Marscher, A., P., & McHardy, I., M. 2004, ApJ, 613, 725
- Sokolovsky, K., V., Kovalev, Y., Y., Pushkarev, A., B., & Lobanov, A., P. 2011, A&A, 532, A38
- Stevens, J., Edwards, P., G., Ojha, R., et al. 2012, in 2011 Fermi & Jansky: Our Evolving understanding of AGN
- Szostek, A. 2011, ATel #3329
- Tagliaferri, G., Foschini, L., Ghisellini, G., et al. 2008, ApJ, 679, 1029
- Tammi, J. & Oksman, M. 2013, in XXXII Finnish URSI Convention on Radio Science and SMARAD Seminar 2013
- Tavecchio, F., Pacciani, L., Donnarumma, I., et al. 2013, MNRAS, 435, 24
- Taylor, G., B., Perley, R., A., Inoue, M., et al. 1990, ApJ, 360, 41
- Thompson, D., J. 1993, ApJS, 86, 629
- Urry, C., M. 1996, ASP Conference Series, 110, 391
- Urry, C., M. & Padovani, P. 1995, P.A.S.P, 107, 803
- van der Laan, H. 1966, Nature, 211, 1131
- Wagner, S., J. 1996, A&AS, 120, C495
- White, G., L., Jauncey, D., L., Savage, A., et al. 1988, ApJ, 327, 561