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RADIO VARIABILITY OF ACTIVE GALACTIC NUCLEI: ANALYSIS OF LONG-TERM MULTIFREQUENCY DATA

Thesis for the degree of Doctor of Science in Technology

Talvikki Hovatta

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Faculty of Electronics, Communications, and Automation
Department of Radio Science and Engineering

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Modified Very Long Baseline Array image of the jet of quasar 3C 273 at 15 GHz from the epoch 12-9-2008 (image from the MOJAVE database that is maintained by the MOJAVE team, Lister et al., 2009, AJ, 137, 3718) and modified flux curve of 3C 273 between 1985 and 2007 at 37 GHz from Metsähovi Radio Observatory.

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Abstract

A large sample of Active Galactic Nuclei (AGN) has been monitored on a regular basis in Metsähovi Radio Observatory since the 1980s. These observations form an extensive database of about 100 brightest Northern compact extragalactic objects at high radio frequencies. In this thesis the Metsähovi observations are complemented with lower frequency radio data from the University of Michigan Radio Astronomy Observatory, and with higher frequency data from the literature.

The main focus in this thesis is to understand the long-term radio variability behaviour of AGN by using various methods. Several statistical methods, and their capability to detect variability timescales, are examined in detail. In addition, the flux curves are examined visually to study the flare characteristics, and to verify the timescales obtained.

The results show that variability behaviour of AGN is complex, and multiple characteristic timescales are common. Flares in the radio regime are long-lasting, on average, 2.5 years at 37 GHz. In addition, large outbursts occur quite rarely, only once in every four to six years. None of the sources were seen to exhibit strict periodicities. These results together show that long-term monitoring is essential in understanding the true behaviour of AGN.

In this thesis, differences between various statistical timeseries analysis methods are investigated in detail for the first time using a large sample of sources and long datasets. Especially the wavelet method has never before been used to study a large sample of AGN at high radio frequencies. A useful property of wavelets is that they show when the timescale has been present and how it has changed. Thus, it is ideal for studying sources which are not strictly periodic and which change their behaviour.

The long-term total flux density observations are also used to calculate the Doppler boosting factors, Lorentz factors and viewing angles of the jets. Quasars are found to be more Doppler boosted and to have faster jets than BL Lacertae objects. The various parameters obtained in this thesis, describing the characteristics of AGN, can be further used to study the physical processes and the relationships between different emission regions in these sources.

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Tiivistelmä

Metsähovin radiotutkimusasemalla on 1980-luvun alusta lähtien säännöllisesti havaittu aktiivisia galaksinytimiä (AGN). Nämä havainnot muodostavat laajan tietokannan, joka sisältää dataa noin sadasta kirkkaimmasta pohjoisen taivaan kompaktista ekstragalaktisesta lähteestä. Näiden havaintojen lisäksi tässä väitöskirjassa käytetään alempien radiotaajuuksien havaintoja, jotka ovat Michiganin radioastronomisesta observatoriosta ja lisäksi korkeampien radiotaajuuksien dataa, joka on kerätty kirjallisuudesta.

Työn päätavoitteena on ymmärtää AGN:ien pitkäaikaista radiomuuttuvuutta. Tutkimme useiden tilastollisten menetelmien eroja ja kykyä löytää tyypillisiä aikaskaaloja. Tämän lisäksi vuokäyriä tarkastelemalla on laskettu purkauksille tyypillisiä ominaisuuksia ja varmistettu tilastollisilla menetelmillä lasketut aikaskaalat.

Tulokset osoittavat, että AGN:ien muuttuvuuskäyttäytyminen on monimutkaista ja niiden vuokäyrissä on nähtävissä useita aikaskaaloja. Suuria purkauksia tapahtuu tyypillisesti vain noin 4–6 vuoden välein ja purkaukset ovat pitkäkestoisia, keskimäärin 2.5 vuotta 37 GHz taajuudella. Yksikään kohteista ei ole tarkasti jaksollinen. Näin ollen pitkäaikainen monitorointi on tärkeää, jotta kohteiden todellinen muuttuvuuskäyttäytyminen saadaan selville.

Väitöskirjassa on ensimmäistä kertaa tutkittu useiden tilastollisten menetelmien ominaisuuksia käyttäen pitkiä havaintosarjoja ja suurta määrää kohteita. Erityisesti wavelet-menetelmää käytetään nyt ensimmäistä kertaa korkeammilla radiotaajuuksilla AGN:ien tutkimiseen. Menetelmä on erittäin hyödyllinen, koska sen avulla voidaan selvittää milloin aikaskaalat ovat näkyvissä vuokäyrissä ja miten ne ovat muuttuneet. Tämä on tärkeää kun tutkitaan kohteita, jotka eivät ole tarkasti jaksollisia ja joiden käyttäytyminen muuttuu ajan kuluessa.

Pitkäaikaisia havaintoja on käytetty myös plasmasuihkujen Doppler-kertoimien, Lorentz-kertoimien ja katselukulmien laskemiseen. Havaitsimme, että BL Lacertae -kohteiden Doppler-kertoimet ovat pienempiä ja niiden suihkut hitaampia kuin kvasaarien. Väitöskirjassa laskettuja parametreja voidaan tulevaisuudessa käyttää tutkittaessa AGN:issä tapahtuvia fysikaalisia prosesseja ja eri emissioalueiden välisiä yhteyksiä.

Asiasanat Radioastronomia, aktiiviset galaksinytimet, tilastolliset menetelmät	
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Preface

This thesis work was carried out at Metsähovi Radio Observatory, Helsinki University of Technology (TKK).

First of all I want to thank my instructor docent Merja Tornikoski for teaching me how to do science and how the scientific world works. I am grateful to her for having introduced me to the very interesting topic of my thesis, thanks to which I remember the flux curves of my favorite sources by heart. I would also like to thank my thesis supervisor Prof. Martti Hallikainen for useful comments on my manuscript.

The staff at Metsähovi provided the relaxed and inspiring environment in which I could concentrate on my thesis work - a very big thanks to all of you! I would especially like to thank the rest of our GIX research group, Dr. Anne Lähteenmäki, Elina Nieppola and Dr. Ilona Torniainen for the scintillating scientific conversations and fun conference trips and summer schools.

The staff at Tuorla Observatory were also helpful during these past three years, and a very special thanks goes to Prof. Esko Valtaoja who I consider to be my other instructor and who always had the patience to explain his great ideas in enough detail. I am grateful to Dr. Harry Lehto for teaching me all about timeseries analyses and Dr. Markku Lainela for help with structure function analyses. Additionally I would like to thank William Martin from the Faculty of Electronics, Communication and Automation for consultation on language issues.

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Finally I want to thank my husband Tomi for all these years together and for the unconditional love and support. Thank you for encouraging me to study astronomy and for the interesting conversations about the Universe and everything :).

Helsinki, March 2009

Talvikki Hovatta

Contents

List of Publications

This thesis consists of an overview and of the following publications which are referred to in the text by their Roman numerals.

I **Hovatta, T.**, Tornikoski, M., Lainela, M., Lehto, H. J., Valtaoja, E., Aller, M. F. and Aller, H. D.:
"Statistical analyses of long-term variability of AGN at high radio frequencies",
Astronomy & Astrophysics, Vol. 469, pp. 899-912, 2007 .

II **Hovatta, T.**, Nieppola, E., Tornikoski, M., Valtaoja, E., Aller, M. F. and Aller, H. D.:
"Long-term radio variability of AGN: flare characteristics",
Astronomy & Astrophysics, Vol. 485, pp. 51-61, 2008.

III **Hovatta, T.**, Lehto, H. J. and Tornikoski, M.:
"Wavelet analysis of a large sample of AGN at high radio frequencies"
Astronomy & Astrophysics, Vol. 488, pp. 897-903, 2008.

IV **Hovatta, T.**, Valtaoja, E., Tornikoski, M. and Lähteenmäki, A.:
"Doppler factors, Lorentz factors and viewing angles for quasars, BL Lacertae objects and radio galaxies",
Astronomy & Astrophysics, Vol. 494, pp. 527-537, 2009.

V Nieppola, E., **Hovatta, T.**, Tornikoski, M., Valtaoja, E., Aller, M. F., Aller, H. D.:
"Long-term variability of radio-bright BL Lacertae objects",
The Astronomical Journal, 2009, accepted for publication.

Author's contribution

In Papers I and III, the author was responsible for compiling the data, making the final interpretation of the analyses and writing the articles, whereas the data analysis programmes were written in collaboration with H. Lehto.

For Papers II and V, the author compiled the data, and made preliminary data analysis by decomposing the flux curves into individual flares. In Paper V, the author was also responsible for calculating the statistical timescales, whereas the final data analysis, interpretation, and writing of the article was completed by E. Nieppola. In Paper II, the author was also responsible for the final data analysis and writing the article.

In Paper IV, the author was responsible for compiling the data, making all the analyses, and writing the article. In addition, the author made observations for all the papers.

List of Abbreviations

AGN	Active Galactic Nucleus or Active Galactic Nuclei
BLO	BL Lacertae Object
CMB	Cosmic Microwave Background
DCF	Discrete Correlation Function
GAL	Radio Galaxy
EIC	External Inverse Compton
FR I	Fanaroff-Riley type I galaxy
FR II	Fanaroff-Riley type II galaxy
FSRQ	Flat Spectrum Radio Quasar
HPQ	Highly Polarised Quasar
IC	Inverse Compton
IR	Infrared
IRAM	Institut de Radioastronomie Millimétrique
IUE	International Ultraviolet Explorer
JCMT	James Clerk Maxwell Telescope
LPQ	Low Polarisation Quasar
MOJAVE	Monitoring Of Jets in Active galactic nuclei with VLBA Experiments
RXTE	Rossi X-ray Timing Experiment
SED	Spectral Energy Distribution
SEST	Swedish-ESO Submillimetre Telescope
SF	Structure Function
SMBH	Supermassive Black Hole
SSC	Synchrotron Self-Compton
UMRAO	University of Michigan Radio Astronomy Observatory
UV	Ultraviolet
VLBI	Very Long Baseline Interferometry

List of Symbols

c	Speed of light (299 792 458 m s^{-1})
D	Doppler boosting factor
D_{IC}	IC Doppler boosting factor
D_{var}	Variability Doppler boosting factor
d_L	Luminosity distance
F	Flux density (1 Jy = 10^{-26} W m^{-2} Hz^{-1})
H_0	The Hubble Constant (km s^{-1} Mpc^{-1})
S	Flux density (Jy)
S_{max}	Maximum flux density at a certain frequency (Jy)
s	Electron energy distribution index
T_b	Brightness temperature
$T_{\mathrm{b,int}}$	Intrinsic brightness temperature
$T_{\mathrm{b,var}}$	Variability brightness temperature
z	Redshift

α	Spectral index
β	Speed of a component in the jet
β_{app}	Apparent transverse speed of a component in the jet
Γ	Lorentz factor of the jet
Γ_{var}	Variability Lorentz factor
θ	Viewing angle
θ_{var}	Variability viewing angle
ν	Frequency (Hz)
ν_{max}	Frequency of the flare maximum
ν_{obs}	Observing frequency
τ	Optical depth
τ_{obs}	Observed variability timescale
ϕ	Opening angle of the jet

1 Introduction

The Universe consists of billions of galaxies. Normal galaxies, like our own Milky Way, shine in the sky due to the combined light of billions of stars that form the galaxies. In the early Universe there were also different kind of galaxies called active galaxies. Their centre conceals a supermassive black hole and matter is accreted in the close vicinity of the black hole producing relativistic velocities. The energy output of the centre of the galaxy, called an Active Galactic Nucleus (AGN), is so high that it outshines the starlight of the galaxy.

In about ten percent of these galaxies, the activity somehow produces jets that can emanate from the centre or the core to as far as the neighbouring galaxy, millions of light years away. The jets consists of plasma accelerated to relativistic velocities and they shine brightly in the radio frequencies due to synchrotron emission.

The basic structure of an AGN is shown in Fig. 1.1. In the centre of the AGN resides a supermassive black hole which is surrounded by a hot disk of matter accreting to the black hole. The central region may be obscured by a molecular dust torus, which blocks the direct view to the nucleus, if the source is viewed at a large angle to the observer. In addition, there are broad emission line clouds close to the central region and narrow emission line clouds further away from the core. In some AGN long radio jets are formed.

All AGN have a supermassive black hole (SMBH) in their centre. The mass of the black hole is of the order of 10^6 – 10^9 solar masses. Evidence for the presence of an SMBH is found in different ways. The first indication of a massive central object comes from the fast variations in the flux of AGN. Variations can be seen in timescales of days (or even less), which indicate that the emission must come from a region comparable to the size of light-days. As the sources are so distant, and at the same time the most powerful objects in the Universe, nothing else, except for an SMBH, can be the initiator of such rapid variations (e.g. Robson 1996; Krolik 1999, and references therein).

Also, the widths of the emission lines of AGN show large velocities of over 5000 km/s in the broad line region. This also supports the view of a large mass in the centre. In addition, stellar dynamics around AGN indicate a massive central object. By studying the velocity dispersion of stars around the centre, it is possible to estimate the mass of the central object. This is a generally used method to determine the black hole masses in some of the nearest AGN (e.g. Gebhardt et al. 2000; Peterson et al. 2004; Kaspi et al. 2007). Other good evidence of an SMBH is the stability of the sources over millions of years. Radio observations reveal good alignment between small-scale and large-scale jets, which requires long-term stability of the jet production. This can only be achieved if there is a SMBH in the centre.

There is an accretion disk around the SMBH. In this region the matter falling towards the black hole is accreted to large velocities and therefore heated to high temperatures. In AGN it is not possible to directly observe the accretion disk since its spatial scale is still too small to be observable with current methods. It is possible, however, to study the X-ray emission of AGN, and especially the broadening of the iron K_α (6.4 keV) line, which gives indications of the accretion disk structure (e.g. Tanaka et al. 1995). Interac-

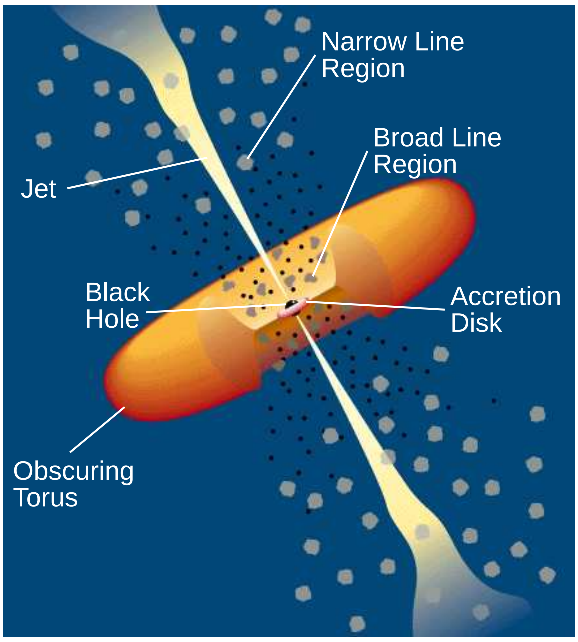

Figure 1.1: Structure of an AGN. Credit: C.M. Urry ja P. Padovani

tions between the accretion disk and magnetic fields somehow produce the long radio jets observed in some of the AGN.

Quasars are generally classified into radio-loud and radio-quiet, depending on the ratio of their radio luminosity versus optical luminosity. Kellermann et al. (1989) defined that quasars are radio-loud if their radio luminosity is at least ten times greater than the optical luminosity. In addition, they state that there are at least 5–10 times more radio-quiet than radio-loud quasars, meaning that only about 10% of the quasars are radio-loud. This thesis concentrates on the radio-loud objects only and therefore the radio-quiet objects are not discussed further.

Radio-loud AGN can be divided into subgroups by various parameters such as the shape of the radio spectrum or their optical properties. They can be divided into core-dominated or lobe-dominated by their radio emission. Core-dominated objects are generally quasars and BL Lacertae objects (BLO) whereas lobe-dominated radio sources are associated with elliptical galaxies. The main difference is that in quasars the core emission is so strong that the host galaxy may not be visible. It is thought that the radio galaxies are viewed from the side so that the jet emission is not enhanced by Doppler boosting, whereas quasars and BLOs are viewed facing the direction of the oncoming jet (e.g. Urry & Padovani 1995).

Radio galaxies (GALs) were divided into low luminosity Fanaroff-Riley type I (FR I) and high luminosity FR type II (FR II) galaxies by Fanaroff & Riley (1974), the division occurring at luminosity $5 \times 10^{25}\mathrm{WHz}^{-1}$ at the frequency 178 MHz. In FR I type galaxies the smooth jets are brightest closest to the core and the luminosity gradually decreases towards the edge-darkened radio lobes. In these sources jets emanate from both sides of the core and the jets may show significant bends. The FR II type objects have prominent radio lobes with "hot spots" at the edges. The jet is typically seen only on one side of the core and its emission is weaker than in the lobes.

Based on the unification model (Barthel 1989; Urry & Padovani 1995), quasars are often considered to be the beamed counterparts of FR II type galaxies, viewed at small angles towards the observer. These are high radio power sources which show strong emission lines. They can be further divided into low- and high-polarisation quasars (LPQ and HPQ), depending on their optical polarisation degree. Typical low-polarisation quasars have a flat radio spectrum and a steeper optical spectrum with $\alpha_o \sim -0.5$. They are intrinsically polarised with a polarisation of 0% to 2% (Stockman et al. 1984). LPQs are viewed at a smaller angle between the jet and the line of sight than galaxies, so that their emission is enhanced by Doppler boosting effects. The emission from the core outshines the surrounding host galaxy which may be difficult to detect.

A quasar is called highly polarised if its optical polarisation exceeds 3% (e.g. Moore & Stockman 1981). Other general properties are that they exhibit strong and rapid optical variability, have steep optical spectra ($\alpha_o \sim -1$ Scarpa & Falomo 1997), are radio loud, and have flat radio spectra. They are compact radio sources and show superluminal motion. According to the unification models, they are also viewed at a smaller angle to the line of sight than LPQs. The degree of polarisation may vary, and therefore some of the LPQs can in reality be HPQs but they have not been observed in the right, highly polarised state.

BL Lacertae objects differ from quasars in that their spectra do not show emission lines or the lines are weak (by definition the equivalent width of the line < 5Å). The strong synchrotron component totally outshines the thermal emission but sometimes in a non-active state, weak emission lines can be detected. The optical emission of BLOs is also often highly polarised which makes them similar to HPQs. BLOs have been suggested to be similar to HPQs, except for the weaker emission lines (Scarpa & Falomo 1997). BLOs are often associated with the low radio power FR I type galaxies. However, recent studies suggest that many of the BLOs are in reality FR II type objects, and that the basic unification scheme is not so simple (Landt & Bignall 2008).

HPQs and BLOs together are commonly referred to as blazars because of their similar properties. In both classes the optical spectra are steeper and smoother than in normal LPQs. They also appear highly polarised. In addition they are thought to be highly variable at all wavelengths. Blazars often are active also at X-ray and gamma-ray wavelengths.

However, the connection between the different classes is not simple. In Paper I and Paper III of this thesis, we found indications that large flares in BLOs occur more rarely, and thus shocks are formed less frequently in BLOs than in quasars. In Paper II and Paper V we could not, however, find large differences between the source types when the flare characteristics were studied. In Paper IV we show that BLOs have smaller Doppler boosting factors and slower jets than quasars, and that LPQs and HPQs are quite similar when these intrinsic parameters are considered. Some of these discrepancies may be due to our sample selection which favours bright and extreme sources. Even though our sample size in the analyses is large (55–87 sources), it is still not complete. One must bear in mind that in order to make firm conclusions about the differences between the source types, complete samples, including, for example, either all the sources above some flux limit or all the sources in a certain area of the sky, must be studied.

Metsähovi Radio Observatory was founded in 1974, and regular monitoring of extragalactic radio sources has been performed since 1980. These total flux density observations at 22, 37 and 90 GHz form the basis of this thesis. Understanding the long-term behaviour of AGN is especially important for the Planck satellite mission, which will study the Cosmic Microwave Background (CMB) and its small variations. In order to observe the small-scale variations in detail, all the foreground objects, like AGN, must be accurately removed from the maps. Metsähovi is actively taking part in these actions, and this thesis forms a part of the studies made for understanding the effects of the foreground objects.

In Chapter 2, the radio jets and their properties are discussed in detail. Variability behaviour of AGN over the whole electromagnetic spectrum is reviewed in Chapter 3, and long-term radio variability and methods to study it are discussed in Chapter 4. Finally, Chapter 5 summarises the articles of this thesis, and conclusions are drawn in Chapter 6.

2 Relativistic jets

All radio-loud AGN have jets from which the observed synchrotron and inverse Compton radiation is emanating. There are, however, many open questions in the jet formation, and we do not even know if the jets are constituted of normal or pair plasma. The accretion disk is a very important factor in the jet formation. Currently the process which forms the jets is not known in detail (e.g. Kataoka 2008; Fragile 2008, for reviews). It is thought that the jets are either dominated by Poynting flux in which the magnetic field lines extract energy from the ergorsphere of the rotating black hole and transport the energy to large distances, or that the jets are dominated by matter extracted from the accretion disk by hydrodynamic winds. Based on observations, the most likely scenario is that the jets are first Poynting flux dominated, and are converted to matter dominated at some later stage (e.g. Sikora et al. 2005). Recent general relativistic magnetohydrodynamic simulations also show that often the jets form a spine-sheath structure in which the inner fast spine is Poynting flux dominated and the outer slow sheath matter dominated (Mizuno et al. 2007; Fragile 2008). This sort of structure has been reported based on polarisation observations of AGN jets (e.g. Pushkarev et al. 2005), and is used to explain especially the TeV emission in some objects (e.g. Tavecchio & Ghisellini 2008).

The jets are stable and collimated over long distances. The collimation is possibly caused by external medium which puts pressure on the relativistic material. If the jet has a spine-sheath structure, the outer slower sheath can also work as a collimator for the fast inner spine. Also, in order to form long jets of the order of megaparsecs, the particle acceleration in the jets must be efficient. In this thesis the jet properties are considerably simplified, and the observational properties rather than the theory are mainly studied.

A simple illustration of a jet is presented in Fig. 2.1 where the basic parameters are shown. The jet originates at some distance from the central engine where a radio core is seen. In reality the jet formation starts closer to the central engine, but the jet is opaque in radio wavelengths until it reaches the radio core. The basic properties of a jet are the opening angle ϕ, angle to the line of sight of the observer θ, and the Lorentz factor Γ, describing the speed of the jet flow. There may be shock events which show up as flares in continuum observations. The nature of the radio core is not yet certain; its location is frequency dependent, and it can be different at different frequencies. Possibilities are, for example, a surface where the opacity changes from optically thick to optically thin, a standing shock, or a bend in the jet which changes the Doppler boosting factor at that point (Marscher 2006). The jet half-opening angles are observed to be of the order of 0.1 to 4 degrees and they are inversely propotional to the Lorentz factor (Jorstad et al. 2005).

The real picture is not as simple and the observed jet morphology depends greatly on the viewing angle θ. If the source is seen directly from the side, usually two jets are seen to emanate from both sides of the central engine. These sources are often classified as Radio Galaxies. If the source is seen at a very small viewing angle, Doppler beaming starts to affect how the jet is seen by the observer. The counterjet is usually not visible because the Doppler boosting increases the luminosity of the approaching jet and diminishes the

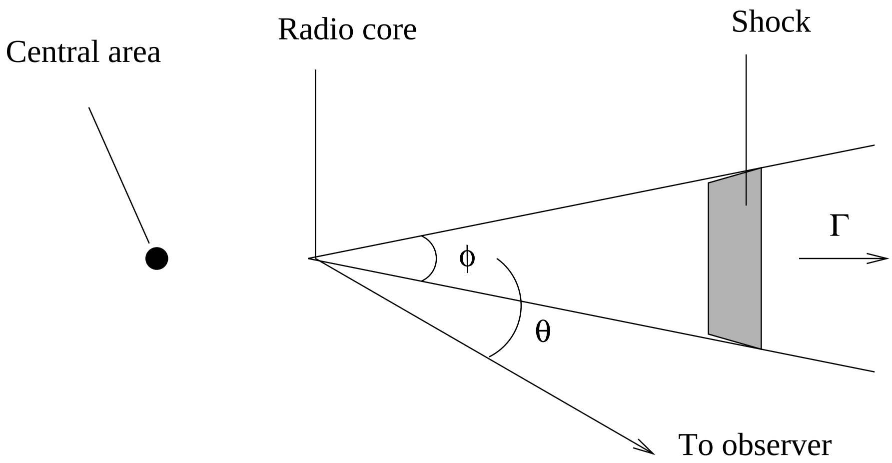

Figure 2.1: A simple illustration of a jet.

receding jet according to Eq. 2.1 (e.g. Kembhavi & Narlikar 1999)

$$\frac{F_{\rm in}}{F_{\rm out}} = \left(\frac{1+\beta\cos\theta}{1-\beta\cos\theta}\right)^{2+\alpha}. \quad (2.1)$$

The Doppler boosting effect depends on the viewing angle θ, the Lorentz factor of the jet flow Γ, and the speed of the beam $\beta = v/c$ in the source's frame as shown in Eq. 2.2 (e.g. Kembhavi & Narlikar 1999)

$$D = \frac{1}{\Gamma(1-\beta\cos\theta)}, \quad (2.2)$$

where $\Gamma = (1-\beta^2)^{-1/2}$. The smaller the viewing angle the bigger the Doppler boosting factor D is. The most significant effect of the Doppler boosting is that it changes the way we see the sources. The observed flux density is enhanced as shown in Eq. 2.3 (e.g. Kembhavi & Narlikar 1999)

$$F(\nu) = \left(\frac{D}{1+z}\right)^{3+\alpha} F'(\nu), \quad (2.3)$$

where $F(\nu)$ is the observed flux density at frequency ν, z is the redshift, α is the spectral index, and $F'(\nu)$ is the intrinsic flux density of the source. Because of the Doppler boosting, we also see the jets shorter, fatter, and more sharply bent than would be seen when faced side-on (Marscher 2006).

The jets can be directly observed in the radio regime with the Very Long Baseline Interferometry (VLBI) technique. In VLBI, many radio telescopes are observing the source simultaneously, forming an antenna which has an aperture of the size of the distance between the telescopes. The observations are later combined to form an image or a map of the source. It is the only way to get a close look of the radio core and to see the shocks moving along the jet. An accuracy of sub-milliarcseconds can be obtained with the current VLBI methods. The first sources were seen to show apparent superluminal motion in the VLBI images already in the early 1970s (Whitney et al. 1971; Cohen et al. 1971) and later on, the number of sources showing superluminal motion has increased tremendously (e.g. Jorstad et al. 2001; Kellermann et al. 2004; Piner et al. 2007). The apparent superluminal motion can be explained by using the fast speeds of the jets and the small viewing angles. If the emitting source in the jet is moving at a speed β, the observer measures apparent transverse speed $\beta_{\rm app}$ (Eq. 2.4, Kembhavi & Narlikar e.g. 1999)

$$\beta_{\rm app} = \frac{\beta \sin\theta}{1 - \beta\cos\theta}. \tag{2.4}$$

This can be seen to exceed the speed of light c if the viewing angle θ is small enough.

The viewing angle or Lorentz factor Γ cannot be observed directly but they can be derived using Eqs. 2.7 and 2.8 (e.g. Kembhavi & Narlikar 1999) if the Doppler boosting factor D and the apparent transverse speed $\beta_{\rm app}$ are known. We can get $\beta_{\rm app}$ from the VLBI observations by assuming that the pattern speed of the observations corresponds to the speed of the jet flow. This is more likely if the fastest observed pattern speed is used as it probably propagates at a speed close to the speed of the flow.

The Doppler boosting factor can be estimated in various ways. The most common way to estimate the Doppler boosting factor is to compare VLBI observations with X-ray observations (Ghisellini et al. 1993; Guijosa & Daly 1996; Guerra & Daly 1997; Britzen et al. 2007). Using VLBI component fluxes, it is possible to estimate the amount of X-ray emission if it is assumed that the X-rays are produced by the Inverse Compton (IC) mechanism and that the same synchrotron photons producing the lower frequency emission are also responsible for the IC emission. Assuming also that the VLBI observations are carried out at the spectral turnover frequency, the predicted X-ray flux can be calculated. This can be compared to the observed X-ray fluxes, and by interpreting the excess flux as due to Doppler boosting, the Doppler boosting factors can be calculated. The main disadvantage of this method is that the VLBI observations are not often performed at the spectral turnover frequency. In addition, most studies use non-simultaneous VLBI and X-ray data which enhances the errors. Lähteenmäki & Valtaoja (1999) showed that the IC Doppler factors are not very accurate.

In Paper IV of this thesis, the Doppler boosting factors are calculated by using the total flux density observations. In this approach the variability timescale is assumed to correspond to the light-travel accross the emitting source. We estimate the brightness temperature of the source by using a variability timescale $\tau_{\rm obs} = {\rm d}t/{\rm d}(lnS)$ obtained from the observations, and calculating the brightness temperature by using Eq. 2.5 (Paper IV)

$$T_{\rm b,var} = 1.548 \times 10^{-32} \frac{S_{\rm max} d_{\rm L}^2}{\nu^2 \tau_{\rm obs}^2 (1+z)}, \tag{2.5}$$

where ν is the observed frequency in GHz, z is the redshift, $d_{\rm L}^2$ is the luminosity distance in metres, and $S_{\rm max}$ is the maximum amplitude of the flare in janskys. The numerical factor in Eq. 2.5 corresponds to using $H_0 = 72\,\mathrm{km\,s^{-1}\,Mpc^{-1}}$, $\Omega_m = 0.27$ and $\Omega_\Lambda = 0.73$, and to assuming that the source is a homogeneous sphere. Relativistic beaming enhances the observed variability brightness temperature by a factor of D^3, and thus we can estimate the variability Doppler boosting factor by relating $T_{\mathrm{b,var}}$ to the intrinsic brightness temperature of the source (Eq. 2.6, Paper IV)

$$D_{\mathrm{var}} = \left[\frac{T_{\mathrm{b,var}}}{T_{\mathrm{b,int}}}\right]^{1/3}. \tag{2.6}$$

It is often assumed that the maximum intrinsic brightness temperature for a source would be $\sim 10^{12}K$, limited by the inverse Compton catastrophe (Kellermann & Pauliny-Toth 1969). However, Readhead (1994) argued that a more reasonable value can be obtained by assuming equipartition between the magnetic field energy density and the radiating particle energy density. This equipartition temperature T_{eq} is of the order of $10^{11}K$. Lähteenmäki et al. (1999) confirmed the value by estimating the intrinsic brightness temperatures by using various observational data. Therefore, in our analysis the value 5×10^{10}K for $T_{\mathrm{b,int}}$ is used (Readhead 1994; Lähteenmäki et al. 1999).

$$\Gamma = \frac{\beta_{\mathrm{app}}^2 + D^2 + 1}{2D} \tag{2.7}$$

$$\theta = \arctan \frac{2\beta_{\mathrm{app}}}{\beta_{\mathrm{app}}^2 + D^2 - 1} \tag{2.8}$$

The typical values for Doppler boosting factors are around 12 in our sample. There are differences between the source types with HPQs being more boosted than the other types, with a median D of 16. The GALs are the least boosted, as expected, with a median D of 2.7. The LPQs and BLOs are in between these two with median Ds of 11.9 and 6.3, respectively. As is argued in Paper IV, it is more reasonable to combine the HPQs and LPQs in our sample to a single group of flat spectrum radio quasars (FSRQs), because in our sample we do not see ordinary quasars which have larger viewing angles. All quasars in our sample are seen at a viewing angle of less than 20 degrees, and therefore we can only draw conclusions about the behaviour of the blazar-type objects.

In Paper IV we also found that the BLOs have slower jets than FSRQs. The median Γ_{var} for BLOs is 10.3 while for FSRQs it is 16.2. As expected, the GALs have the slowest jets with a median Γ_{var} of 1.8. The differences between the source classes are significant, and according to the Kruskal-Wallis analysis, the BLOs and FSRQs differ with a 99% probability. The situation is similar when the viewing angles are studied. The FSRQs are seen in smaller viewing angles with a median θ_{var} of 3.4°, whereas for the BLOs the median is $\theta_{\mathrm{var}} = 5.2°$. Again the GALs differ greatly from others with a median $\theta_{\mathrm{var}} = 15.5°$. It must be noted that we have only five GALs in our sample, which are also the most variable and compact objects of their type, and therefore do not represent typical radio galaxies seen at large viewing angles.

All this becomes more complicated when the bending of the jet and different component speeds at different parts of the jet are taken into account. Curved component trajectories have been seen in VLBI images, and bending of as high as 210 degrees has been detected in at least one source (Savolainen et al. 2006). Standing or subluminal shocks are also common features in these sources (Jorstad et al. 2001; Kellermann et al. 2004). These properties make the analysis more complicated and our estimation of the parameters more demanding.

3 Total flux density variability of AGN

Quasars were first discovered by their radio properties and their optical counterparts were only later identified. It was, however, first in the optical wavelengths that they were claimed to be variable (Matthews & Sandage 1963). Radio variability was first reported for the blazar 3C 279 by Dent (1966), and a larger sample of sources with multiple frequencies was reported to show variability by Pauliny-Toth & Kellermann (1966). In 1966 Martin Rees suggested that it was the relativistic motion of the emitting region which caused the observed variability (Rees 1966). Since then variability at all wavelengths has been detected. The variations in the different wavelength regions are often correlated, indicating a common origin for the variations. This thesis concentrates mainly on radio variability which is studied in Papers I, II, III, and V of this thesis, and therefore variability behaviour at other wavelengths is only briefly reviewed.

The spectral energy distributions (SEDs) of blazars consist of two peaks. An example is shown in Fig. 3.1 where the SED of the blazar 3C 279 in different activity states is shown. The shape of the SED is smooth from radio to X-ray frequencies indicating that the same physical processes (mainly synchrotron emission) are responsible for the variations at all these wavelengths. The peak of the synchrotron component is often in the infrared to optical region (Impey & Neugebauer 1988) but in some BL Lacertae objects it occurs in the X-ray regime (e.g. Giommi et al. 1995). The second high-frequency peak is thought to be caused by Inverse Compton radiation. It is formed when photons gain energy from collisions with the electrons from the synchrotron radiation, and the radiation is shifted to higher frequencies. This component is not as well understood as the synchrotron component due to the lack of decent light curves at the high X-ray and γ-ray frequencies. In this Chapter the variability properties of these two regimes, concentrating on the synchrotron component, are discussed.

3.1 The synchrotron component

Synchrotron radiation is the most important emission mechanism in the radio to X-ray regime of AGN. It is produced when relativistic electrons interact with magnetic fields. Electrons spin around magnetic field lines (see Fig. 3.2), producing a cone of radiation emitting towards the direction of the movement. The frequency of the synchrotron radiation is directly proportional to the strength of the magnetic field, and therefore synchrotron radiation in AGN is seen at radio to X-ray frequencies.

The spectrum of the synchrotron radiation is shown in Fig. 3.2. In the optically thick part of the spectrum the radiation is self-absorbed so that the electrons absorb photons emitted by other electrons. The spectral index at this region is +2.5. The synchrotron self-absorption turnover in AGN usually occurs at radio frequencies. At this point the emission turns into optically thin emission, which is described with a power-law with spectral index $\alpha = (1 - s)/2$ where s is the electron energy distribution. A value of $\alpha \sim -0.7 - -0.5$ is obtained from observations. At higher energies (usually far-IR and UV) a high-energy cutoff occurs, and radiation losses steepen the spectrum.

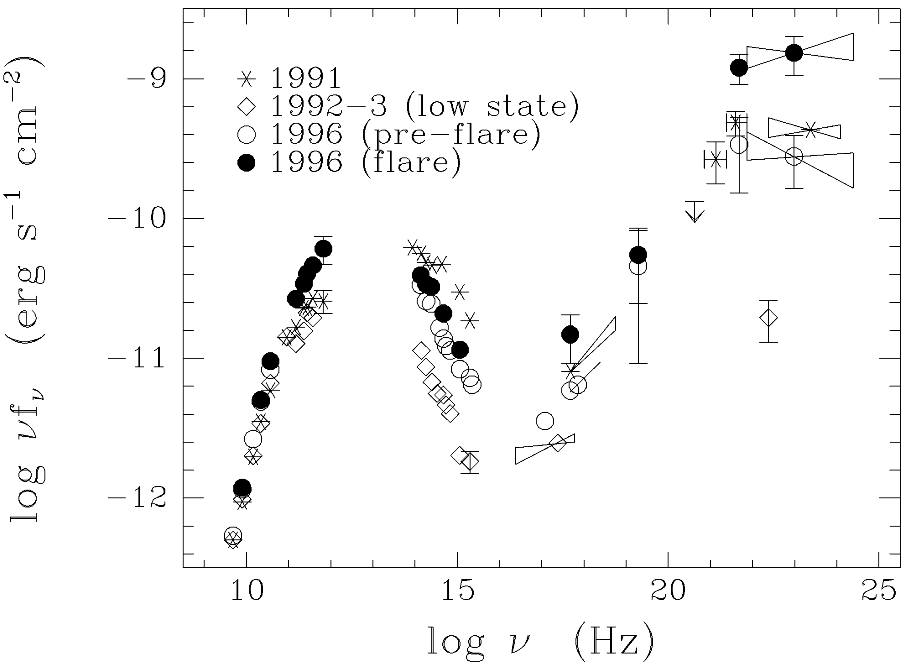

Figure 3.1: Spectral energy distribution of the blazar 3C 279. High and low activity states are shown in different symbols. (Figure is from Wehrle et al. 1998.)

Synchrotron radiation is linearly polarised and often variable. When the self-absorption turnover and the linear size of the emitting object are known, it is possible to calculate the magnetic field strength.

The variations in radio to submillimetre to far-infrared regions are closely related and flare development can be traced through all the regions (Stevens et al. 1994, Paper II). The flares start to develop in the far-infrared to submillimetre region and peak somewhere in the millimetre domain (Stevens et al. 1994, Paper II). The flares in the mm- to cm-wavelengths are quite long-lasting with average duration of 2.5 years at 37 GHz (Paper I), but short-term variability is also common in these sources (Paper I; Paper III). There can also be quiescent periods which last for years, and therefore, in order to study the variability behaviour in the cm- to mm-wavelengths, long-term monitoring is needed.

The far-infrared variability was studied by Impey & Neugebauer (1988) who found that in their small sample of blazars, 40% were found to be variable over 3 to 9 months timescales. The amplitude of the far-infrared variability was about half of the amplitude in the optical. Similar variability timescales were found by Edelson & Malkan (1987) for three blazars which were variable in a sample of five blazars. The results in both studies are limited by the short time span of less than a year in which the observations were carried out. Nowadays it is clear that the sources are also variable in the infrared region, and the variability is correlated with lower frequencies. In other AGN than blazars the infrared emission is dominated by thermal dust emission rather than the non-thermal

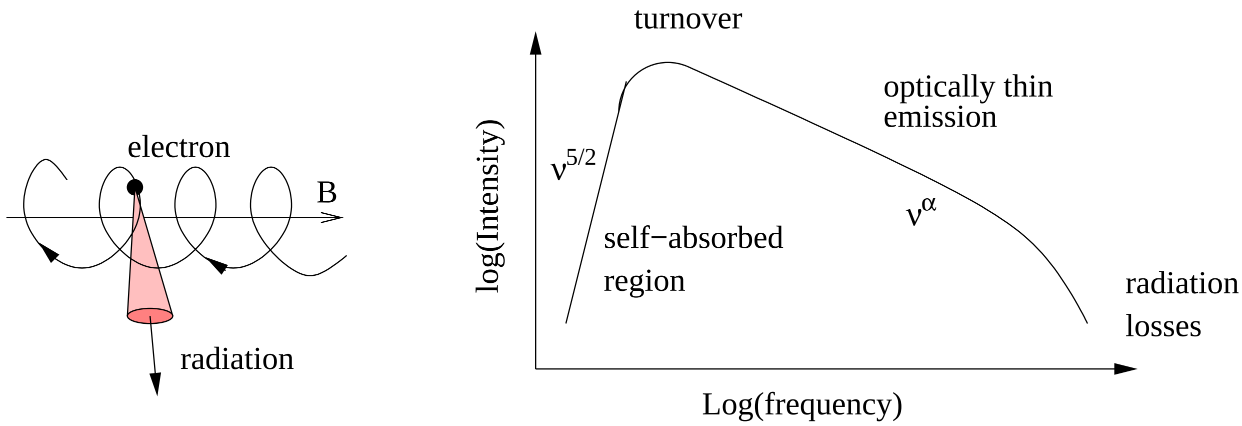

Figure 3.2: Electron spinning in a magnetic field producing synchrotron radiation and the spectrum of the radiation.

synchrotron emission. Also, some of the infrared emission may come from the accretion disk.

In the optical, already early long-term monitoring projects showed that the sources are variable over timescales from months to years (Webb et al. 1988). In the optical, many sources also show variations in timescales of less than days (Wagner & Witzel 1995). The mechanism producing this intra-day variability is probably different to the shocks propagating along the jet which are used to explain the long-term variability. The correlation between optical and radio frequencies has been studied using large datasets (Hufnagel & Bregman 1992; Tornikoski et al. 1994b; Clements et al. 1995; Hanski et al. 2002). The flares in the optical and radio seem to correlate but the gaps in especially the optical data make the analysis difficult. Tornikoski et al. (1994b) concluded that it seems that every radio flare has an optical counterpart but it does not apply vice versa. All optical flares are not seen to have radio counterparts which could be due to the different origin of these flares, or long time delays between the frequencies which causes the identification of the corresponding flare to be difficult or even impossible.

At ultraviolet wavelengths the variability of blazars is mostly caused by the same synchrotron processes as at longer wavelengths, while in ordinary quasars and galaxies its origin is the accretion disk (Edelson 1992). The International Ultraviolet Explorer (IUE) provided data for 13 years, and the results of this large dataset were analysed in Edelson (1992). Although there were only 14 sources with more than 5 datapoints in the sample, they concluded that the variations in the UV region correlate with longer wavelengths, and therefore the origin of the variations is the same. The long-term timescales of UV variability were found to be of the order of 4 years while also short-term daily variations were seen. However, at least some of the UV radiation probably originates from the central regions of AGN and not from the synchrotron jet (e.g. Marscher 2005). Indeed in the faint state, some blazars are observed to have a rise in their UV continuum indicating emission from the accretion disk and the broad line region (e.g. Raiteri et al. 2006, 2008).

Several models have been constructed to explain the synchrotron variations, and currently the best models include shocks moving downward in the jet.

3.1.1 Shock models

In the first models trying to explain AGN variability, the variations were caused by a spherical, adiabatically expanding cloud of plasma, emitting incoherent synchrotron radiation from electrons with a power-law energy distribution (van der Laan 1966; Pauliny-Toth & Kellermann 1966). Today it is generally accepted that the radio flares in AGN are produced by shocks propagating in the relativistic jet. The first such model was introduced by Blandford & Rees (1978). These models soon proved to be more realistic than the simple expanding source model by van der Laan (1966) and Pauliny-Toth & Kellermann (1966) which failed, for example, to explain the variability amplitudes at higher frequencies (e.g. Blandford & Konigl 1979; Marscher 1980).

Marscher & Gear (1985) studied the 1983 flare of the quasar 3C 273, and developed a shock model to describe the properties of the flare. In the model, shocks propagate in a conical, adiabatic jet, which has a constant flow speed described by the Lorentz factor Γ. The viewing angle θ between the jet axis and the line of sight to the observer is assumed to be much larger than the constant jet opening angle ϕ. This way it is possible to assume a constant Doppler factor to the flow.

The shocks are formed when minor disturbances propagate along the jet and encounter a pressure gradient in the jet. A pressure gradient forms if there is a slight change in the pressure of the jet flow, or if the bulk Lorentz factor increases. The spectral shape of the shock is that of a homogeneous synchrotron source.

The evolution of the shock is described by three stages. In the first, the growth stage of the shock, Compton losses dominate and the flux density rises at all frequencies. The turnover frequency of the spectrum does not change during this stage. When the photon energy density equals the magnetic field energy density, synchrotron losses start to dominate. In this stage the peak flux of the spectrum stays approximately constant, and the turnover frequency moves to lower frequencies. In the final stage adiabatic losses dominate and the shock decays.

It is possible to see these effects observationally if the evolution of a flare can be monitored at many frequencies simultaneously. This is a difficult task because long-term monitoring at multiple frequencies is often hard to accomplish, especially at higher optical and infrared frequencies, where the variations are faster and the data often contain large gaps. Stevens et al. (1996) were able to study the evolution of the centimetre-submillimetre spectrum of the blazar 3C 345, and to test the shock model of Marscher & Gear (1985). By removing the quiescent spectrum from the flare, they were able to show that the flare spectrum is indeed that of the homogeneous synchrotron source. The same result was earlier obtained by Valtaoja et al. (1988). Stevens et al. (1996) were able to follow the evolution of the spectrum over a period of two years, and their results showed that the evolution of the turnover frequency corresponded to the predicted behaviour. They also noticed that the model, which assumes a conical jet, could not explain all the properties seen, and therefore the jet is probably bending away from the line of sight during the flare.

Hughes et al. (1985) developed a shock model to describe the lower centimetre frequency linear and polarised variability of AGN. The model is numerical and the code is provided in Hughes et al. (1989). In their model, hot plasma with a turbulent magnetic field acts like a piston and drives the shock along the adiabatic and constant velocity jet. The shock is formed in the optically thick part of the jet, and a flare is seen when the shock emerges from behind an optically thick surface of the jet. The flux starts to rise when the shocked region becomes visible and reaches its maximum when the whole shock is visible. The flux decays when the shock expands adiabatically.

The model was tested in Hughes et al. (1989) and Hughes et al. (1991), and it was able to explain the centimetre wavelength linear and polarised variability very well. It fails, however, at higher frequencies because the initial growth phase of the shock, which cannot be ignored at higher frequencies, is not implemented in the model.

A generalisation of the Marscher & Gear (1985) model was constructed by Valtaoja et al. (1992). This generalised model does not consider any physical parameters, but concentrates on the observational properties of the flares. In this model, the flares are described also by three stages in which the evolution of the synchrotron spectrum is followed. In the growth stage, the peak flux density of the spectrum is strongly dependent on the turnover frequency. The second stage is a plateau, where the peak flux is constant, and in the third stage the peak flux decays and is weakly dependent on the turnover frequency. How the flare is observed depends on the observing frequency ν_{obs}, and whether it is higher or lower than the frequency where the flare reaches its maximum $\nu_{\rm max}$. A high-peaking flare is seen when $\nu_{obs} < \nu_{\rm max}$. In this case there are time delays from higher to lower frequencies, and the maximum flux density S_{max} is strongly dependent on the frequency. It is also likely that an optical spike is observed simultaneously with the high-frequency radio maximum.

A low-peaking flare is seen when $\nu_{obs} > \nu_{\rm max}$. The frequencies follow closely each other and no time delays are seen. S_{max} is weakly dependent on frequency and increases towards lower frequencies. A new VLBI component is likely to be seen because the flare is still growing when it reaches the lower radio frequencies at which VLBI observations are usually made.

The model was tested with a sample of sources in the paper itself and also in Lainela (1994), and Paper II in this thesis. The flare evolution seems to follow this simple model quite well, and the shock model can explain most of the observed flare characteristics seen during the flares.

More detailed studies of individual sources and how they are described by the shock model of Marscher & Gear (1985) have been made by Türler et al. (1999, 2000) and Lindfors et al. (2005, 2006, 2007). In Türler et al. (1999) the flux curves of the quasar 3C 273 are decomposed into a set of self-similar flares, which are described by the Marscher & Gear (1985) model. It is seen that again the lower frequencies are described very well by the model but at higher frequencies the model sometimes fails to reach the observed flare amplitudes. In general, however, the agreement between the model and the observations is very good. Türler et al. (2000) modified the model to include curved, non-conical and non-adiabatic jets which can also be accelerating or decelerating. In this paper a more physical approach is also tested, where the onset values of the Doppler factor, magnetic field strength and electron energy density normalisation are varied. Again the correspondence between the model and the observations is very good. They also noticed that some of the flares are high-peaking and others low-peaking as was explained in Valtaoja et al. (1992). The decomposed flare components also correspond very well to VLBI observations, so there is clearly a physical connection between the decomposition model and the actual shocks.

In Lindfors et al. (2005) similar decompositions were made for the data of the blazar 3C 279 to test if the Synchrotron Self Compton (SSC) mechanism is able to explain the observed gamma-ray flux in the source. They concluded that the SSC mechanism describes well the observed X-ray flux but is not alone able to explain the gamma-ray flux.

All the decompositions show that in general the shock model of Marscher & Gear (1985) is able to explain the observed properties, but the weakness of the model is that it does not take into account the variable Doppler factor or the bending of the jet. These effects are thought to explain some of the features that are seen but are not explained by the model. Björnsson & Aslaksen (2000) also criticise assumptions made in the initial Compton scatter phase of the shock, and suggest that at high frequencies it is pitch angle scattering rather than Compton cooling which dominates. This addition to the Marscher & Gear (1985) model was tested on the galactic microquasar Cyg X-3 by Lindfors et al. (2007). They found a very good correspondence between the observations and the model. This study also showed that the same jet models used for AGN modelling can be used to understand the behaviour of galactic sources and jets.

Sokolov et al. (2004) have taken a slightly different approach where the flares are seen when a moving shock collides with a stationary feature in the jet. In their model the flare is first seen when the moving shock collides with the stationary feature that forms the VLBI core of the jet. The VLBI core first brightens due to the shock collision and the plasma moving downstream is later seen as a superluminal feature in the jet. A recent study of the blazar BL Lac showed that the acceleration of the particles occur upstream of the radio core where the emission feature is moving along a helical magnetic field (Marscher et al. 2008). A radio flare is seen when the emission region crosses the core which is a standing shock. This is the first time there has been dense enough observations at all wavelengths to prove such a scenario observationally.

An important note, however, is that all the models produce flares with a plateau but in reality the observed flares are better described by a sharp peak with exponential rise and decay (Valtaoja et al. 1999, Paper IV), which so far has not been explained in any models. This should be taken into account when improving the current models.

3.2 The high-frequency component

There are currently two types of models which try to explain the high-frequency emission in blazars. In leptonic models the emission is dominated by ultrarelativistic electrons and/or pairs. The process in which electrons from synchrotron radiation collide with photons is called Inverse Compton scattering (IC). The photons gain energy from the electrons and the radiation is transferred to higher frequencies. This mechanism dominates the higher X-ray to gamma-ray frequency radiation of AGN, and is seen as the second peak in a SED (Fig. 3.1). If the seed photons are the synchrotron photons, the mechanism is called Synchrotron Self Compton (SSC). Another option is that the photons originate from, for example, the accretion disk, or from clouds in the broad line region. This process is called External Inverse Compton (EIC). It is still not clear which of the two produces the high energy radiation in AGN, or if both mechanisms contribute. In any case, the variations at high-frequencies should correlate with the variations of the synchrotron component.

Another possibility are hadronic models in which the second peak of the SED is formed by proton and muon synchrotron radiation. These models require the acceleration of relativistic protons to energies where $p\gamma$ pion production is possible, and also very high magnetic fields of tens of Gauss are needed. A recent review by Böttcher (2007) discusses both leptonic and hadronic models in more detail. Currently the leptonic models seem to better explain the high-frequency variations, and therefore are discussed in more detail below.

Only quite recently the Rossi X-ray Timing Experiment (RXTE) observations showed that the X-ray variations in some blazars are indeed correlated with lower optical to radio frequencies (Marscher et al. 2004; Marscher 2005; Chatterjee et al. 2008). They find that the radio and optical observations precede the X-ray observations in at least two well monitored blazars (Marscher et al. 2004), indicating that the emission originates from the jet and not from the region close to the central engine as has been thought previously. On the other hand, detailed analysis of the observations of the blazar 3C 279 from radio to X-ray frequencies show that in some flares, the X-ray variations precede the optical ones (Chatterjee et al. 2008), and in others the variations are nearly simultaneous, or the optical precedes the X-ray variations. The emission mechanism responsible for producing the X-rays in these models is thought to be SSC, in which case there should be strong correlations between the synchrotron components and the X-ray variability, as is seen in these sources. The differences between the flares can be explained with light-travel delays and different acceleration times of the electrons at various energies. In Chatterjee et al. (2008) it is also shown that the change in the source behaviour can be due to change in the direction of the jet.

In some high-peaking BLOs the X-rays are part of the synchrotron component (e.g. Giommi et al. 1995). In non-blazar radio-loud quasars the situation is more complicated, and at least some of the X-ray emission may arise from the accretion disk (Marscher et al. 2004).

Also the γ-ray emission correlates with radio variability (Jorstad et al. 2001; Tornikoski et al. 2002; Lähteenmäki & Valtaoja 2003; Lindfors et al. 2005). All of these studies show that the radio variations precede the γ-ray activity, which indicates that the emission originates in the jet and not from the close vicinity of the central engine as previously assumed. It is presumed that the same SSC mechanism responsible for the X-ray emission also produces the γ-rays but in Lindfors et al. (2005), in which the blazar 3C 279 is studied, it is shown that the SSC mechanism alone cannot explain the γ-ray emission for this source. The problem is the lack of decent flux curves at γ-rays. Most of the observations are from the EGRET instrument on board Compton Gamma-Ray Observatory, and they only indicate whether or not the source was observed in a high γ-ray state.

Another explanation for the origin of γ-rays is the External Inverse Compton (EIC) mechanism where the seed photons originate from, for example, close to the accretion disk, or from the broad line region, and are not the synchrotron photons as in the SSC mechanism. Especially in quasars some models explain the second peak in the SED with EIC models (e.g. Sambruna et al. 1997), while in BLOs the mechanism is thought to be SSC dominated (e.g. Böttcher 2007). Gamma-ray flux curves will soon be available when the Fermi Gamma-ray Space Telescope, which was launched in June 2008, has operated long enough to produce more observations. These will help to distinguish which of the two methods better describes the high-frequency component in AGN.

One problem with the current SED models is that they usually do not take all the wavebands into account and often, for example, radio frequencies are totally ignored in the models. The situation is even more complicated when the highest TeV energies are modelled. In the past ten years, a few blazars have been detected with the atmospheric Cherenkov telescopes to emit at high TeV energies . Most of the current models require very high Doppler boosting factors for these high-peaking objects (e.g. Finke et al. 2008), while observational evidence indicate low Doppler boosting for the objects (Wu et al. 2007; Nieppola et al. 2008). It is often difficult to model these sources with a single-zone jet model, in which the radiation at all wavelengths is thought to come from the same region of the jet. In some cases the models may require a hadronic component to explain the TeV observations (Böttcher 2007). Since the number of detected TeV objects is currently only about 20, it is difficult to make any general conclusions about their behaviour. Therefore upcoming improvements of the current Cherenkov telescopes and also new missions will hopefully give more insight into this field as well.

4 Long-term radio variability

Modern AGN studies usually concentrate on short multiwavelength campaigns lasting for some days or weeks. The basic idea is to get as a good wavelength coverage as possible, hopefully during a flaring state of an object. While this may work in high X-ray and optical frequencies where the flares last from days to a few weeks, it is not sufficient for the lower frequencies. As is shown in Paper II in this thesis, the flares in the radio regime last on average for 2.5 years. In addition, the time delays between different frequency bands can be of the order of months (e.g. Tornikoski et al. 1994a). It is clear that a short campaign lasting for a few weeks does not give a complete picture of the source behaviour.

4.1 Long-term monitoring data

Currently there are two dedicated AGN monitoring projects in the radio regime, which have provided densely sampled flux curves for decades: longer cm-wavelength monitoring at the University of Michigan Radio Astronomy Observatory (UMRAO) and shorter cm- and mm-wavelength monitoring at Metsähovi Radio Observatory. The UMRAO monitoring programme started already in the 1960s, and large sets of different types of objects have been monitored on a weekly to monthly basis. At Metsähovi the monitoring programme began in 1980, and a sample of about 100 brightest northern compact sources have been monitored on a monthly basis. In addition, various source samples are studied either on a weekly basis or on longer timescales of months.

At the shorter mm- to submm-wavelengths, the current situation is not as good. The Metsähovi AGN group used the Swedish-ESO Submillimetre Telescope (SEST) located in Chile, for monitoring of AGN at 90 and 230 GHz from 1986 until 2003 (Tornikoski et al. 1996) when the telescope was shut down. Other monitoring programmes at the submm-wavelengths have been conducted with the Institut de Radioastronomie Millimétrique (IRAM) 30-metre telescope located at Pico Veleta, Spain (Steppe et al. 1988, 1992, 1993; Reuter et al. 1997). Unfortunately they have not published any monitoring data since 1997. A set of AGN has also been monitored at the James Clerk Maxwell Telescope (JCMT), at six wavelength bands between 2 to 0.35 mm (Stevens et al. 1994; Robson et al. 2001). However, the datasets are shorter, only of the order of a few years, and they have not been published lately.

An example of well-sampled flux curves can be seen in Fig. 4.1, which shows ten years of observations of the blazar 3C 279 from cm- to optical wavelengths (Lindfors et al. 2006). This source is one of the best monitored AGN, and the flux curves at all wavelengths are very well sampled. Such dense monitoring enables detailed studies of the structure of the flux curves at various frequency bands. Fig. 4.1 also shows a model curve, which tries to explain the variations based on the shock model by Marscher & Gear (1985). Especially at the lower radio frequencies, the curve closely follows the datapoints.

Unfortunately such densely sampled flux curves at every frequency band are extremely rare. Usually the monitoring is much sparser especially at the higher frequencies.

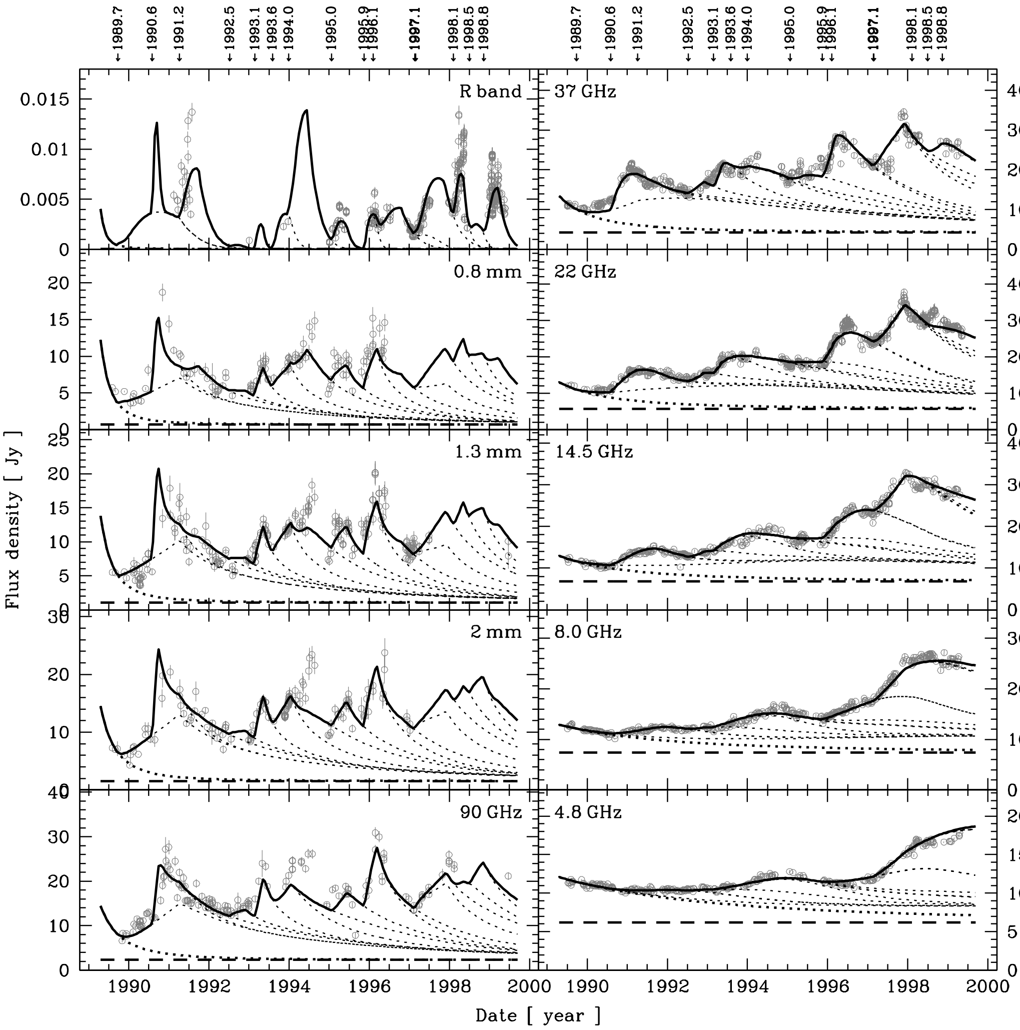

Figure 4.1: Flux curves of the blazar 3C 279 from the optical to radio frequencies. A shock-model fit is also shown. (Figure is from Lindfors et al. 2006)

An example is shown in Fig. 4.2, where the flux curves of the radio galaxy 0007+106 at 37 and 90 GHz are plotted. The 37 GHz data are from the Metsähovi monitoring project (Salonen et al. 1987; Teräsranta et al. 1992, 1998, 2004, 2005), including unpublished data from 2001 to the end of 2006. The 90 GHz data are from the SEST (Tornikoski et al. 1996, and unpublished data). At 37 GHz the source is quite densely monitored but as can be seen, there are not many datapoints at 90 GHz. It is easy to see that there have been flares at 90 GHz (e.g. around 1997), but due to the lack of data, the structure, or even the true peaks, cannot be determined.

Densely sampled flux curves at various frequency bands enable studies of the long-term variability of AGN. As can be seen from the example figures, the AGN flux curves form timeseries which are usually unevenly sampled and may contain large gaps. This

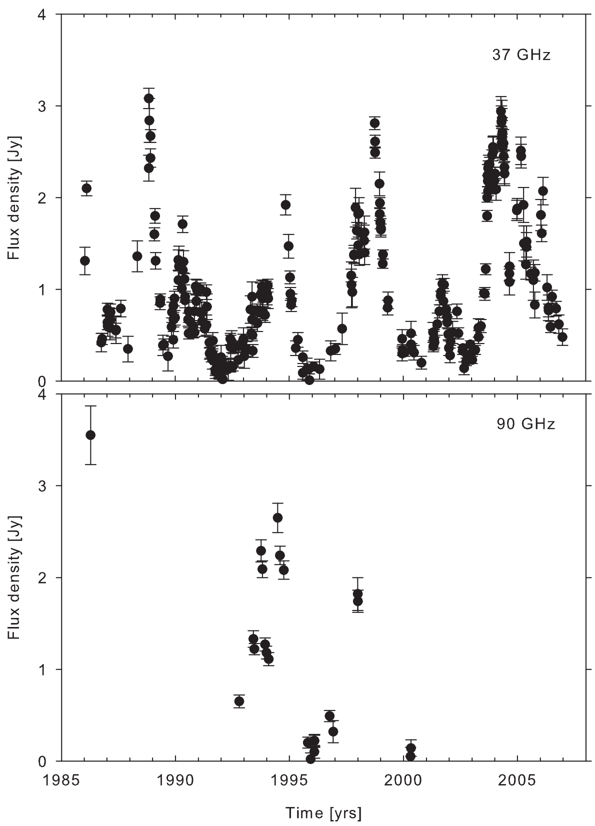

Figure 4.2: Flux curves of the radio galaxy 0007+106 at 37 and 90 GHz. The 37 GHz data are from the Metsähovi monitoring programme and the 90 GHz data are from our monitoring programme at the SEST.

constrains the methods we can use to study the flux curves. There are methods developed for unevenly sampled data, and in this thesis the performance of various statistical methods has been studied when the characteristic timescales of AGN are considered (Paper I; Paper III).

It can be tricky to choose the right method to use with different types of data. The length of the dataseries is one crucial parameter in choosing the right method, as is also the sampling density. It also has to be kept in mind that statistical methods are restricted by the data. For example, if the average sampling density is 2 weeks, it is not possible to reliably detect any timescales of less than 2 weeks in the data. This should be clear using just common sense but unfortunately it is often forgotten by scientists trying to analyse sparse data. Often it is also ignored that studying only a few years of observations does not necessarily reveal the complete variability behaviour of the sources, and as is shown in Paper I and Paper III, even 10 years can be too short a monitoring time for some sources.

Often statistical methods are used for studying periodicities in the flux curves of AGN.

In many cases, however, insufficient amount of data is used. The periods obtained are relatively long compared to the total length of the timeseries, and therefore have not repeated sufficiently many times. Kidger et al. (1992) suggest that the monitoring time should be at least six times the length of the period in order to even consider it as a periodicity. Even in such a case, the behaviour of the source can later change and alter or destroy the period.

Large individual outbursts also affect the results from the statistical methods. Periods are more easily detected between stronger outbursts, and the methods may overlook smaller variations. In multifrequency analysis, in which the timescales of individual sources at many frequency bands are studied, it can also happen that a certain flare is missing from one frequency band, changing the timescale compared to others. All these restrictions should be taken into account when the timescales or periodicities are studied, and results from the statistical methods should not be blindly accepted but verified with other methods and by visual inspection of the flux curves.

4.2 Timeseries analysis methods

Fourier-based methods, such as the Lomb-Scargle periodogram (Lomb 1976; Scargle 1982), are commonly used in studying timescales and possible periodicities in the flux curves of AGN. The Lomb-Scargle periodogram is specially developed for unevenly sampled timeseries. The most severe restriction in using this method is that it is developed to search for sinusoidal periods in the flux curves. As the example flux curves in Figs. 4.1 and 4.2 show, the flux curves do not resemble sinusoidal behaviour. Also, the sources are almost never strictly periodic so that the methods always give more than one timescale. Harmonics of these timescales also complicate the analyses.

Other commonly used methods are the Discrete Correlation Function (DCF) (Edelson & Krolik 1988; Hufnagel & Bregman 1992) and the structure function (SF) (Simonetti et al. 1985). They are directly related to each other, the SF giving usually about half of the DCF timescale. This is because the SF searches for timescales with a maximal difference, for example times between flare peaks and minima, i.e. the rise and decay times of flares. DCF, on the other hand, is usually used to study maximum correlations so that it gives timescales of phenomena that are similar in flux scale, usually detecting flare peaks or minima between the flares, and therefore giving a timescale between the flares.

The Lomb-Scargle periodogram and the DCF were used in Paper I to study the characteristic variability timescales. It was seen that multiple timescales were common, and none of the sources were strictly periodic. The methods could, however, distinguish the typical characteristic timescales from the flux curves, and they usually corresponded to peak to peak intervals between the flares. This way we were able to determine how often the sources typically are in a flaring state. The timescales of individual sources were studied in more detail in Paper V with a subsample of BL Lacertae objects. These results showed that the methods also give different variability timescales for the same sources, and may pick different variations as the most significant ones in the flux curves. In most cases, however, both methods gave the same timescale if less significant timescales were also considered.

The SF was also used in Paper I to study the characteristic variability timescales. We found that the SF is good in representing the rise and decay times of flares in most cases. In addition to giving the timescales, the SF enables studies of the noise processes behind the variations. In most cases the AGN flux curves can be characterised with a shot noise process but in some cases white noise may be dominant. In the case of the shot noise, we are seeing a process which is slowly responding to white-noise impulses. In the shock-in-jet scenario, this would indicate that the shocks are caused by random disturbances rather than some cyclic mechanism (Hughes et al. 1992). Occasionally the interpretation of the SF curve can be difficult, and it is not as straightforward as in the DCF and periodogram, in which clear peaks or spikes are produced at characteristic timescales.

There are two main reasons why the above-mentioned methods are not the best tools for studying the timescales in AGN. First of all, they are global methods, which means that the flux curve is treated as a single entity. Even though they are developed for unevenly sampled data, large gaps substantially affect the analyses. Similarly, few outlier points can change the result of the analysis. Secondly, in the Lomb-Scargle periodogram, a sinusoidal function is fitted to the flux curves, and if the curves are not well represented by sinusoids, as is the case for AGN, spurious timescales can be easily produced.

These disadvantages can be overcome with wavelet analysis. This method has not been used as much for studying the timeseries of AGN, and it has been used in astronomy for only about ten years (e.g. Foster 1996; Priestley 1997; Scargle 1997). The main advantage of the wavelet method is that it is a local method. This means that the flux curve is treated separately for all time epochs, and gaps or outlier datapoints do not affect the analysis as much as in the global methods. Because of the locality, it is possible to study the timescales both in the time and in the frequency domain. We can see when the timescale is visible in the flux curve, in addition to seeing its frequency. Another good property of wavelets is that it is possible to choose the waveform used in the analysis. The most commonly used waveform for AGN flux curves is the Morlet wavelet, which can be thought of as a localised plane wave tapered with a Gaussian function. This way the analyses do not suffer from non-sinusoidal flux curves.

We used the wavelet method to study the timescales of AGN in Paper III. The analyses showed that the timescales are often only transient phenomena in the flux curves, and long-lasting timescales are rare. In many cases the timescales either weakened in power or totally disappeared over long periods of time. The variability behaviour of objects changed and none of the sources were strictly periodic. The accuracy of determining a timescale with the wavelet analysis is less than in Fourier-based methods but when the sources are not strictly periodic or characterised by sinusoidals, wavelets are better as they indicate the moment at which the timescale is present.

Figures 4.3 and 4.4 show the analyses with these different methods for the blazar 4C 29.45 (1156+295). In panel *a* of Fig. 4.3, the flux curve is shown. The DCF in panel *b* gives a timescale of 3.49 years which is only 0.2 years longer than the Lomb-Scargle periodogram timescale of 3.29 years. Indeed, there are flares visible in the flux curves, with about 3 years in between them. The structure function in panel *d* settles on a plateau at a timescale of 1.21 years. This timescale is also seen in the flux curve as the rise and decay times of the flares. Therefore we can conclude that the Fourier-based methods can

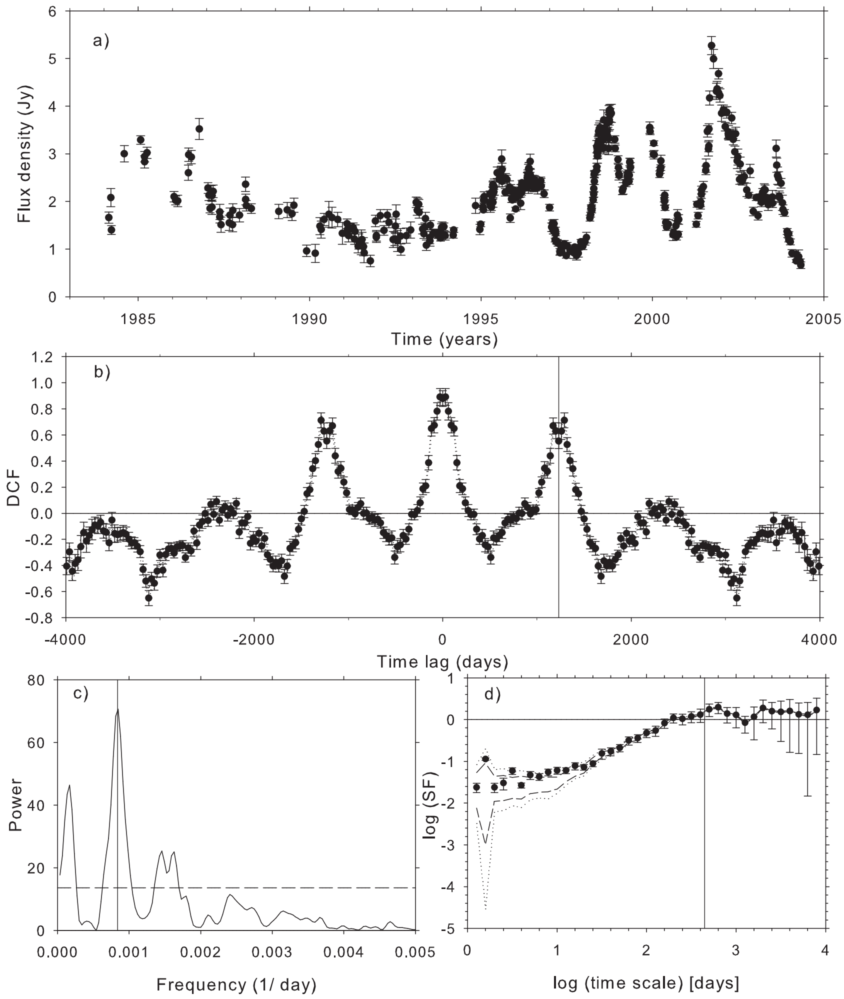

Figure 4.3: SF, DCF and Lomb-Scargle periodogram analyses of the blazar 4C 29.45 at 22 GHz. a) flux curve b) DCF c) Lomb-Scargle periodogram d) SF (Figure is from Paper I).

find the characteristic variability timescales for a source. However, if the wavelet analysis in Fig. 4.4 is studied, it is evident that the timescale of 3.4 years (log($10^{0.53}$) years) is only visible in the latter half of the flux curve, starting around 1995. Based on the wavelet analysis, it is clear that the source is not periodic at a 3.4 year timescale, but this represents its characteristic timescale of variability. It can also be seen that the source has changed its behaviour in the mid-1990s.

All these statistical methods require long-term observations. Our requirement was to have at least 10 years of data for every source. Of course it is possible to use the methods also for shorter datasets, but in those cases only short term variability can be studied. Another way to study the sources is to visually examine the flux curves. This method is

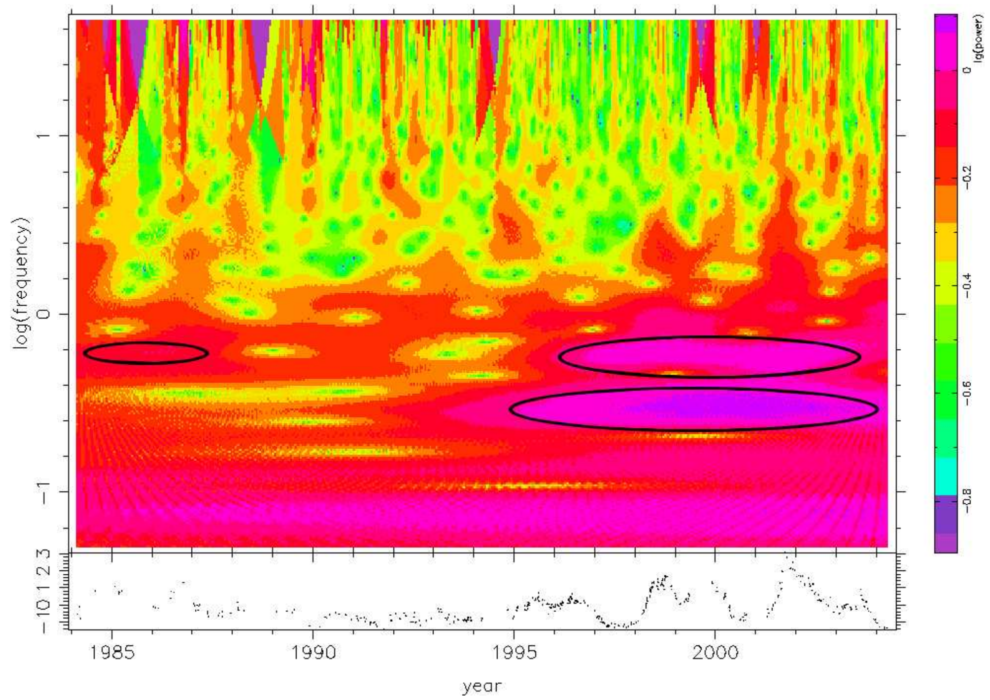

Figure 4.4: Wavelet transform of the source 1156+295 at 22 GHz. The y-axis is frequency 1/year so that a timescale of 1 year corresponds to frequency 0 and a timescale of 10 years corresponds to frequency −1 in the log-axis. A long-term variability timescale of 3.4 years ($10^{0.53}$ years) is visible in the latter half of the flux curve starting at 1995. A flare timescale of 1.7 years ($10^{0.23}$ years) is also seen.(Figure is from Paper III)

very subjective and various people can obtain different results. We have used this sort of approach to study the flare behaviour of the sources (Paper II; Paper V). The flux curves are divided into individual flares, and parameters such as the rise time, peak flux and duration of the flare are calculated. This way long-term data are not as crucial but dense sampling is still needed. As is seen in the lower panel of Fig. 4.2, gaps in the data make it impossible to determine the peak times or starting times of flares accurately.

In Paper IV we used a more sophisticated method and tried to model the flux curves with exponential functions (Valtaoja et al. 1999; Lähteenmäki & Valtaoja 1999). The idea was to model the flux curve with as small a number of superposed exponential flares as possible. This can tell us more details about the individual shock components as is explained in Chapt. 2. In this method, gaps in the data do not cause as much problems as in the visual examination because the exponential components fit the data even if there are gaps. Naturally, the results are more reliable when there is a sufficient number of observations. Even though the method basically only needs one well-defined flare for each source, long-term observations are crucial if we want to be sure that the one flare represents a good example of the source behaviour.

4.3 Long-term timescale analyses

By studying the timescales, it is possible to gain an understanding of how often the AGN are in a flaring state and how long the flares typically last. It is interesting to discover differences between the source classes and also between the various frequency bands. We can relate the timescales between the flares to physical properties of the jets, for example, by interpreting them as time intervals between the shocks in the jet. Most of the bright AGN show almost constant variability at least in small scales but in the long-term analyses, usually the large-scale variations, such as the strong outbursts, are studied.

In the radio regime, the first long-term timescale studies were made by Hughes et al. (1992) using the UMRAO cm-wavelength data and by Lainela & Valtaoja (1993) using the Metsähovi data at 22 and 37 GHz. Both groups used the SF to study characteristic variability timescales. Hughes et al. (1992) used data from over 25 years of observations and Lainela & Valtaoja (1993) used 12-year-long datasets. In both studies the aim was to find typical timescales of a larger sample of sources, and also to study the physical processes behind the variations. The results were similar, and typical timescales were of the order of 2 to 3 years. The variations could be described with a shot noise process in most of the cases. Lainela & Valtaoja (1993) concluded that the centimetre and millimetre variations of these AGN originate from the same location in the jet. They also found indications that HPQs and LPQs differ from each other with LPQs having longer timescales. Updated analyses of both databases were conducted in Paper I, where we found that the timescales are now slightly shorter at 22 and 37 GHz, and we could not find any differences between the source classes. We also found that at lower frequencies the timescales are slightly longer than at higher frequencies, which is consistent with the basic shock models. In addition, we noticed that some of the sources had changed their variability behaviour completely in the new analyses, showing that even 12 years of monitoring can be too short for understanding the true variability behaviour of some sources.

The UMRAO database has also been used for a wavelet analysis by Kelly et al. (2003). They studied 30 sources in the Pearson-Readhead VLBI survey sample, finding quasi-periodic behaviour in a little over half of the sources they studied. The median timescale they found was 2.4 years. About half of the sources showing quasi-periodicity also repeated this in at least one other frequency band. In Paper III the wavelet method was used for the first time at higher radio frequencies to study the timescales in a large sample of AGN. We conducted wavelet analysis for a sample of 80 sources which had been monitored for at least 10 years at Metsähovi. The average timescale at 37 GHz is 4.4 years, which is longer than the median found by Kelly et al. (2003) at the lower frequency bands. This is mainly because in our analysis we determined two types of timescales, a long-term trend and a flare timescale, which describes the typical flare timescales, for example, the duration of flares in a source. We had nine sources in common with Kelly et al. (2003), and in nearly all the cases we could find a corresponding timescale, but it was the flare timescale rather than the long-term trend. We also found that 63% of the sources in our sample showed indications of quasi-periodicity at one frequency band, with a long-term timescale that had repeated at least twice during the time it was present. However, only eight sources in the sample showed a timescale repeating at least four cycles in two frequency bands, and none of these was strictly periodic.

The general total flux density and linear polarisation variability properties of AGN have also been studied for larger samples of sources at radio frequencies. The radio variability of the Pearson-Readhead VLBI survey sample was studied by Aller et al. (1992) by using the long datasets of UMRAO, and the results were updated by Aller et al. (2003). The same database was used in Aller et al. (1999) to study a complete sample of BLOs. In Aller et al. (1992) and Aller et al. (2003) variability indices and spectral indices between 4.8 and 14.5 GHz were calculated. The BLOs of their sample were all flat-spectrum sources while some quasars had a steep spectrum between those frequency bands. Aller et al. (2003) also noted that some sources, which showed no variability in Aller et al. (1992), were found variable due to the monitoring period which was twice as long. In Aller et al. (2003) also the Lomb-Scargle periodogram was used to study if the sources exhibited periodicity, but strong evidence of periodicity was not found for any of the sources.

In Aller et al. (1999) a complete flux limited sample of BLOs was studied using the SF and by calculating the variability indices. They found that the SF for BLOs were more difficult to determine compared to the sample of Hughes et al. (1992), which also included quasars. The BLOs were seen to be more variable than quasars. The differences were explained with different polarisation properties and magnetic field alignments in the jets of BLOs and quasars. The changes in the polarised flux and the position angle are more common in BLOs than in quasars. In Paper II the variability indices were calculated for a sample of 55 sources at six frequency bands between 4.8 and 230 GHz. The results confirmed that at least the BLOs in this sample are more variable than quasars. In Aller et al. (1999) the jets of BLOs were also thought to be slower than in quasars (this was confirmed in Paper IV), and therefore instabilities can be produced more easily in the jets of BLOs (Hughes et al. 2002).

A large sample of 112 sources observed at Metsähovi was studied by Wiren et al. (1992). They used only two-epoch observations, obtained in 1988 and 1989 to study the variability and spectral index at 22 and 37 GHz. They did not find significant differences between the source classes. Considering the limited number of observations, and the short time in which they were obtained, this is not surprising. Our current knowledge of these AGN shows that more data are needed to understand their true behaviour.

Long-term Metsähovi data has also been studied by Lainela (1994) who continued the work of Valtaoja et al. (1988) and Valtaoja et al. (1992) by comparing the observed flare properties to the generalised shock model. Lainela (1994) also used the UMRAO data in the analyses, and concluded that most of the flares can be explained with the shock model of Marscher & Gear (1985). In Paper III we used updated databases, which had almost twice as long flux curves, also high frequency 90 and 230 GHz data, and more sources. Instead of using just the overall minimum and maximum fluxes of each source, as was done in Valtaoja et al. (1992), we divided the flux curves into individual flares. In Lainela (1994) similar approach was also used, but they could determine the flare spectrum in 28 cases in 16 sources, while we have used 159 flares of 55 sources. The results we obtained are almost identical to the previous studies, which confirms that the shock model can in general explain the variations of AGN at radio frequencies.

Many individual sources and smaller samples have also been studied using the extensive UMRAO and Metsähovi databases. For example, Raiteri et al. (2001) studied the radio and optical variability of the BLO 0235+164, and found a possible periodicity of 5–6 years in the flux curves by using the DCF. Even though they used more than 20 years of data, the period disappeared when the source had been monitored for a longer time (Raiteri et al. 2006).

Ciaramella et al. (2004) used the Metsähovi and UMRAO databases to search for periodicities in the sample sources. Out of the 77 sources which had sufficiently data between 1980 and 2001, only five sources showed indications of periodicity. They used the Lomb-Scargle periodogram and the autocorrelation matrix in their analyses. Three of the periods were also seen in the UMRAO data. Visual examination of the flux curves does not show the periods clearly and more data should be used when periodicities in the radio frequencies are suggested. In addition, they calculated the variability indices and structure functions for a sample of 39 sources in the UMRAO database, out of which 25 sources have also been monitored in Metsähovi. The analysis of this relatively small sample indicates that BLOs have higher variability indices than quasars, and that the variability is larger at higher frequency bands. In Paper III we calculated the variability indices for 55 sources and obtained similar results. The BLOs seemed to be more variable than the quasars. However, the differences between the frequency bands were not as clear and only at 4.8 GHz the variability indices were significantly smaller than at other frequency bands. The reason for this is that at the lower frequency bands, the synchrotron self-absorption starts to affect and flares are observed later. The flux density is lower, and it is more difficult to distinguish individual flares from each other.

Pyatunina et al. (2006, 2007) used a slightly different approach by dividing the flux curves of seven sources, monitored at UMRAO and Metsähovi, into Gaussian flares. They studied the frequency dependence of the flares, and tried to divide them into core or jet flares based on the time delays between the frequency bands. Using the Gaussian flares, they estimated activity cycles for the sources. These were quite long for all the sources, of the order of 10 to 14 years, considering the relatively short monitoring period of 25 years for most of the sources. Our timeseries analyses in Papers I and III also confirmed the existence of such a long timescales but the median was only 4.4 years at 37 GHz. Therefore, due to the much larger sample used in our analyses (80 sources), it is more likely that the typical activity cycles or timescales of AGN are slightly shorter than those obtained for the seven sources.

Shorter mm-wavelength variability at 90 and 230 GHz has been studied by Tornikoski et al. (1993, 2000), by using the data obtained at the SEST telescope. In Tornikoski et al. (2000) the variability indices for 45 southern sources were calculated, and their spectral shapes over the 2.3 to 230 GHz range were studied. They noticed that the variability indices are larger for sources with more observations. Therefore, as the number of datapoints at 90 and 230 GHz for these sources is relatively small compared to Paper III, the variability indices are also smaller.

All the above-mentioned analyses show that long-term monitoring is essential for understanding the true variability behaviour of these sources. Monitoring programmes of as long as 25 years are still not long enough to reliably determine periodicities in the radio flux curves. We can, however, study the characteristic variability timescales, and try to better understand the origin of the emission in the various source types and frequency bands. Currently there is only one source, the BL Lac object OJ 287, which shows strong evidence for an optical periodicity of about 12 years (e.g. Sillanpää et al. 1988; Lehto & Valtonen 1996; Valtaoja et al. 2000; Valtonen et al. 2008). This source has a historical optical light curve which is over 100 years long, and therefore claims of periodicity are justified. In addition, it is the only source for which a detailed physical model for explaining the periodicity has been made (Lehto & Valtonen 1996).

In Paper III we made "predictions" which sources in our sample would possibly be in an active state during the early operations of the Fermi Gamma-ray Space Telescope in 2008–2009, by using the results of the wavelet analysis and combining them with results of Paper I, and visually examining the flux curves until the end of 2007. The analysis was performed in the beginning of 2008, and we came up with six possible sources. Out of these six sources, one (1749+096) is in a flaring state and three others (0007+106, 0333+321 and 1156+295) show a rising trend in the flux curves at the time of writing this thesis (November 2008). This shows that even though the sources are not strictly periodic, we can at least estimate when the sources could be flaring, by using the timescales obtained with the various methods. It must be noted, however, that most of the sources studied in this sample show some variability almost continuously and are never in a truly quiescent state. In our analyses, we have concentrated on the large scale activity and flares.

5 Summary of the papers

5.1 Timeseries analysis methods

Paper I: *Statistical analyses of long-term variability of AGN at high radio frequencies*
by **Hovatta, T.**, Tornikoski, M., Lainela, M., Lehto, H. J., Valtaoja, E., Torniainen, I., Aller, M. F., Aller, H. D.
Paper III: *Wavelet analysis of a large sample of AGN at high radio frequencies*
by **Hovatta, T.**, Lehto, H. J., Tornikoski, M.

All the papers in this thesis used the long-term data obtained at Metsähovi Radio Observatory and the University of Michigan Radio Astronomy Observatory. In Paper I and Paper III several statistical methods, which are designed to find characteristic timescales or periodicities in timeseries, were used. We tested the methods, and their differences and properties, by using the datasets spanning over 25 years.

In Paper I we applied the commonly used methods, the Discrete Correlation Function (DCF) and Lomb-Scargle periodogram, to search for characteristic variability timescales in a sample of 80 AGN at frequency bands of 4.8, 8, 14.5, 22, 37, 90 and 230 GHz. The DCF searches for maximum correlation between events in the flux curves. Autocorrelation gives the time between the flare peaks or minima. The periodogram analysis in principle fits a sinusoidal function to the flux curve, and possible periods are seen as spikes in the frequency domain. Using these methods, we found that flares in these sources typically occur every 4 to 6 years and that multiple timescales are common. None of the sources showed strict periodicities and often the periodogram produced spurious spikes. In addition, harmonics were often visible in the periodogram.

We also used the Structure Function (SF) in Paper I. It was earlier used by Lainela & Valtaoja (1993), and one of our aims was to study if the timescales had changed during the 10 subsequent years of monitoring. The SF was interpreted in a way which gives the timescale of maximal difference, for example, the rise and decay times of flares. In addition to giving the timescale, the SF can also be used to study the noise processes behind the variations. We found that the variations in AGN can mostly be characterised with a shot noise process, which in the view of a shock-in-jet model indicates that shocks are caused by random disturbances, rather than some cyclic phenomenon (Hughes et al. 1992).

The typical rise and decay times of flares are of the order of one to two years. In many sources the timescales had changed during the 10 more years of monitoring, and some sources had completely changed their behaviour. Similar conclusions could be drawn in Paper III, in which the timescales were studied using the wavelet transform. This was the first time wavelets were used to study timescales in a large sample of sources at the high radio frequencies of 22, 37 and 90 GHz. The main difference between the SF, DCF, periodogram and wavelet methods is that wavelets can be considered as local methods and the others as global. This means that, in addition to finding a timescale characterising the whole dataseries, also time information is used in the analyses. This way we can identify the moments at which the timescale has been present in the flux curve, and if it is continuous over the whole timeseries or just a transient phenomenon.

Our analyses in Paper III showed that only a handful of the 80 sources exhibit long-lasting timescales over the total monitoring period. We could confirm the average flaring timescale of 4 to 6 years also using the wavelets, but in addition, we found that peaks in the periodogram analysis or correlations in the DCF do not represent a long-lasting timescale in most of the cases.

These results show that long-term monitoring is essential in understanding the true behaviour of AGN. Suggestions of periodicities in these sources, especially at the radio frequencies, should be taken with caution because monitoring periods of as long as 25 years are sometimes inadequate in describing the complete variability range of some sources. In the study of characteristic timescales, wavelet analysis is superior compared to traditional Fourier-based methods, as it also shows when and for how long a timescale is present in the timeseries.

5.2 Flare characteristics

Paper II: *Long-term radio variability of AGN: flare characteristics*
by **Hovatta, T.**, Nieppola, E., Tornikoski, M., Valtaoja, E., Aller, M. F., Aller, H. D.
Paper V: *Long-term variability of radio-bright BL Lacertae objects*
by Nieppola, E., **Hovatta, T.**, Tornikoski, M., Valtaoja, E., Aller, M. F., Aller, H. D.

In Paper II and Paper V we studied the radio flare characteristics using the long-term data from Metsähovi and UMRAO. In Paper II we used a sample of 55 sources, and by visual examination divided the flux curves into individual flares. The criterium for selecting a flare for further analysis was that it had to be well-sampled at 22 and 37 GHz, or at 90 and 230 GHz for the southern sources which were observed during our monitoring project at the SEST. Complementary low frequency data from UMRAO and high frequency data from the SEST and the literature were also used.

For each flare, we determined its start, peak, and end epoch, and calculated absolute and relative peak fluxes. Using the different epochs we calculated the rise and decay times, and the duration of the flares at the various frequency bands. We found that flares in the radio regime are relatively long, on average 2.5 years at 22 and 37 GHz. When this is combined with the average interval between the flares, which is 4 years at 37 GHz (Paper I; Paper III), the need for long-term monitoring becomes evident.

In addition, we compared the observed properties to a theoretical model, the generalised shock model (Valtaoja et al. 1992), which is used for explaining the variations in AGN. We found that, on average, the flares follow the predictions of the shock model well, but there is large scatter in the values, mainly due to the poor sampling of the highest frequencies.

In Paper V a smaller subsample, consisting only of BLOs, was studied in a similar manner. Analyses of Paper I and Paper II were combined, and individual sources were studied in more detail. Comparison of the statistical timescales to timescales calculated directly from the flares revealed that these correlate very well, which gives credibility to the statistical methods. However, the scatter was large, and it was noted that when studying individual sources, it is better to use more than one method to verify the timescales obtained. The differences between the basic flare properties of BLOs and quasars were not substantial, although it was seen that all the BLOs in our sample had flare peaks reaching only 10 Jy at maximum, while some quasars were seen to exhibit large flares of tens of Jys.

5.3 Jet parameters

Paper IV: *Doppler factors, Lorentz factors and viewing angles for quasars, BL Lacertae objects and radio galaxies*
by **Hovatta, T.**, Valtaoja, E., Tornikoski, M., Lähteenmäki, A.

Various jet parameters for a sample of 87 AGN were determined in Paper IV, using the total flux density observations at 22 and 37 GHz. Following Lähteenmäki & Valtaoja (1999), we decomposed the flux curves into exponential flares, from which we determined the observed brightness temperature for each source. By assuming an intrinsic brightness temperature corresponding to the equipartition temperature (Readhead 1994; Lähteenmäki et al. 1999), we calculated the Doppler boosting factors. For 67 sources we also received apparent jet speed data from the MOJAVE project (Lister et al. in preparation), and were able to calculate the Lorentz factors and viewing angles.

Our analysis showed that quasars have larger Doppler boosting factors and faster jets than BLOs. Our sample consisted mainly of blazar-type objects, and as expected, almost all were seen at a viewing angle of less than 20 degrees. Even though many of the sources were seen close to the critical angle, defined as an inverse of the Lorentz factor, there were many sources seen at both smaller and at larger angles. Therefore the commonly used assumption of all blazars being seen close to the critical angle does not hold for all sources.

When comparing our results to the earlier study by Lähteenmäki & Valtaoja (1999), we found that the Doppler boosting factors have remained almost the same, even though we now had ten more years of observations. The Lorentz factors, however, had changed, and were about twice as large as in Lähteenmäki & Valtaoja (1999). This could mainly be explained by the twice as high apparent speeds in our new analysis. The new apparent speed values and Doppler factors should be more accurate because we have more data, and therefore also the new Lorentz factors should be more reliable.

In addition, we found indications that at least in our sample of blazar-type objects, the high- and low-polarisation quasars should be treated as a single group of flat spectrum radio quasars because the differences between the groups were modest. We also found indications that the observed optical polarisation may depend on the viewing angle, at least in BLOs and HPQs.

6 Conclusions

This thesis includes long-term radio variability studies of large samples of AGN using various methods. All the papers use monitoring data at 22 and 37 GHz obtained at Metsähovi Radio Observatory. In many papers also lower frequency data from the University of Michigan Radio Astronomy Observatory, and higher frequency data from the Swedish-ESO Submillimetre Telescope are used. In all the papers the 22 and 37 GHz data of over 25 years is used for the first time to study large samples. Previous studies have either contained shorter datasets or used smaller source samples.

Two of the papers concentrate on statistical methods which are used to find characteristic timescales in the sources. In Paper I, commonly used Fourier-based methods are utilised, and in Paper III a much less frequently used wavelet method is applied. When the different methods are compared, it is seen that even though the Fourier-based methods can be used to search for variability timescales, the wavelet method is superior due to its local nature. In addition to finding the timescales, it also shows the time intervals at which the timescale occurs in the flux curve and if it is a long-lasting phenomenon or just a transient one. These two papers are the first ones to investigate in detail the differences between the various statistical methods using a large sample of sources and long datasets. Also, in Paper III the wavelet method is used for the first time to study the timescales at high radio frequencies.

We find that the average time interval between large flares is four to six years in these sources. The rise and decay times are on average one to two years. The variability behaviour of AGN is complex and multiple timescales are commonly seen in the flux curves. Only a small number of sources showed persistent timescales lasting over the total monitoring period. Also in these sources, it was difficult to find clear periods and outbursts occurring only on a certain interval. Most of the earlier studies suggesting a periodicity at radio frequencies are based on inadequate amounts of data and should be treated with caution.

Flare characteristics of the various source types were studied in Paper II, and of the BLOs in Paper V, by visually dividing the flux curves into individual outbursts. This was the first time when such analyses has been done for a large sample of sources. Again the diversity between the individual sources was large, for example, the duration of individual flares varied from a few months to over 10 years. The median duration of flares was 2.5 years at 37 GHz, which is quite long, considering the typical duration of a multifrequency campaign, which may last from a few days to a few weeks. It is clear that during such a short period, no conclusions about the complete behaviour of a source can be drawn.

The correspondence between the statistically determined timescales and ones obtained directly from individual flares, is quite good according to the study of BLOs in Paper V. The various methods may, however, find different timescales as the most significant ones, and therefore more than one method should be used when studying the timescales of individual sources.

The long-term data were used to calculate various jet parameters in Paper IV. We obtained Doppler boosting factors, Lorentz factors and viewing angles for a large sample of various types of AGN. We found that quasars are more Doppler boosted and have faster jets than BLOs and radio galaxies. Our findings support the basic view of the AGN unification scheme. We also found that the method we use for calculating the Doppler boosting factors is reliable, as our values correlate well with other studies that use different methods to determine the Doppler factor (Jorstad et al. 2005; Britzen et al. 2008), and because they have remained almost identical compared to a previous study by Lähteenmäki & Valtaoja (1999) which was made using shorter datasets.

The main outcome of this thesis is a better understanding of the long-term radio behaviour of AGN and the methods which are used to study the variability. This will especially benefit the Planck satellite mission, which will map the small-scale variations in the CMB. Understanding the behaviour of the foreground sources, for example AGN, is crucial for detailed studies of the CMB. In addition, we now have a large number of parameters we can correlate with each other and other relevant parameters characterising AGN. Interesting results were already obtained by Nieppola et al. (2008) who defined the spectral energy distributions of the synchrotron component for a large sample of AGN, and corrected the peak values with the Doppler boosting factors obtained in Paper IV.

In the future we are going to examine correlations between our jet parameters, variability timescales, and intrinsic parameters, such as the black hole mass and accretion rate. We may expect correlations between the black hole mass and, for example, the speed of the jet. In addition, we can consider the times between flares as times between shocks in a jet, and correlate that value with the jet speed. This correlation was already studied in Paper I, by using older estimates of Lorentz factors. We are planning to redo the calculations with our new, more accurate, estimates. Thus, the various observed and intrinsic parameters we have obtained in this thesis form a basis for future studies in understanding the physical properties of AGN.

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