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MULTIFREQUENCY STUDIES OF GIGAHERTZ-PEAKED SPECTRUM SOURCES AND CANDIDATES

Thesis for the degree of Doctor of Science in Technology

Ilona Torniainen

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Abstract

Gigahertz-peaked spectrum (GPS) sources are compact radio sources located in centres of distant active galaxies. The shape of the radio continuum spectrum of GPS sources is convex, the flux density increases towards high frequencies and decreases above a turnover at gigahertz-frequencies. Whereas the majority of extragalactic radio sources extend well outside of their host galaxies, these compact sources reside only in the central regions of their host. For this reason studying GPS sources can provide us with information on the structure and the properties of active galactic nuclei.

In this thesis, the radio spectra and the total flux density variability of GPS sources are studied. We have collected an extensive database of radio observations of GPS sources and candidates from the monitoring programmes of Metsähovi Radio Observatory and University of Michigan Radio Astronomy Observatory, and from the literature. We have also made new observations of the sources. In the literature, the GPS classification is often done using few non-simultaneous data points presuming that the sources are not variable. Our results show that this approach has produced samples that are heavily contaminated by misclassified sources. Among the quasar-type GPS sources classified in the literature, there is only a small fraction of genuine GPS sources as highly variable sources with temporary GPS features in their radio spectrum have been misclassified as GPS sources. The fraction of genuine GPS galaxies was found to be larger but the contamination was significant also in galaxy-type samples. In addition, the genuine GPS sources were found to be variable contrary to earlier conception.

Cluster analyses of GPS sources presented in this thesis also support the view of heterogeneous GPS samples. The blazar-type sources with temporarily gigahertz-peaked spectra clearly stood out as their own cluster, and the sources with confirmed GPS-type spectra formed several different clusters. This result supports the view that there are different types of genuine GPS sources.

Keywords Radio astronomy, radio continuum spectrum, active galactic nuclei, extragalactic radio sources

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Tiivistelmä

Joidenkin etäisten aktiivisten galaksien ytimissä on radiosäteilyä lähettäviä kohteita, joiden spektrihuippu osuu gigahertsitaajuuksille. Tällaisia lähteitä kutsutaan gigahertsitaajuuksilla taittuvan spektrin lähteiksi eli GPS-lähteiksi. Suurin osa ekstragalaktisista radiolähteistä ulottuu kauas keskusgalaksin ulkopuolelle, mutta GPS-lähteet yltävät vain galaksinsa sisäosiin. Tämän vuoksi niitä tutkimalla voidaan saada tietoa aktiivisten galaksinytimien rakenteesta ja ominaisuuksista.

Tässä väitöskirjassa on tutkittu GPS-lähteiden vuontiheyden muuttuvuutta ja kontinuumispektrin muotoa radioalueella. Työtä varten kerättiin laaja tietokanta GPS-lähteiden radiodataa Metsähovin radiotutkimusaseman ja Michiganin yliopiston radioastronomisen observatorion havainto-ohjelmista, kirjallisuudesta sekä tekemällä uusia havaintoja. Kirjallisuudessa esitellyt GPS-lähteet on oletettu muuttumattomiksi ja luokiteltu usein vain muutaman eriaikaisen havaintopisteen perusteella. Tutkimuksemme osoittavat tällaisen menettelytavan tuottaneen virheellisiä otoksia. Kirjallisuudessa esiteltyjen kvasaarityyppisten GPS-lähteiden otoksissa suurin osa kohteista on erittäin muuttuvia lähteitä, joiden spektri on GPS-spektrin kaltainen vain ajoittain, ja vain pieni osa on aitoja GPS-lähteitä. Galaksityyppisissä otoksissa aitojen GPS-lähteiden osuus oli suurempi, mutta väärin luokiteltujen kohteiden määrä oli silti huomattava. Vastoin aiempaa käsitystä vuontiheysvaihtelut osoittautuivat yleisiksi aidoillakin GPS-lähteillä.

Tässä väitöskirjassa esitelty GPS-lähteiden klusterianalyysi tuki aiempia tuloksiamme GPS-otosten sekalaatuisuudesta. Voimakkaasti muuttuvat, vain ajoittain GPS-spektrin omaavat blasaarit erottuivat selkeästi omaksi ryppääkseen. Aidot GPS-lähteet jakautuivat useiksi toisistaan poikkeaviksi ryppäiksi, mikä tukee näkemystä, että aidotkaan GPS-lähteet eivät ole homogeeninen ryhmänsä vaan muodostavat erilaisia lähdepopulaatioita.

Asiasanat Radioastronomia, radiokontinuumi, aktiiviset galaksinytimet, ekstragalaktiset radiolähteet

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Preface

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

My first and foremost thanks go to my mentor docent Merja Tornikoski, who introduced me to radio astronomy and to the concept of GPS sources, and without whom this thesis would not have been realized. As the Beloved Leader :) of our research team, she has demonstrated that it is an advantage rather than an obstacle to be a young female scientist in a male-dominated field. The rest of our GIX team, Dr. Anne Lähteenmäki, Talvikki Hovatta and Elina Nieppola, as well as our Great Leader :) Professor Esko Valtaoja, are gratefully acknowledged for scientific discussions, mental support, practical help, and fun conference trips. Special thanks to Anne for language consulting! I also want to thank the rest of the Metsähovi staff for an encouraging and easy-going atmosphere to work in. I am grateful also to the supervisor of this thesis, professor Martti Hallikainen, who has attended to my thesis matters without delays despite of his own scientific affairs overseas.

I gratefully acknowledge the financial support from Finnish Graduate School in Astronomy and Space Physics, and Vilho, Yrjö and Kalle Väisälä Foundation.

I want to thank my parents, Erkki and Ulla Jussila, and my sister Helena for their wholehearted love and support during the years. I am indebted to my mother for inspiring me to look up to the night sky, and to my father for the numerous scientific discussions and debates, which have (hopefully) taught me to reason and to state my views in an unambiguous and explicit way. I have been fortunate to have a caring and dedicated nanny to take care of my son, so that I have never had to worry about his wellbeing during my working hours. Kiitos Pirjo hyvästä hoidosta! Also my parents and my father-in-law, Pertti Torniainen, have provided my family with invaluable help in childcare, especially during the last hectic months of finishing this thesis.

This thesis would not have been possible without the unconditional support from my own family, Kalle, Eino and Ahti. I especially want to thank Kalle for his personal sacrifices that have supported and enabled my scientific career. Thank you for the love, the laughs, the comfort, and the opposition :) over the last 14 years!

I want to dedicate this thesis to my late friend Arja, who never got a chance to fulfil her dreams.

Heinola, April 2008

Ilona Torniainen

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 Tornikoski, M., **Jussila, I.**, Johansson, P., Lainela, M., Valtaoja, E.:
"Radio spectra and variability of gigahertz-peaked spectrum radio sources and candidates",
The Astronomical Journal, Vol. 121, pp. 1306-1318, 2001.

II **Torniainen, I.**, Tornikoski, M., Teräsranta, H., Aller, M.F. and Aller, H.D.:
"Long term variability of gigahertz-peaked spectrum sources and candidates",
Astronomy & Astrophysics, Vol. 435, pp. 839-856, 2005.

III Sambruna, R. M., Markwardt, C. B., Mushotzky, R. F., Tueller, J., Hartman, R., Brandt, W. N., Schneider, D. P., Falcone, A., Cucciara, A., Aller, M.F., Aller, H.D., **Torniainen, I.**, Tavecchio, F., Maraschi, L., Gliozzi, M., Takahashi, T.:
"Discovery of an Extreme MeV Blazar with the Swift Burst Alert Telescope",
The Astrophysical Journal, Vol. 646, pp 23-35, 2006.

IV **Torniainen, I.**, Tornikoski, M., Lähteenmäki, A., Aller, M.F., Aller, H.D. and Mingaliev, M.G.:
"Radio continuum spectra of gigahertz-peaked spectrum galaxies",
Astronomy & Astrophysics, Vol. 469, pp. 451, 2007.

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

VI **Torniainen, I.**, Tornikoski, M., Turunen, M., Lainela, M., Lähteenmäki, A., Aller, M.F., Aller, H.D. and Mingaliev, M.G.:
"Cluster analyses of gigahertz-peaked spectrum sources with self-organizing maps",
Astronomy & Astrophysics, Vol. 482, pp. 483-498, 2008

Author’s contribution

In Paper I, the author (née Jussila) was responsible for processing and analysing the data, and the preliminary interpretation of the results, whereas the final interpretation and writing of the paper were completed by M. Tornikoski.

For Papers II, IV and VI the author made observations, had the main responsibility of planning and coordinating the research, compiling the data, interpreting the results and writing the articles. In Papers II and IV the author also conducted all the analyses, whereas in Paper VI the practical details of the analyses were carried out by M. Turunen under the guidance of the author.

The author was responsible for the Metsähovi contribution to Paper III by making the observations, reducing the data and taking care of the correspondence with R. Sambruna, who coordinated the co-operation and wrote the article.

For Paper V, the author made observations, took part in data processing and conducted some of the preliminary periodogram analyses.

List of abbreviations

AGN	Active Galactic Nucleus
BAT	Burst Alert Telescope
CATS	Catalogs support System
CD	Compact Double
cj	Core-jet morphology
CMB	Cosmic Microwave Background
CSO	Compact Symmetric Object
CSS	Compact Steep-Spectrum
DDRG	Double-Double Radio Galaxy
ESA	European Space Agency
FR I	Fanaroff-Riley class I radio galaxy
FR II	Fanaroff-Riley class II radio galaxy
FFA	Free-Free Absorption
GPS	Gigahertz-Peaked Spectrum
HFP	High Frequency Peaker
IC	Inverse Compton
MSO	Medium-size Symmetric Object
pc	parsec ($3.086*10^{16}$ m)
SEST	Swedish-ESO Submillimetre Telescope
SOM	Self-Organizing Map
SSA	Synchrotron-Self Absorption
UMRAO	University of Michigan Radio Astronomy Observatory
VLBI	Very Long Baseline Interferometry
WENSS	The Westerbork Northern Sky Survey

List of symbols

c	Speed of light (299 792 458 m s^{-1})
h	The Hubble constant expressed as H_0 = 100 h km s^{-1} Mpc^{-1}
LS	Linear size
$M_\odot$	Solar mass (1.989 $*$ 10^{30} kg)
P_{178MHz}	Luminosity at 178 MHz (W Hz^{-1} sr^{-1})
p	Fraction of polarized emission
p_{median}	Median value of the fraction of polarized emission
S	Flux density (1 Jy = 10^{-26} W m^{-2} Hz^{-1})
S_{max}	Maximum flux density at a certain frequency (Jy)
S_{min}	Minimum flux density at a certain frequency (Jy)
$Var_{\Delta S}$	Fractional variability index at a certain frequency band
$Var_{\Delta S,MAX}$	Maximum value of the fractional variability index at any frequency band
v_B	Advance velocity of a beam
v_L	Expansion velocity of a radio lobe
z	Redshift

α	Spectral index
α_{above}	Spectral index above the turnover frequency
α_{below}	Spectral index below the turnover frequency
$\Delta\alpha$	Curvature of the spectrum
ν	Frequency (Hz)
ν_{break}	Frequency at which the radiation losses begin to dominate (Hz)
ν_{peak}	Frequency of the turnover

1 Introduction

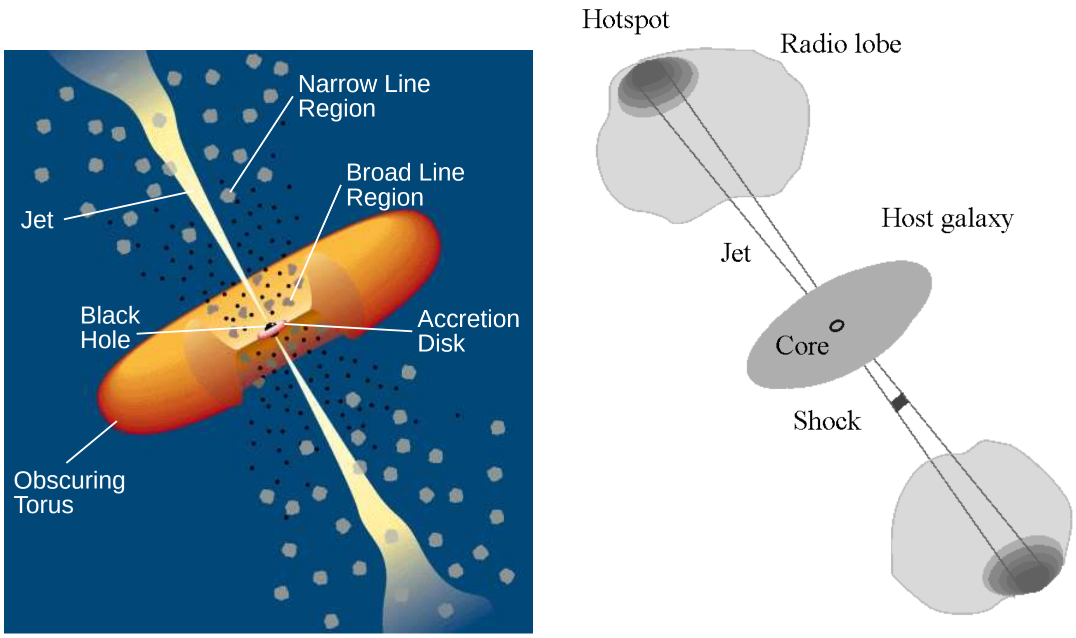
The stars we see in the night sky are stars of our galaxy, the Milky Way. Like all nearby galaxies, the Milky Way is dominated by the optical light emitted by its stars. However, as we look deeper into the sky with astronomical instruments, we can find galaxies which have central regions so bright that they outshine the stellar light from the rest of the galaxy.

According to the present knowledge, there is a supermassive black hole in the centre of every large galaxy, and even of some dwarf galaxies as well. Supermassive black holes have masses of the order of $10^5 - 10^{10}$ Solar masses ($M_\odot$), and they show different levels of activity depending on, e.g., their mass. The smaller ones, like the black hole with a mass of $\sim 10^6$ $M_\odot$ residing in the centre of our Milky Way, have affected only the central parts of the host galaxy. The most massive, and therefore the strongest ones have created phenomena outshining the rest of the galaxy and extending over intergalactic distances. When the radiation generated by the galactic centre exceeds the luminosity of the stars of the host, the galaxy is called an active galaxy and its centre an active galactic nucleus (AGN).

In addition to the central black hole, the most essential building blocks of an AGN (Fig. 1.1(a)) are the accretion disk surrounding the black hole, formed by the infalling matter; the broad line region, where spectral lines are broadened due to the gravitational effects; the molecular torus enclosing all the foregoing; the narrow line region with emission lines less affected by the gravitational effects of the black hole; and for a minority of 10 % of AGN, the so-called radio-loud AGN, jets of relativistic plasma traversing the whole system, from the vicinity of the poles of the black hole outwards to the direction of its spinning axis. The jets emit synchrotron radiation, which is created when relativistic electrons spin around magnetic field lines. The emission can be detected in the radio regime because the magnetic fields are rather weak in the jets, typically of the order of $\sim 10^{-3}$ G. At the end of the jet, from hundreds to millions of parsecs away from the core, there is a vast structure called a radio lobe, and sometimes, at the outer edge of the lobe, a bright area called a hotspot, where the jet plasma rams against the external medium. The radio flux density variability in AGNs is mostly due to shock fronts that advance downstream along the jets. The shockfronts reaccelerate the electrons in the jets and thus boost the radio emission.

There is a vast variety of different kinds of AGNs. One way of classifying the objects, and the most relevant way for the scope of this thesis, is by the size and the appearance of the radio jets.

For large radio sources (overall size > 15 kpc) two main groups can be distinguished. The division was first noticed by Fanaroff & Riley (1974), after whom the classes were named. Fanaroff-Riley class I (FR I) sources are less luminous than Fanaroff-Riley class II (FR II) sources, with a dividing value of $P_{178MHz} \sim 2 * 10^{25}$ W Hz^{-1} sr^{-1}. FR I sources have often symmetrical bright jets and lobes, which are brighter towards the central engine and fainter at the outer edges. FR II sources are often asymmetrical with only one radio lobe visible, or if there are two lobes, the other is clearly brighter then the other. The lobes are edge-brightened, i.e. the brightest spots are at the farther edges.



(a) (b)

Figure 1.1: (a) Structure of a radio loud active galactic nucleus. The radius of the molecular torus is of the order of 100 pc. (Figure credits: C. M. Urry & P. Padovani) (b) Outline of the structure of a large-scale radio galaxy. The total length of the radio structures is of the order of a Mpc.

For the smaller sources (overall size < 15 kpc), the division can be made on the basis of the radio continuum spectral shape and the size of the radio source. Most of the compact radio sources have flat radio spectra, where the flux density observed from the source is approximately constant over the radio frequencies (Fig. 2.2(b)). These objects are often blazars, highly variable sources, which are intrinsically large objects seen almost straight from the direction of the jet. Therefore their projected size is small and they appear to be compact. Due to the small viewing angle, relativistic effects such as Doppler boosting, dominate the radio emission and result in, e.g., high luminosity and apparent superluminal motion. Several flare components along the jets have each a convex spectrum peaking at different radio frequencies, and due to the overlapping of the component spectra, the observed total radio spectrum is flat.

Compact steep-spectrum (CSS) sources have a steeply falling spectrum, which can have a turnover at low radio frequencies (<500 MHz) resulting in a convex shape of the spectrum. Their linear sizes are in a range of 1 - 15 kpc and they are either completely embedded in the host galaxy or just about to extend outside of it, i.e. the radio structures that reach out far into the intergalactic distances in large-scale sources (in Fig. 1.1(b)) are smaller or comparable in size with the host galaxy.

Gigahertz-peaked spectrum (GPS) sources are smaller (< 1 kpc) than the CSS sources, and their turnover is at higher frequencies, typically at few gigahertz. Their radio structures are embedded in the nuclear regions of their host galaxies. Their little siblings, high frequency peakers (HFPs), sometimes also referred to as extreme GPS sources, are even smaller and have even higher turnover frequency. The continuous anticorrelation between linear size and turnover frequency observed in all the aforementioned source classes has been interpreted as a sign of their common origin. This, together with the fact that some of these sources are morphologically similar to symmetric FR I sources but magnitudes smaller, may hint that in HFPs we see newborn AGNs which grow in size, and decrease in turnover frequency, as they evolve into GPS and later CSS sources.

There is currently no information on how and why a galactic nucleus ignites and becomes an AGN, but the curtain of the mystery may be drawn aside by studying the smallest and thus possibly the youngest of AGNs.

Radio astronomy is a branch of astronomy where the sky is studied in the radio domain of the electromagnetic spectrum. In a wide definition this can be considered to cover the frequencies up to ~ 300 GHz (wavelength of ~ 1 mm). Today, astronomical research uses the multifrequency approach, combining information from different regions of the spectrum to deduce the physical nature of the objects. The famous metaphor describes astronomers as blind men examining an elephant and trying to guess what they are dealing with; as long as every one just keeps his findings to himself, no one can deduce the species of the animal, but as soon as they share their knowledge, they can reason together how the soft and long trunk, the thin and wide earlobes, and the stubby and steady leg can reveal the true nature of the being they have encountered. Radio observations are an important piece of the puzzle in studying astronomical objects, also the AGNs and especially the GPS sources, which have been defined by their radio properties.

The angular resolution of any observing system is inversely proportional to the diameter of the lens or reflector and to the observed frequency. The larger the antenna and the higher the frequency, the smaller details can be resolved in the observations. Radio astronomical antennas are usually large, the diameters extend from a couple of meters to ~ 300 meters of Arecibo telescope. Despite of their large diameters, even the largest of radio telescopes cannot compete with the high resolutions obtained in other branches of astronomy, due to the fact that the radio domain is in the low-frequency end of the electromagnetic spectrum.

Extragalactic radio sources are too small to be resolved with a single telescope of any kind. In general, a radio telescope does not form an image of the observed object, but detects the flux density of a single pixel in the sky. Because the antenna beam is larger than the angular diameter of the extragalactic radio sources, no imaging techniques, e.g., scanning over a source can be used. Thus, the single dish observations measure the integrated flux density from the entire source.

The resolution limit can, however, be evaded in radio astronomy by using interferometry. In interferometry, two or more telescopes observe the same target at the same time, forming a virtual telescope of a diameter as large as the largest distance between the telescopes. This way radio images of the objects can be obtained. An extreme case, with telescopes located at different continents and even in space, is called very long baseline interferometry (VLBI). The unparalleled resolution capabilities of VLBI result from the large diameter of the virtual telescope and can be enhanced further by developing the technique towards even higher frequencies.

The resolution of VLBI extends down to milli-arcsecond scales, allowing the compact radio structures of the AGNs to be resolved. This way it has been possible to study even the parsec-scale structures in the GPS sources. However, the innermost parts of the AGNs are still too small to be resolved with the current VLBI techniques and we have to rely on indirect ways in studying the composition of the central engine.

The single dish observations are still the main tool to study AGNs in radio astronomy. Flux density monitoring allows us to study the variability of the sources and to develop models for the jet physics. Observations at various frequencies provide us with the shape of the continuum spectrum, which can be used to deduce, for example, the radiation mechanisms contributing the radio emission of the source.

In this thesis, the radio properties of the GPS sources and HFPs are studied, and some conclusions on their nature are drawn. For simplicity, I use the term GPS source for both HFPs and GPS sources in most of the discussion and articles in this thesis.

2 Gigahertz-peaked spectrum sources

In this section I review the basic properties and significance of GPS sources, their location in the taxonomy of the AGNs, and, with this background, present the results and the importance of this thesis work.

Before going into details, one important quantity must be introduced to assist the discussion. The spectral index α is used to describe the slope of a spectrum. It can be calculated by

$$\alpha = \frac{\log S_2 - \log S_1}{\log \nu_2 - \log \nu_1}, \tag{2.1}$$

where S_1 is the flux density at the frequency ν_1, and S_2 the flux density at the frequency ν_2. Thus, we define the spectral index α such that $S \propto \nu^{\alpha}$. In the literature the convention $S \propto \nu^{-\alpha}$ is sometimes used, but we have chosen the former convention for its clarity; the spectral index is positive for rising slopes.

2.1 Radiative processes in GPS sources

In this section the most important radiation mechanisms are presented in a qualitative way. A more detailed and quantitative presentation can be found in, e.g., Pacholczyk (1970).

2.1.1 Synchrotron emission

Electromagnetic radiation is created when a charged particle is in accelerated motion. This is the case when a charged particle, generally an electron, spins around a magnetic field line (Fig. 2.1). For non-relativistic electrons, this is called the cyclotron mechanism and the radiation is directed to the direction of the magnetic field and at moderate angles. If the electrons are moving at relativistic velocities, the radiation is concentrated to a narrow cone in the direction of the instantaneous velocity vector perpendicular to the magnetic field, and the process is called the synchrotron mechanism. In AGN jets, the magnetic fields are of such strength that synchrotron radiation is observed mainly in the radio domain.

When a population of electrons with a power law energy distribution emits synchrotron radiation, the observed spectrum is of power law form $S \propto \nu^{\alpha}$. The spectral index α is proportional to the power law index of the electrons. When the emitting regions are optically thin, i.e. transparent to the radiation, the spectral index $\alpha \sim -0.5$ - -1. In optically thin emission the intensity of the radiation and the radiation density are low enough so that the absorption by the emitting electrons is negligible, This is the case, e.g., in the extended radio lobes of AGN. The opposite case of self-absorption is introduced in the next section, where the cause for the turnover in the GPS spectrum is discussed.

Synchrotron emission from a single electron is elliptically polarized, i.e. the electric field vector oscillates tracing out an ellipse normal to the direction of propagation. This is also observed when the electron is viewed with a tilted viewing angle relative to the

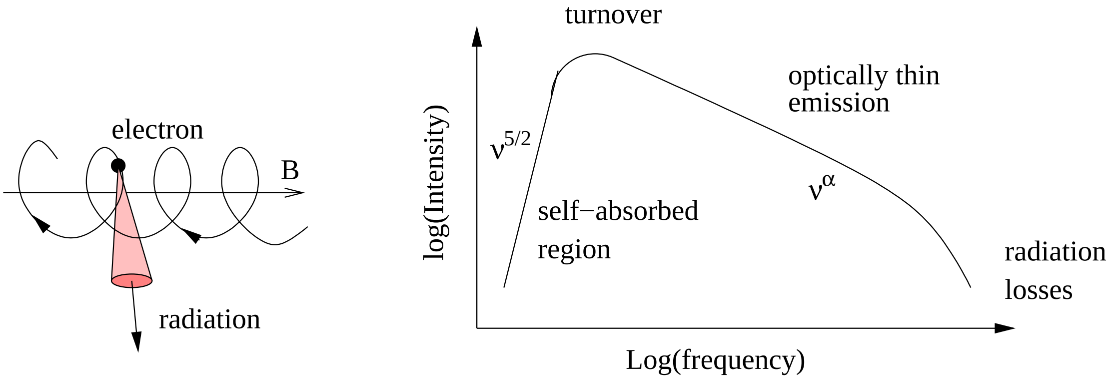


Figure 2.1: (a) A relativistic electron orbiting a magnetic field line, emitting synchrotron radiation in the direction of instantaneous velocity. (b) Generic synchrotron spectrum.

direction of the magnetic field. The direction of the polarization depends on whether the electron is coming towards the observer or receding away from her. As the viewing angle approaches normal to the field, the observer sees the emission cone directly, and the polarization seems to be linear. When a population of electrons is observed, there are statistically as many electrons seen from angles smaller and greater than perpendicular to the field, and therefore there are similar amounts of opposite elliptical polarizations, cancelling out each others. Theoretically, the observed emission is therefore partially linearly polarized, with a rather high degree of polarization, of the order of ~ 70 % (e.g. Altschuler 1989). In reality, the polarization is never that high, for reasons discussed in Sect. 2.3.3.

2.1.2 Low-frequency cut-off

For most of the AGNs the synchrotron spectrum is steeply declining throughout the radio frequencies. The most distinctive feature in the GPS sources is the turnover in the spectrum, i.e. the slope of the spectrum turns down at the GHz frequencies, and the flux density decreases towards the low radio frequencies. This low-frequency cut-off can result from two fundamentally different physical processes: either the emission of the source is suppressed at low frequencies or something absorbs the low-frequency emission of the source. Both mechanisms have various possible processes, which each create a characteristic signature in the source spectrum and variability behaviour. Ideally, it could be possible to identify the correct radiation process by studying the shape of the spectrum and variability of the GPS sources, but unfortunately nature does not always act ideally, and no examples of clear cases have been observed.

In the 1960s, both of the approaches, suppression and absorption, were considered (e.g., Kellermann 1966; Hornby & Williams 1966). The suppression of emissivity could be simply due to low-frequency cut-off of electron energy distribution, but it was not supported by observations (Hornby & Williams 1966).

Razin-Tsytovich effect is another way to induce lower emissivity at low frequencies. The refractive index of the emitting plasma is less than unity, i.e. the phase velocity of electromagnetic radiation in the medium is greater than the speed of light and hence also greater than the velocity of the relativistic electrons. This creates interference between the radiation emitted by an electron at different locations of its orbit, and therefore suppresses the emissivity of the plasma at low frequencies. However, this effect was found inconsistent with the observations by Simon (1969) and was not discussed later, until Tingay & de Kool (2003) found that in the source B1718-649 Razin-Tsytovich effect can suppress the emission below 3 GHz and dominate over the internal free-free absorption (introduced below) if the emitting gas is hotter than 10^4 K.

The other approach, absorption of the intrinsically bright low-frequency emission, has produced the two alternatives that remain to be the main candidates to date.

Synchrotron self-absorption

When the luminosity and the radiation density are high enough, which is the case in luminous and compact AGNs, the emitted photons interact with the emitting electron population. A photon is absorbed by an electron, which therefore makes a transition to a higher energy level. This is called synchrotron self-absorption (SSA), since the electron population absorbs the photons it has emitted by itself and no external absorber is needed. The SSA coefficient is inversely proportional to frequency and therefore the source is said to become optically thick (it cannot transmit its own radiation) below a certain frequency; the spectrum decreases towards lower frequencies below this turnover frequency ν_{peak}, where the observed flux density reaches its maximum (Fig. 2.1 b)).

Theoretically, the spectral index α_{below} in the optically thick part of the spectrum, below ν_{peak}, is 5/2. This value is constant regardless of the power law index of the electron population, unlike the spectral index above the turnover frequency, α_{above}. When compared to the observed values, this optically thick spectral index is quite steep, and before Paper VI, no source had been observed with such a large positive spectral index. The highest spectral index below the turnover in the sample of Paper VI is 2.65 from the source B1843+356, but this value is rather unreliable since the single low-frequency observation from the Westerbork Northern Sky Survey (WENSS) is unlikely simultaneous with the data points closer to the ν_{peak}. Simultaneous observations at $\sim$ 300 MHz and $\sim$ 1 GHz are needed to confirm whether this high spectral index is real.

The synchrotron theory predicts that the frequency ν_{peak} is inversely proportional to the angular size of the source, i.e. the smaller the source is, the higher is its spectral turnover. Indeed, such a relation has been observed in GPS sources by, e.g., O'Dea & Baum (1997), and is discussed further in Sect. 3.1.

Free-free absorption

Free-free absorption (FFA) occurs in thermal plasma when an electron absorbs a photon, and is therefore accelerated in a field of an ion, which is needed for momentum conservation. The electron is not bound to the ion but remains free before and after the interaction, hence the name free-free absorption. Free-free absorber becomes optically thick at a certain frequency ν_{peak}, above which the absorption is negligible, and below which the intensity of the unabsorbed radiation decreases exponentially towards lower frequencies.

The absorbing electron population can be located within the emitting region or it can reside outside of it. When the absorber is within synchrotron emitting plasma, the change of spectral index (curvature) at the turnover is $\Delta\alpha = -2$ (e.g., Kembhavi & Narlikar 1999). Thus, as the optically thin part of the synchrotron spectrum has usually $\alpha_{above} \sim -0.5$ - -1, the spectral index below the turnover can be calculated to be $\sim +1$ - $+1.5$.

If the absorbing ionized plasma forms a screen external to the emission region and the screen is uniform, the optically thick spectral index should be $\alpha_{below} = 2.1$, which has not been reported in the literature. Therefore, Bicknell et al. (1997) have proposed that the external absorber is not uniform but in form of clouds with varying optical depths. In their model, the relativistic jet drills its way inside a region of dense clouds of the ambient medium forming a fast radiative bow shock, which ionizes the clouds by photo-ionization beforehand and by shock-ionization as is traverses them. This way a cocoon of clumpy ionized plasma is formed around the jet. Their calculations show that a shock with the velocity of $\sim$1000 km s^{-1} and an ambient hydrogen density of $\sim$ 100 cm^{-3} would create a situation where the free-free absorption generates a gigahertz-peaked spectrum. Bicknell et al. (1997) also show that it is possible to produce the observed peak frequency-size anticorrelation with their model.

2.2 General properties of GPS sources

GPS sources can be divided into two groups by their optical identification: quasars and galaxies. Generally, quasar-type objects are pointlike in appearance, i.e. the light from the very compact central engine outshines the host galaxy, whereas in the galaxy-type objects the host is visible. This is due to an orientation effect. In quasars, the bright emission of the core is not obscured by the molecular torus of the AGN as we see them from the direction that is rather close to the jet axis. The galaxy-type objects are seen from a larger viewing angle, so the molecular torus obscures the core and allows the stellar emission to stand out. However, there are several differences between GPS quasars and galaxies, and they are believed to represent different objects by their physical nature, not just due to orientation (e.g., Snellen et al. 1998; Stanghellini 2003).

Galaxy-type GPS sources are found at lower redshifts than quasar-type GPS sources: the redshifts of galaxies are typically $0.1 \leq z \leq 1$ and of quasars $1 \leq z \leq 4$ (O'Dea et al. 1991; O'Dea 1990). This result is also confirmed by this thesis: when considering only the genuine GPS samples, the average redshift for galaxies is 0.59 (Paper IV) and for quasars 1.92 (data in Paper VI). This implies that GPS quasars existed in the early Universe whereas GPS galaxies appeared later, and that evolution of galaxies and their cluster environments at those epochs may have affected the formation and evolution of these sources (O'Dea et al. 1996).

The hosts of GPS galaxies are often distorted elliptical galaxies and there is evidence of interactions with close companions (O'Dea et al. 1996). The host galaxies of GPS quasars may be protogalaxies with very dense and clumpy interstellar media (O'Dea et al. 1991).

The VLBI morphologies of compact radio sources are also thought to be different for quasars and galaxies. The radio sources in galaxies are often compact symmetric objects (CSOs, see Sect. 2.4.1) or compact doubles (CDs), whereas quasars show distorted or core-jet (cj) morphologies (Stanghellini et al. 2001). This implies that the GPS quasars are seen closer to the direction of the jet axis than the GPS galaxies. Thus, their compact sizes are likely due to projection effects. This is a claim often quoted in the literature. However, most of the studies of the GPS quasars presented in the literature are heavily contaminated by non-GPS sources (Papers I and II), and the results for GPS quasars cannot be considered well-grounded. Our sample in Paper VI has 31 strictly classified GPS galaxies, out of which 17 sources (54.8 %) were CSOs, 4 CDs (12.9 %) and one (3.2 %) was a cj object. The rest were either unresolved or had no information on the VLBI morphology. Out of 19 genuine GPS quasars, there were 3 CSOs (15.8 %), 2 CDs (10.5 %), one core-jet (5.3 %) and one complex-structured source. The rest had not been resolved or observed at all. Our results imply that GPS galaxies are indeed often CSOs, but the claim of GPS quasars being often core-jet objects seems to be invalid. The unclear nature of the CDs, as they can be either CSOs or core-jets, gives some uncertainty to the result, but even if all the quasar CDs were core-jets, that would increase the percentage of core-jets only to 15.6 %. Many of the core-jet GPS sources have actually been flaring flat-spectrum sources misidentified as GPS sources as demonstrated in the Papers I, II, IV and VI.

2.3 Radio behaviour of GPS sources

2.3.1 Radio continuum spectrum

As their name implies, the shape of the radio continuum spectrum is the key feature of GPS sources. Whereas most of the AGN have a simple flat or steep spectra, the shape of the spectra of GPS sources is convex (Fig. 2.2(c)). In the low-frequency optically thick part of the spectrum, the flux density increases towards the higher frequencies. The spectrum reaches its maximum at the turnover frequency ν_{peak}, which is often limited between 0.5 – 5 GHz for GPS classification, and higher than that for HFPs or extreme GPS sources. Above the turnover frequency, the flux density decreases and at some high frequency ν_{break} the decline gets even steeper due to radiation losses. The mechanism that produces the absorption in the optically thick part is still unclear. The question is discussed in Sect. 2.1.

De Vries et al. (1997) constructed a canonical GPS spectrum (Fig. 2.3(a)) by normalizing the spectra of 72 GPS sources. They obtained a typical spectrum where the optically thick spectral index is ~ +0.5. After the turnover there is a plateau with $\alpha = -0.36$, and the spectral index of the optically thin part is ~ -0.7. However, even though they refer their normalized spectra to have ”limited scatter of datapoints”, Fig. 2.3(a) shows prominent scatter at frequencies below the turnover. Our version (Fig. 2.3(b)) is constructed from the spectra of 52 genuine GPS sources from the sample of Paper VI. We find the spectral indices to be steeper below the turnover ($\alpha_{below} \approx +0.8$) and flatter above it ($\alpha_{above} \approx -0.5$). We excluded the flattening near the turnover ($0.5\nu_{peak} < \nu < 2\nu_{peak}$) in order to model the optically thick and thin parts better. In our normalized spectrum, the

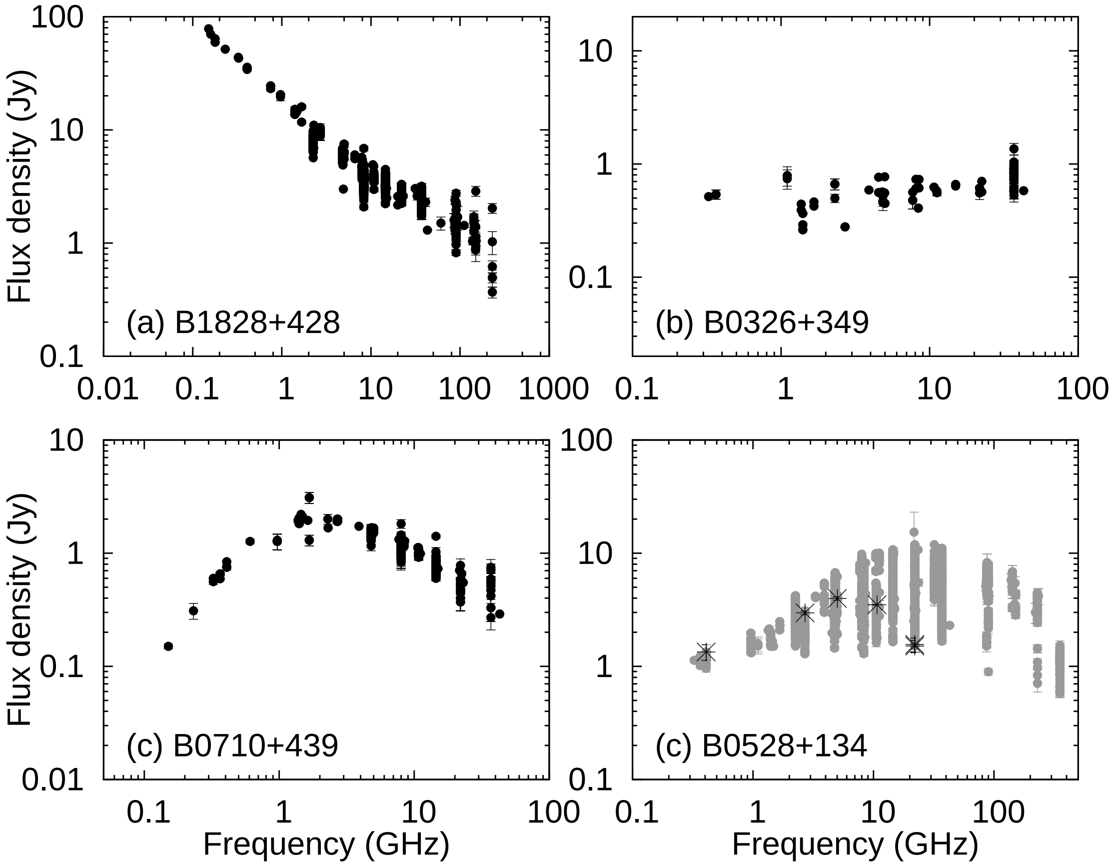
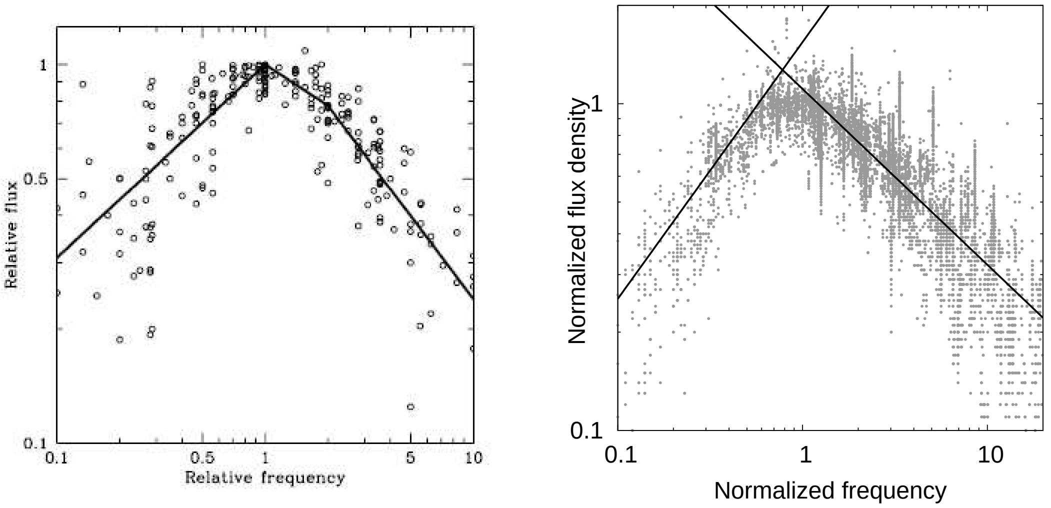


Figure 2.2: Examples of different types of radio continuum spectra of AGN. (a) Steep spectrum (Paper II). (b) Flat spectrum (Data from our database). (c) Gigahertz-peaked spectrum (Paper IV). (d) Variable source with inverted spectrum during outbursts. This source has been identified as a GPS source using the data from Kühr et al. (1981) marked with black crosses, whereas combining all available data (grey dots) reveals the variability and overrules the identification (Paper II).

scatter is more prominent above the turnover.

The width of the continuum spectrum of GPS sources has been studied by, e.g., O'Dea et al. (1991) and Edwards & Tingay (2004). They have calculated the interpolated full width at half maximum (FWHM) of the fitted spectra and found similar results: the narrowest spectra were from sources B0108+388 and B1934-638 with the values of ~ 0.95 and ~ 1.0 decades of frequency, respectively. O'Dea et al. (1991) note that the narrowest reasonable spectrum, assuming homogeneous self-absorbed synchrotron source with a power law electron energy distribution, would be 0.77 if the spectral index below the peak is assumed to be +0.8. The width of the spectrum would be even smaller for sources with steeper rise in the spectrum. The median value in the sample of O'Dea et al. was 1.20. In our sample of genuine GPS sources the median is congruent: ~1.2. However, the smallest values in our sample are smaller than has previously been reported; there are



(a)

(b)

Figure 2.3: (a) Canonical GPS spectrum from de Vries et al. (1997). (b) Normalized GPS spectrum based on the genuine GPS sources in the sample of Paper VI.

seven GPS sources with FWHM values ≤0.95 decades of frequency. The lowest value of 0.73 is from the GPS quasar B1518+046, but the low-frequency slope of the spectrum is not very well grounded due to lack of data. We get somewhat lower values possibly because the function we have fitted to the data (Papers IV and VI) is different from the function used by O'Dea et al. and Edwards & Tingay. Nevertheless, the curvature of the spectrum for four out of these narrow-spectrum sources is ≥ 2.0, which is the the typical maximum value for free-free absorbed sources, and the slope of the optically thick part is very steep ($\alpha_{below} > 1$), so this could provide some evidence for SSA rather than FFA in these sources.

2.3.2 Variability

GPS sources have often been quoted as the least variable class of compact extragalactic radio sources (e.g., O'Dea 1998). The origin of this conception can be found in Rudnick & Jones (1982), where a sample of seven sources with simple-convex spectra were found "relatively quiescent" (median fractional variability ca. 7%). The multifrequency spectra were compiled from non-simultaneous data points from Kühr et al. (1981) and variability was estimated from two observations at 5 GHz with a timespan of 6 - 8 years. In fact, five out of the seven sources have been studied also in the papers presented in this thesis and they have been found either very variable or not convex at all - or both (Figure 2.4). The median fractional variability of them is ca. 390% of the minimum flux density, however, this value has been taken from the frequency with the highest variability (median 37 GHz)

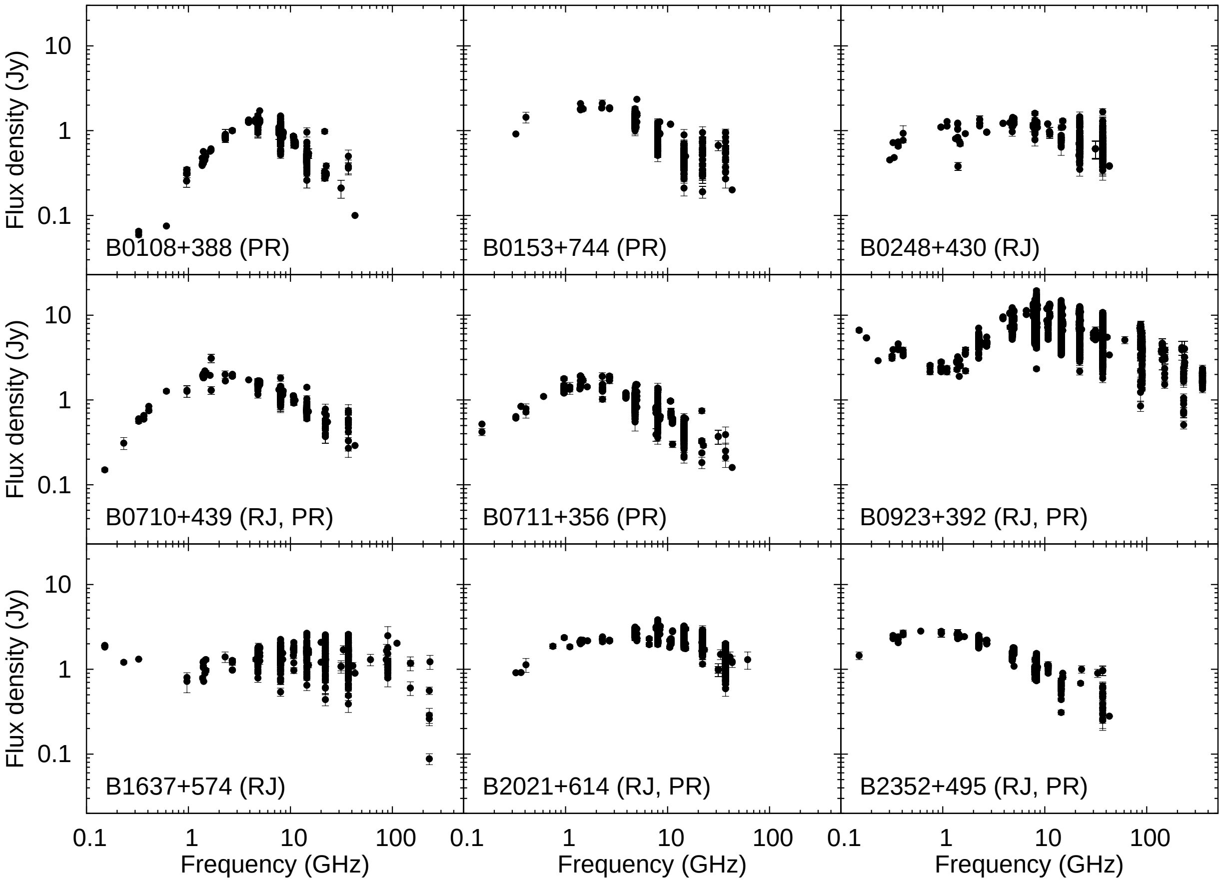


Figure 2.4: The spectra of convex-spectrum sources studied in Rudnick & Jones (1982) (RJ) and Pearson & Readhead (1988) (PR).

and is therefore not directly comparable with the median variability at 5 GHz found by Rudnick & Jones (1982). Thus, already the very first assumptions about the properties of convex-spectrum sources were made on a sample contaminated by variable sources.

Another approach to the subject has been taken with compact symmetric objects (CSOs), or compact doubles (CDs) as some of them were earlier called. This class of compact extragalactic sources overlaps with GPS sources, and often the results of one class have been considered indicative for the other (see Sect. 2.4.1). E.g., Pearson & Readhead (1988) have reported that compact doubles - both with steep and flat spectrum - have low variability. However, the sample (altogether seven sources) included three sources studied by Rudnick & Jones (1982), and although the rest have clearly convex spectra, none of them can be said to have low variability (also in Fig. 2.4). It must be noted, though, that the frequency bands studied in these papers were quite low and the highest variability in these sources is found mostly at high frequencies.

Also some recent studies have confirmed the low variability of GPS sources but also examples of variable GPS sources have been found. Jauncey et al. (2003) found that $\sim$ 10% of GPS sources have flux density variability over a period of 30 months. They presented five variable southern GPS sources and one with ephemeral GPS-type spectrum.

The ephemeral GPS-type spectrum is attributed to slow variability evolution commonly found in flat-spectrum sources. Although their result implies that ~90% of GPS sources do not vary, they note that it is possible that variability will be found more common among GPS sources on timescales of decades or more.

Indeed, long-term monitoring has revealed that a significant fraction of GPS sources exhibit variability. Aller et al. (2002) found 10 out of 18 well observed GPS sources to have variability at some level over a period of almost twenty years. Most of the sources maintain their GPS shape during this time. The characteristic variability timescales of these sources are longer than of the other sources monitored by the UMRAO group.

One of the most important results presented in the papers of this thesis is the observation that low variability is, in fact, quite rare among GPS sources identified in the literature. We have used the fractional variability $Var_{\Delta S}$ index to describe the variability of the flux density at a certain frequency band. The index is defined by

$$Var_{\Delta S} = \frac{S_{max} - S_{min}}{S_{min}}, \tag{2.2}$$

where S_{max} and S_{min} are the highest and the lowest observed flux density, respectively. Thus, the fractional variability index illustrates how large the amplitude of variability is in proportion to the lowest flux density value. We have chosen to use this rather crude estimate instead of the more conservative approach that takes the error estimates of the observations into account. The reason for this is that not all the observations in our database have error estimates. This way we get consistent, even though perhaps slightly exaggerated, results independent of the availability of the error estimates at each frequency band. When studying the presumed low variability of the GPS sources, it is the highest observed variability index $Var_{\Delta S,MAX}$ at any frequency that carries the most information. Therefore, the variability indices discussed below are the maximum values that a source has had at any frequency band.

Variability was also observed in the few southern GPS sources in the sample of Tornikoski et al. (2000). A closer look first in southern GPS quasars (Paper I) and then in northern GPS sources (Paper II), also mostly quasars, confirmed that variability is common and notably strong (median value of $Var_{\Delta S,MAX} \approx 3.1$) among sources that previously have been identified as GPS sources in the literature. Most of the sources in our samples turned out to have a GPS-type spectra only temporarily (Fig. 2.2(d)), and the sources with unchangeable GPS shape in their spectra also varied with an index of $Var_{\Delta S,MAX} > 1.05$ at some of the monitoring frequencies (4.8, 8.0, 14.5, 22, 37 and 90 GHz). We then wanted to study if the galaxy-type GPS sources would behave more like anticipated by the classical GPS view. In Paper IV, we gathered a sample of 96 GPS galaxies and found that only a third of them had acceptable GPS spectra and moderately low variability ($Var_{\Delta S,MAX} \leq 3.0$). A third of the sources were candidate GPS sources, but lack of low-frequency observations prevented us from confirming the existence of the turnover, and another third were variable sources with either temporary GPS-type spectra or consistent convex shape of the spectra, or steep-spectrum sources with no traces of turnover in their spectra.

Even for the genuine GPS sources, i.e. the sources confirmed to have a gigahertz-peaked spectrum in the papers in this thesis, the variability was unexpectedly high. For the genuine GPS quasars (19 sources) in Paper VI, the smallest value of the maximum variability index at any of the observed frequency bands was 0.34 (source B0703+468 at $\sim$ 0.4 GHz), and the median value was 1.41. For the confirmed galaxy-type GPS sources (31 sources) in Paper VI, the median of the variability index $Var_{\Delta S,MAX}$ was lower (0.98), but yet the lowest $Var_{\Delta S,MAX}$ was not lower than 0.28, which is four times the variability reported to be typical of sources with simple-convex spectrum by Rudnick & Jones (1982). The low variability of some genuine GPS sources may be attributed to the fact that these sources have very sparse datasets and no monitoring data. For sources with $Var_{\Delta S,MAX} < 0.5$, the number of datapoints from which the index was calculated was 2 - 18 (median 6), whereas for the sources with $Var_{\Delta S,MAX} > 0.5$ the number of datapoints was 2 - 138 (median 83).

However, selecting the limit of $Var_{\Delta S,MAX} <3$ for genuine GPS sources has not produced a sample of sources which all are likely to lose their identification in time, but there are also sources that have data from well over 20 years at several frequencies. This implies that there, indeed, is a population of sources that remain rather low in variability, even though the degree of variability is higher than previously presumed.

2.3.3 Polarization

The polarization of GPS sources is found to be remarkably low in the radio (e.g., Rudnick & Jones 1982; O'Dea 1990; Stanghellini et al. 1998; Aller et al. 2003b) as well as in the optical (e.g., Cohen et al. 1997). As discussed in Sect. 2.1, the synchrotron radiation is intrinsically highly polarized. The polarization of AGNs has been observed to be typically 1 - 20 % (e.g., Aller et al. 1985; Cawthorne et al. 1993), but in the GPS sources the fraction of polarized emission is typically less than 0.5 % (e.g., Stanghellini et al. 1998). However, there are exceptions. In the sample of Stanghellini et al. (1998), there were three sources (one galaxy and two quasars) with a confirmed GPS classification (Paper VI) that at some radio frequency showed fractional polarization of $\geq$ 2.1 %. In the optical, Cohen et al. (1997) report of four highly polarized (> 3 %) sources out of 25 CSS/GPS sources.

Generally, the depolarization in the AGNs is due to disorganized magnetic fields which do not favour any direction and the net effect results in a low fraction of polarized emission. Another explanation is Faraday depolarization (Faraday rotation), where the polarized emission changes its polarization angle due to propagation through ionized medium which contains magnetic fields. Inhomogeneities in the properties of this Faraday screen change the angle of the polarization differently in different regions and if the size scale of the variations is small enough, the observed net polarization is lower than the polarization before the Faraday screen. The circumnuclear torus of magnetized plasma has been suggested by Peck & Taylor (2000) to act as a Faraday screen depolarizing the radiation from the compact symmetric objects (Sect. 2.4.1). Aller et al. (2003b) found their results to be in accordance with this suggestion. Also Bicknell et al. (1997) suggest that the low polarization of GPS sources is due to Faraday rotation; in their model (discussed in Sect. 2.1.2), the ionized cocoon around the jet acts as a Faraday screen.

2.4 Other classes of compact radio sources

In the literature, there is a variety of different, at least partially overlapping, classes of compact sources associated with GPS sources. The classification can be based on the source VLBI morphology, shape of the spectrum, or size. The classes most relevant to this thesis are presented briefly below.

2.4.1 Compact symmetric objects

When investigating the VLBI morphology of AGNs, most of the compact sources are core-jet objects, which are seen along the jet and therefore appear to be small. The jet axes of compact symmetric objects (CSOs) are nearly perpendicular to the line of sight, and therefore their small size (< 1 kpc) is intrinsic. For a CSO classification (Wilkinson et al. 1994), symmetric radio components must be separated by less than 1 kpc, there must be no emission on scales larger than 1 kpc (or only very faint), and a centre of activity must be identified in between the jets or the lobes, or the structure of the twin lobes must exclude the possibility of misinterpreting the core of a core-jet object as one of the lobes. Sources with compact double (CD) structure are not necessarily CSOs because the CD classification does not differentiate between the cases of two radio lobes, and a radio lobe and a core. No spectral characteristic are required in the CSO classification, yet many of CSOs are also GPS sources and vice versa, but there are also CSOs without convex spectra and GPS sources without compact symmetric structure. Thus, many results on CSOs can be applied to GPS sources, but not necessarily.

Because of their orientation, relativistic beaming does not play a remarkable role in CSOs (Wilkinson et al. 1994) and their high luminosity is intrinsic. In addition to high luminosity, Readhead et al. (1996) list other key properties of CSOs, based on their sample of five sources: no superluminal motion of the hotspots, steep high-frequency spectra, weak radio variability, low polarization, and low core luminosity. However, Gugliucci et al. (2005) found two CSOs with relatively high polarization (2.1 % and 8.8%), and three with variability of 30 % in a period of five years at 8.4 GHz.

2.4.2 Compact steep spectrum sources

Earlier the compact steep spectrum (CSS) sources were often called steep-spectrum cores (e.g., van Breugel et al. 1984b), as they are small to medium-sized radio sources with overall extent of < 20 kpc residing inside their host galaxies. Their radio spectra show a steep decline and possibly a turnover at low radio frequencies. Later Fanti et al. (1990) suggested the name ’compact steep-spectrum source’ to indicate that the source in question is a complete radio source with subgalactic dimensions, not just a core part of extended radio structures. van Breugel et al. (1984b) found CSS sources to be embedded in dense gaseous environments, and suggested that FFA in ionized clouds is responsible for the low-frequency absorption seen in the spectra.

GPS sources are sometimes considered a subsample of compact steep spectrum (CSS) sources. For CSS sources, Fanti et al. (1990) found an anticorrelation between the linear size and the turnover frequency, and later a matching anticorrelation was found also for a combined sample of GPS and CSS sources (O'Dea & Baum 1997), which possibly implies similar radiation mechanism or an evolutionary connection of the two types of sources. The evolution of compact sources is discussed in detail in Sect. 3.1.

Earlier it was found that the VLBI morphologies of CSS sources show a similar split between the quasar- and galaxy-type sources as the GPS sources (Sect. 2.2). However, Fanti et al. (2001) studied the VLBI morphologies of a sample of 87 CSS sources and found no differences in the morphologies of quasars and galaxies. Polarization studies of the same sample revealed that larger CSS sources have similar polarization properties with extended radio sources, whereas the smaller (sizes $< 3 - 5$ kpc) were strongly depolarized (Fanti et al. 2004). The dependence between the polarization and the source size suggests a presence of depolarizing medium with a smooth distribution rather than clumpy medium of magnetized clouds.

2.4.3 High frequency peakers

Dallacasa et al. (2000) presented a sample of 55 sources, both galaxies and quasars, with convex spectra peaking at high radio frequencies (>5 GHz), which they called high frequency peakers (HFPs). The aim of their study was to find sources with higher turnover frequencies and smaller sizes, and thus possibly younger age (see Sect. 3.1 for details) than was found in previous GPS and CSS samples. Their estimates of the source sizes, based on the relation between the turnover frequency and the source size (Sect. 2.3.1 and 3.1), implied that the HFPs are a magnitude smaller than the GPS sources. Variability was found common in HFPs, and the number of sources too high for every bright HFP to evolve into GPS and CSS sources, and the authors note that the sample is likely to contain sources different from GPS and CSS sources.

Indeed, it was found later that many of the HFPs are actually flaring blazars (Tinti et al. 2005), that have happened to be in a flaring state when originally observed by Dallacasa et al. (2000). The true nature of these objects was revealed by later observations, which showed flat spectra and variability. All of these falsely identified HFPs were quasar-type objects and they constitute 25 % of all the sources identified with quasars in the sample. The variability behaviour of other HFPs identified with quasars also invoked a question of them being false identifications. Variability of HFP galaxies was found lower and possibly consistent with them being young or recurrent AGNs.

A clear division between HFP galaxies and quasars was found also by Orienti et al. (2006) who studied the radio morphology of the sources. They found that the galaxy-type HFPs were often double or triple sources (CDs or CSOs), whereas the HFP quasars were either unresolved or core-jet objects. This implies that the radio emission originates from the radio lobes, hot spots, or both in the galaxies, and from the regions near the core and the base of the jets in the quasars.

In Papers II, IV and VI, the samples of GPS sources contain also sources classified as HFPs, and they are dealt with together as a population of moderate to high peaked-spectrum sources.

3 Physical models

In this section the different scenarios explaining the physical nature of the GPS sources are presented. The question why the GPS sources are so small has led to two main hypotheses: the youth scenario and the frustration scenario. Currently the youth scenario is widely accepted as an explanation for the majority of the sources, but the frustration scenario may be possible for some of them. Also a kind of intermediate model between the two, the recurrent source scenario, is presented. It must be emphasized that the above-mentioned models apply only to the galaxy-type GPS sources. At the end of this section, some models for the quasar-type GPS sources are also introduced.

Since their discovery in the early 1960s (Kellermann et al. 1962; Lister 2003), the nature of GPS sources has been a subject to various speculations. One of the first suggestions generated excitement among Soviet scientists as it was argued that GPS sources could be beacons of extraterrestrial civilisations. Kardashev (1964) calculated that the optimum spectral profile for transmitting interstellar signals with a maximum amount of information was similar to the spectra of the first two GPS sources, 0316+161 (CTA 21) and 2230+114 (CTA 102) (Fig. 3.1). No further evidence for the artificial nature of the GPS sources was found (e.g., Kellermann 1966) and the less thrilling but yet a remarkable natural explanation, a supermassive black hole in an active galactic nucleus, became evident.

3.1 Young sources

A natural explanation for the small size of any (possibly growing) object is that it has recently emerged and has not had time to expand any larger. For a GPS source, namely B1934-63, this was first suggested by Shklovskii (1965), shortly after the discovery of sources with convex radio spectrum (Bolton et al. 1963). Without further knowledge of the nature of the quasi-stellar objects, Shklovskii deduced that if such a spectrum is due to re-absorption of synchrotron radiation, the high turnover frequency implies a very small angular size and therefore a very young age, of the order of just 100 years. He concluded that all such objects with convex spectrum represent a very early stage in the evolution of quasars.

Later, as understanding of the nature of AGNs grew deeper, the idea was discussed from a different viewpoint by Phillips & Mutel (1982), who elaborated the evolution of symmetric compact radio sources. Compact symmetric radio sources are similar to extended symmetric sources both in morphology and in optically thin spectral index. The difference in size and in turnover frequency could be explained by evolution: as the radio lobes expand, they will become optically thin and the turnover frequency will move to lower frequencies, maintaining a constant spectral index if the electron energy density stays constant.

Carvalho (1985) developed a more quantitative model for the evolution of compact and extended double sources. In the first phase of his model, two beams are formed symmetrically from the core and energy is channelled through them. A beam ends at a

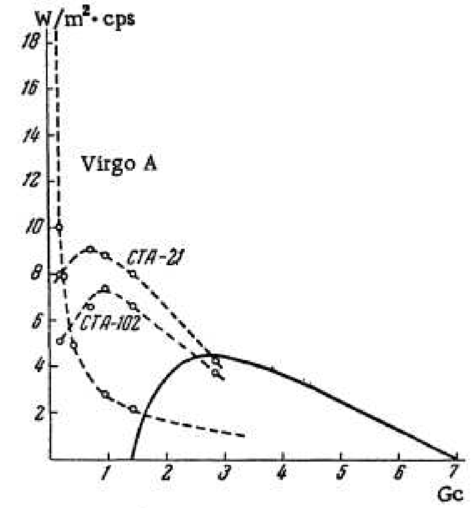


Fig. 2. ——) Anticipated emission spectrum of radio transmitters of extraterrestrial civilizations; – – – –) spectrum of radio sources CTA-21 and CTA-102, suspected of being artificial radio sources, and spectrum of a typical natural radio source Virgo A.

Figure 3.1: Comparison of the spectra of some early radio sources and a hypothetical extraterrestrial signal. (Figure: Kardashev 1964)

hot spot, where the jet materia rams towards the external medium. More extended radio emitting lobes surround the hot spots. The beam advances with a constant velocity v_B through the interstellar medium and the radio lobe expands with velocity v_L. The energy is converted into relativistic particles and magnetic field at the hot spot, but the magnetic field is not strong enough to produce significant radiation losses at this stage. This first phase is what we see in compact double sources. After the beams and hot spots have left the central galaxy, they are surrounded by intergalactic medium, and the lobes continue to expand (phase 2) until they reach pressure balance with the medium. This equipartition phase is the third and the last phase, which can been seen in extended doubles. To test his model, Carvalho (1985) studied a sample of CDs together with a sample of FRII radio sources and compared the results with the evolutionary tracks the model predicts. The agreement was found to be generally good and the model paved the way for later studies on the subject.

The two most fundamental pieces of evidence supporting the youth scenario come from studies on hotspot advance velocities and spectral ageing.

The first reliable detection of hotspot separation speed in a CSO (also a GPS source) was presented by Owsianik & Conway (1998). They found a separation rate of ~0.25 $h^{-1}c$ which, after some assumptions, yields a kinematic age estimate of 1100 ± 100 years. By

2003, there were 10 CSOs (out of which 4 GPS sources and 3 variable convex-spectrum sources by our criteria (Paper IV)) with expansion velocities detected (Polatidis & Conway 2003). The velocities were in the range of ~0.1 $h^{-1}c$ - ~0.4 $h^{-1}c$, resulting in age estimates of $\leq$ 3000 years. The high rate of detection (10 detections out of 13 sources with good quality data) implies that the observed hotspot advance speeds are likely representative of mean hotspot separation speeds over the source lifetime, rather than a brief burst of expansion occurring rarely in these sources. This implies that the age estimates are well-grounded.

Radiative ageing gives us another way to study the age of a source. Since the radio emission is due to synchrotron mechanism, it is possible to relate the features in the radio spectrum to the age of the radiating electrons (Murgia 2003, and the references therein). The spectral age describes the time that has passed since the emitting electrons were accelerated, either at the base of the jet or by the shock of the hotspot seen at the end of the jet. Thus, if we want to study the spectral age of the entire source, we would need to look for electrons that have been accelerated only once, at the base of the jet at the beginning of the activity. This has been done by Murgia (2003) by studying the integrated spectra of lobe-dominated CSS sources. They found radiative ages $\leq 10^5$ years for CSS sources.

Another way to use spectral ageing in determining the source age is to use it to trace the time elapsed since the hotspot traversed a certain region and accelerated the electrons there. Estimating the spectral age of the inner edge of the radio lobe and calculating how far the hotspot has travelled since, gives us an estimate of the hotspot advance speed and allows us to determine the source age. This has been done by, e.g., Nagai et al. (2006) and Orienti et al. (2007). Nagai et al. (2006) studied the kinematics and the spectral age of a GPS source B1607+268, and found a consistent age of 2200 ± 700 yr, which indeed supports the youth hypothesis. Orienti et al. (2007) found the radiative ages of two CSS sources to be ~ 5000 and ~ 50 000 years, which also agrees well with the youth scenario.

Also other studies have confirmed that the age estimates obtained from hotspot kinematics and spectral ageing are in good agreement (Polatidis & Conway 2003). This is a strong piece of evidence for the youth scenario, and it also implies that particles and fields are close to equipartition in these sources and the standard model for radiative ageing is broadly valid (Polatidis & Conway 2003).

Other kinds of studies also support the youth hypothesis. Vink et al. (2006) found that the OIII emission in the GPS/CSO galaxies is relatively low compared with other radio loud AGNs. This can be explained if the sources are so young that their central engine has not yet had time to completely ionize the emission line regions found in full grown AGNs. They calculated that it would require some 300 000 years for a source to ionize its surrounding up to 5 kpc from the core, and therefore the narrow line region is still forming.

Fanti et al. (1990) found an anticorrelation between the rest frame turnover frequency and the projected linear size LS in CSS source, and a concordant result of $\nu_{peak} \propto LS^{-0.65}$ was found for a combined sample of CSS and GPS sources by O'Dea & Baum (1997). They found that the trend is contiguous between the source populations and suggested that CSS and GPS sources are related by their physical properties and the turnover is

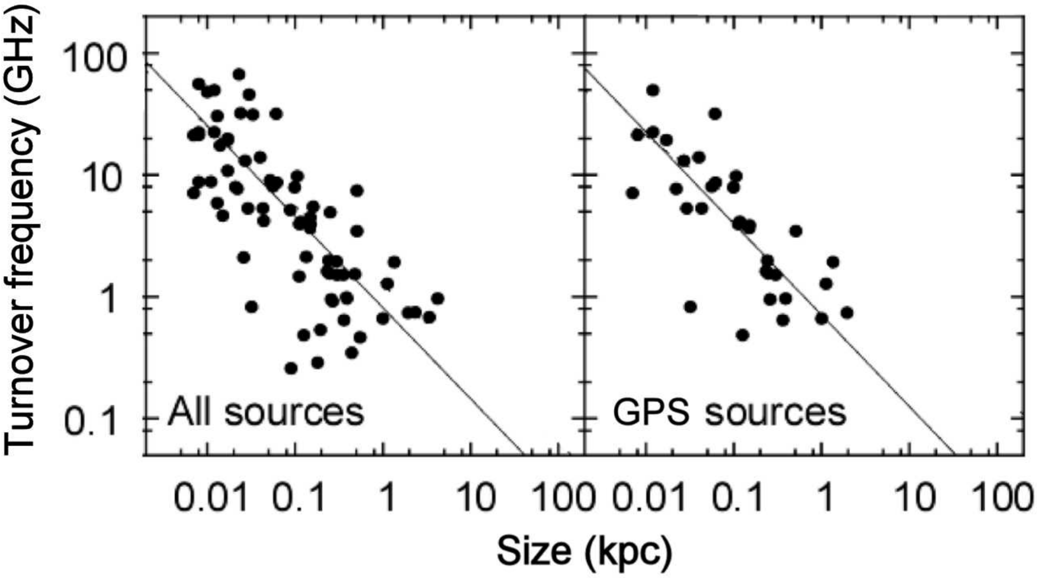


Figure 3.2: Anticorrelation between the linear size of the source and the rest frame turnover frequency in the sample of Paper VI. The left panel displays the data of all the sources, including the blazars misclassified as GPS sources, and the right panel only the genuine GPS sources. (Adapted from Paper VI.)

dependent on the size of the source. However, the luminosities of the compact sources are greater than those of large scale radio sources. In order to explain this inconsistency, a negative evolution of source luminosity must be assumed. This is confirmed by Tinti & de Zotti (2006) for a sample of GPS galaxies. They found that the luminosity of a source is inversely proportional to the source age. The negative luminosity evolution has been explained with a radial density profile of the ambient medium (e.g., Fanti et al. 1995; Readhead et al. 1996). If the radio brightness depends on the density of the materia against which the jets ram, and if the density decreases with increasing radius, the luminosity of the source decreases as the jets advance further away from the core.

Our results confirm the size-turnover anticorrelation (Paper VI), but we find a somewhat steeper correlation factor of −0.75. The factor is the same for the total sample and for the genuine GPS sources (Fig. 3.2). A large fraction of the sources in the high-turnover and small-size end of the distribution are blazars, misclassified as GPS sources. These sources appear to be compact due to the small viewing angles, and their emission is boosted because of relativistic beaming. Therefore the mechanism for small size and high turnover is fundamentally different than in truly compact and possibly young sources. This result implies that a contiguous correlation behaviour of source populations does not necessarily mean they are related by physical properties or evolution.

Currently it seems well-grounded to say that many of the GPS sources are young. However, it is not clear how they will evolve. The relative numbers of medium-sized symmetric objets and large double radio galaxies are consistent with the negative luminosity evolution of sources, but the compact radio sources over-populate the flux-limited samples (O'Dea & Baum 1997). It is possible that only a small number of GPS sources will evolve into larger radio sources, and most of them are short-lived phenomena which will fizzle out after a relatively short period of activity (e.g., Readhead et al. 1994). Another alternative is that compact CSOs (many of which are GPS galaxies) are closer to equipartition than the larger radio sources and this gives them higher efficiency in jet energy - radio luminosity conversion, and thus they would be over-represented in flux limited samples (Conway 2002).

3.2 Recurrent activity

Currently there is a handful of GPS sources known to have faint extended emission around them. This was first discovered by Baum et al. (1990) who detected a faint single-sided extended emission connected with the compact double candidate B0108+388. They found three possible explanations to the nature of the source: the source could be a core-jet object misidentified as a compact double, it could have been a large-scale radio source until the host galaxy had merged with a gas-rich companion and the radio emitting plasma was confined to sub-galactic dimensions by impenetrably thick ambient gas, or the activity in the nucleus has been reborn after a non-active period during which the large-scale radio lobes of the previous phase of activity have dimmed. Based on their observational evidence, they concluded that the latter, the so-called "recurrent activity" hypothesis is the most likely explanation.

Also the discovery of larger double-double radio galaxies (DDRGs) supports the view of recurrent nuclear activity. Schoenmakers et al. (1999) report of seven Mpc-scale radio sources with clear double-double structure. In these sources also the inner structures are usually extended (overall size ∼ hundreds of kpcs) and the outer structures are more luminous than the inner, but Marecki et al. (2003) report of an extreme case of 1245+676, in which the inner lobes are only 9.6 h^{-1} pc in overall size and ∼ 191 years old, kinematically calculated, whereas the outer lobes extend to nearly 500 kpc on both sides of the core.

Schoenmakers et al. (1999) suggest a "metamorphosis model" to explain the nature and appearance of these sources. The production of the jet in the nucleus is temporarily halted and as the jets die out, the channel it has dug through the surrounding medium collapses due to the surrounding pressure. Once the jet is restarted, it has to drill through the medium to make a new channel, and the inner hotspots are formed. The density around the inner structure is smaller than it was when the outer jets expanded into it, and therefore the luminosity of the inner source is smaller compared to the outer source. Schoenmakers et al. (1999) also note that if the outer lobes were smaller, their radiative lifetimes would be smaller ($\sim 10^6$ yrs) due to their stronger magnetic fields, and they would not be detected as such clear double-double sources. Thus, in these large-scale DDRGs the duty cycle of the nucleus must be larger than among the GPS sources exhibiting recurrent activity.

Studies of spectral ages of CSS sources have presented also some evidence for the intermittent activity in the possible HFP/GPS/CSS continuum. Murgia (2003) found that 10 % of a sample of CSS sources had spectra too steep to be explained by simple ageing of the radiative regions. The result was interpreted to be a possible indication of a high total source age and short duration of current activity phase. According to the model, the spectra are doubly steepened: the first break frequency has aged below the observing frequencies and the second break in the spectra is due to ageing of the currently active regions that have already started to fade.

However, Stanghellini et al. (2005) studied 33 GPS sources to find sources with extended emission, and ended up with six sources, three of which were symmetric galaxy-type objects and three quasar-type core-jet objects. They conclude that extended emission is uncommon among GPS galaxies and that B0108+388 is the only probable candidate for recurrent activity in their sample. Their result implies that if the recurrent model is valid, the periods of inactivity in the GPS sources are longer than the radiative lifetimes of the radio lobes created by the previous active period ($\sim 10^8$ yr).

3.3 Frustrated sources

Baum et al. (1990) give also another possible explanation for the extended structure associated with the GPS source B0108+388. They suggested that the host galaxy could have recently swallowed a large amount of gas and dust, which have confined the radio source and prevented it from growing larger. The idea of dense gas confining a radio source was first suggested by van Breugel et al. (1984a), who found it probable that a large-scale radio source B1346+268 is confined by clumpy, dense line-emitting gas. The idea was elaborated to apply to GPS sources by O'Dea et al. (1991), who found that the host galaxies of some GPS sources are interacting and possibly merging with their neighbours. This has been used as evidence for the youth hypothesis, but as O'Dea et al. (1991) note, the time scales of the interactions may be quite long ($\sim 10^9$ yr). The activity has not necessarily been triggered very recently and thus the lifetimes of the GPS sources may also be comparably long. Hence the GPS sources could be old sources, confined to subgalactic dimensions by the dense gas acquired by the nucleus during intergalactic interactions or mergers. Spectroscopic observations at the time also provided evidence for the unusually dense nuclear gas and high pressure. On the ground of their similar radio characteristics O'Dea et al. (1991) also found it possible that the galaxy- and quasar-type GPS sources form a uniform class of smothered sources. They calculated that, the youth hypothesis being valid, the GPS quasars should make up only ~0.1% of high-redshift radio-loud quasars, whereas the estimate then was much larger, even ~50%, which suggests that the compact structures in GPS sources could be much older than estimated by the youth hypothesis.

However, more recent infrared and spectroscopic observations have argued against the frustration model. Fanti et al. (2000) studied a sample of 17 GPS and CSS galaxies with redshifts $0.2 \leq z \leq 0.8$ and radio sizes < 10 kpc, and a comparison sample of larger (≥ 20 kpc) radio sources with similar redshift and radio luminosity. For the frustration scenario to be valid, there should be a large amount of gas in the host galaxy, but whereas typically the gas and dust are found in the disk or torus perpendicular to the radio source, the frustrating gas should be present on the path of the jet. This confining medium should be detectable in the infrared, as it absorbs and re-processes some of the optical and ultraviolet emission from the nucleus and thus produces an extra IR component in addition to the one from the disk or torus (Fanti et al. 2000). The medium - far-infrared emission they studied did not give any evidence for such extra IR component around the GPS and CSS sources, and hence Fanti et al. (2000) concluded that there is no observational evidence for the frustration scenario.

Spectroscopic evidence against the frustration has been presented by, e.g., O'Dea et al. (2005), who studied whether there is dense molecular gas present in the nuclei of GPS sources. They did not find molecular gas in any of the studied six GPS sources and concluded that at least majority of GPS sources are not frustrated.

Even though frustration has not gained much success in explaining the physical nature of GPS sources, it cannot be ruled out completely. Orienti et al. (2007) studied two very asymmetric CSS sources and found that the closer and brighter of the hotspots in both of the sources is digging its way through a dense ambient medium. The density of the interacting clouds is so high that the hotspots have advanced only ~ 15 % of the distance of the other hotspot travelling in intercloud medium. Similar results have also been found for other CSS sources by Morganti et al. (2004) and Labiano et al. (2006). Although none of the sources was a GPS source and they were only partly confined, the results imply that there may as well exist sources which happen to have dense clouds suitably situated on both sides of the core, thus completely frustrating the growth of the radio source. This is, however, just a rather marginal possibility, not a major solution in explaining the nature of GPS sources.

3.4 Decelerated component model

In the frame work of the frustration scenario, Snellen et al. (1998) suggested a decelerated component model to explain the low variability and the symmetric structure of many GPS galaxies and the relativistic motion observed in some of the nearby GPS galaxies. They suggest that these objects are aligned close to the plane of the sky, and therefore the effects of Doppler boosting remain unobserved even though the velocities of newborn radio components can be highly relativistic. In fact, as the emission is boosted to a direction of the plane of the sky, the component seems very faint to us and its effect on the overall variability and broadband spectral shape is unobtrusive (Fig. 3.3). As the component advances, its velocity is decreased by the drag of the external medium to a moderately relativistic speed, and it expands in volume. Eventually the component will slow down to a barely relativistic or non-relativistic velocity, and form a bright mini lobe when interacting with the surrounding medium. The size of the component is supposed to be small enough for the SSA mechanism to dominate for its entire lifetime. As the emission is no longer boosted towards the direction of the plane of the sky, the minilobes are the dominant components in the total flux density and the overall spectrum, producing a peak at the gigahertz-frequencies.

This model would explain the low variability of the genuine GPS galaxies, as the flux density variations, related to the emergence of a new radio component near the core,

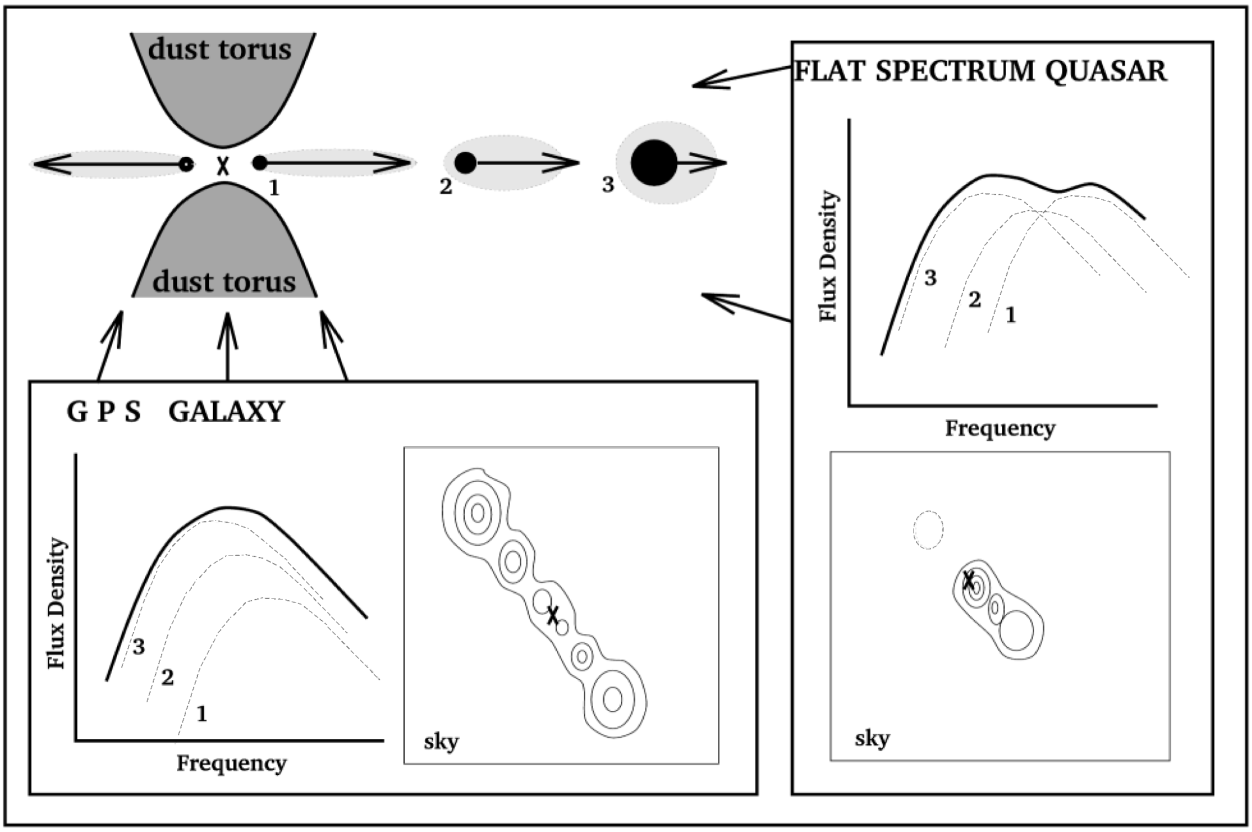


Figure 3.3: The decelerated component model suggested by Snellen et al. (1998). The radio spectrum of a GPS galaxy is a combination of superposed component spectra, whereas if seen from the direction of the jet, the same component spectra would overlap and produce a flat radio spectrum. (Figure: Snellen et al. 1998)

seem faint to us because the boosting occurs to another direction. If a source like this was aligned close to the line of sight, it would be observed as a highly variable flat- or inverted-spectrum quasar or a BL Lac object with a core-jet morphology, because the relativistic effects would blueshift the observed peak frequency of the different components moving towards us. If random orientation of the parent population is assumed, Snellen et al. (1998) suggest that there is one of these beamed sources per 20 decelerated GPS galaxies.

The deceleration model could be tested by observing the evolution of the peak frequency of radio outbursts. In the current shock models the flux density peak moves towards lower frequencies during the entire outburst whereas in the deceleration model the peak frequency should first increase as the Doppler factor increases with the deceleration. Once the expansion starts to dominate, the peak frequency turns down. Determining the evolution of the peak frequency requires monitoring at frequencies on both sides of the turnover. Snellen et al. (1998) found one outburst in the source 3C 454.3 that shows a peak frequency evolution consistent with the deceleration model.

3.5 GPS quasars

The nature of the GPS quasars has not been discussed in the literature as much as the different scenarios of the GPS galaxies. The quasar nature implies that these sources are seen with their jets aligned closer to the line of sight than the GPS galaxies. Due to, for example, the different redshift distribution between GPS quasars and galaxies, it has been deduced that these sources do not belong to the same population seen in different angles but they are different populations with similar shapes of the radio spectra (e.g., Stanghellini 2003; Snellen et al. 1998). Snellen et al. (1998) suggest that seen from the direction of the jet, GPS galaxies would appear as variable flat-spectrum quasars.

If the GPS quasars are seen with their jets pointing towards us, then why do they not show the typical properties of beamed objects, for example, high optical polarization and superluminal motion? Wills et al. (1992) found that out of the 23 GPS or CSS sources with measured polarization in their sample, only two CSS sources showed high polarization: B2230+114 (p_{median} = 7.32%) and B0906+430 (p_{median} = 3.34%). They interpreted these sources to be misclassified, intrinsically large objects that appear to be small due to projection. This result is confirmed in Paper II, where both sources are found to be very variable and the spectrum of B2230+114 very flat even at $\sim$ 300 GHz. Wills et al. (1992) suggest that the lack of high polarization among GPS and CSS quasars is due to either steeper core spectrum, which makes optical emission very weak, or less pronounced Doppler boosting.

Inspired by the gamma-ray detection of some quasar-type GPS sources, Bai & Lee (2005) suggest that GPS quasars could be special blazars with exceptionally dense and dusty environment. This environment would produce such a strong thermal emission that the synchrotron emission would not dominate over it as much as in flat-spectrum quasars, and therefore the total emission would be less polarized and less variable than presumed in beamed sources. However, all their examples of gamma-ray detected GPS quasars (B0528+134, B1127-145 and B2230+114) have been found to be very variable ($Var_{\Delta S,MAX}>3.46$) and not to exhibit a gigahertz-peaked spectrum (Papers II and VI).

A significant proportion of the radio emission of the core-jet GPS quasars has been found to originate from areas close to the core, probably from a knot in the jet, perhaps a compact region in a helical jet where the motion of the particles is aligned towards us (e.g., Stanghellini 2003; Orienti et al. 2006; Lister 2003). This would make the spectrum to appear constantly gigahertz-peaked. Another case for the core-jet type GPS quasars is the fact that since the redshifts of these objects are very high, the possible extended emission is below the detection limit of the VLBI technique (Stanghellini 2003). Therefore, the large size of the object is not seen as only the bright region near the core is detected.

Indeed, many of the GPS quasars identified in the literature have proved to be something else than real GPS sources; their spectrum has had a GPS shape at the time of the classification but combining monitoring data from different frequency bands has shown that the peaked spectrum has been only a temporary feature (Papers I, II, IV, VI). However, there are some quasar-type GPS sources in our sample with confirmed CSO morphology, which Stanghellini et al. (2005) have suggested to be young objects. In Paper VI, the few GPS-CSO quasars are indeed located in a cluster of possibly young sources.

3.6 Case study: X-ray observations

None of the aforementioned models is likely the only right answer. The class of GPS sources is so heterogeneous that a single explanation is not possible. The scenarios may also intertwine differently in individual sources. Every radio source must have been born, therefore there must be sources in their infancy. A large scale source could have been confined for a long time by a dense ambient medium acquired in a merger but once the jets have broken free from the dusty nucleus, they are free to expand with notable velocities. This ambiguous situation is confirmed by observations: all the scenarios have both favouring and opposing evidence. Let us look at, for example, the X-ray observations.

X-rays have conventionally been associated with the accretion disk and the very central parts of the AGNs. Thus X-ray absorption could provide us with information on the gas content of the nucleus. One could presume that X-ray observations could shed some light on the nature of GPS sources, but recent findings have only muddied the waters. First of all, Siemiginowska et al. (2003) discovered large-scale ($\sim$ 30”) X-ray jets associated with two GPS sources (B1127-145 and B0738+313). This surprising result indicates that there is relativistic motion up to hundreds of kpc from the core. These observations are in favour of the recurrent scenario: old electrons from the previous activity phase are detectable in X-rays probably due to inverse Compton scattering of cosmic microwave background photons, while recently born radio components expand into the medium formed by the previous activity. The discovery of a Compton-thick absorber around the nucleus of the GPS source B1404+286 (Guainazzi et al. 2004) provides evidence for the possibility of frustration, but the diffuse extended radio emission around the radio source and the observed separation velocity of the hotspots refer to recurrent activity. On the other hand, Vink et al. (2006) found that X-ray absorption around the five sources in their sample was similar to that of other radio-loud AGNs and did not indicate an exceptionally dense environment that could have confined or smothered the source. This fact together with their other evidence (in Sect. 3.1) led them to support the youth scenario. Thus, The X-ray observations have given us many possible solutions and excluded none.

4 Radio observations on GPS sources

In general, radio observations of AGNs can be done with two different techniques: single dish observations and interferometric observations. Due to the small resolution of a single radio telescope, the extragalactic radio sources cannot be resolved, but the total flux density of the entire source is detected. Good resolution is achieved with interferometric observations, especially with the very long baseline interferometry (VLBI), which enables us to form images of distant radio sources. VLBI has uncovered the parsec-scale structures of the GPS sources, and therefore provided us with many clues on the nature of the sources.

However, the single dish observations still remain the main tool for studying the AGNs. Flux density monitoring in the radio domain has enabled us to study the variability of the AGNs, i.e. what is happening in the jets, whereas combining flux density measurements from various frequencies provides us with the continuum radio spectrum, a way to study the radiation processes that generate the radio emission. In this section, I review the use and the significance of single dish flux density monitoring of the GPS sources.

4.1 Multifrequency monitoring

The flux density of the radio emission from AGNs can vary in time scales of days to decades. According to standard shock models (e.g., Marscher & Gear 1985; Hughes et al. 1985), the variations originate from jets where advancing shocks reaccelerate the relativistic particles. In general, major outbursts happen in AGN on the average every six years (Paper V), and the typical time scales for the outbursts are over two years (Hovatta et al. in prep.), so in order to study the variability behaviour of a source and to model its spectrum at different stages of activity, it must be monitored at several frequencies for several years.

At Metsähovi Radio Observatory, AGN monitoring (e.g., Salonen et al. 1987; Teräsranta et al. 1992, 1998, 2004, 2005) begun in 1980 with a sample of 48 sources. Since then, the monitoring sample has grown to include more than 700 sources that are observed on a weekly to yearly basis. The main observing frequency is 37 GHz, but earlier 22 GHz and 87 GHz have been also used regularly. At present, 22 GHz-observations are done more sparsly. Metsähovi Radio Observatory has therefore a unique archive of high frequency (22, 37 and 87 GHz) observations of AGN spanning over 25 years. Our quasar research group in Metsähovi Radio Observatory also has the benefit of almost unlimited telescope time and the complete freedom of choice for selecting the observing targets. This allows us to concentrate on the sources we find interesting and take part in multifrequency campaigns with a short notice.

Our group has also been able to observe equatorial and southern sources with the late Swedish-ESO Submillimetre Telescope (SEST) at 90 GHz and 230 GHz (Tornikoski et al. 1996). The SEST database contains data from over 155 sources from years 1987 - 2003.

At University of Michigan Radio Astronomy Observatory (UMRAO), AGNs have been monitored since 1965 (e.g., Aller et al. 1985, 1996, 2003a). They first used only the frequency of 8 GHz but in 1974 started observations also at 14.8 GHz and in 1977 at 4.8 GHz. They have a sample of over 200 sources, out of which the most active sources are observed at all three frequency bands weekly and others once every month or three months.

Combining the monitoring data from Metsähovi and the SEST together with the data from UMRAO monitoring programme, we have gathered an unparalleled database of observations, which allows us to study the long-term variability and changes in the shape of the spectrum of AGNs. Completed with the archive data from the CATS database (Verkhodanov et al. 1997), these data have enabled us to study the spectra and variability of GPS sources with unmatched reliability.

4.2 Importance of long-term multifrequency monitoring of GPS sources

In the literature, the classification of GPS sources has been conducted by combining radio data from different catalogues, or at best by observing sources at several frequencies simultaneously, and then studying the resulting radio spectra. However, both of these approaches are inadequate to reveal the overall behaviour of the spectra. When the historical data are combined from different databases, the observations at different frequencies may represent the flux density of the source several years, even decades, apart from each other. In many studies the variability has been neglected, and the spectral indices obtained this way are considered to be indicative of the physical processes of the source. But as we have seen in Sect. 2.3.2, the variability of even the genuine GPS sources can be remarkable and such non-simultaneous datapoints should not be used for any solid conclusions.

Simultaneous observations at different frequencies allow us to study the true shape of the instantaneous spectrum, but again the variability is ignored. The radio flares in AGNs can last for several years and there is no way of knowing whether the shape of the spectrum is convex due to an ongoing outburst or is it intrinsic to the source. Thus, even several simultaneous multifrequency observation runs spanning over a couple of years are not enough to deduce the true shape of the spectrum. This can be clearly seen in Fig. 4.1, where a variable source with ephemeral GPS spectrum ((a) B0238-084) and a genuine GPS source ((b) B0742+103) have been compared. During the first years of observations, there is no significant difference between the sources, but as the dominant outburst in the variable source decays, the flat shape of the spectrum becomes evident. The sparse and incomplete datasets are indicative of the difficulty of these kinds of studies: despite of the hard work done in AGN monitoring at different frequencies, there rarely are sufficient datasets to study the sources in this way. These two sources are among the most monitored GPS sources and yet it was impossible to find exactly simultaneous data or continuous lightcurves for them.

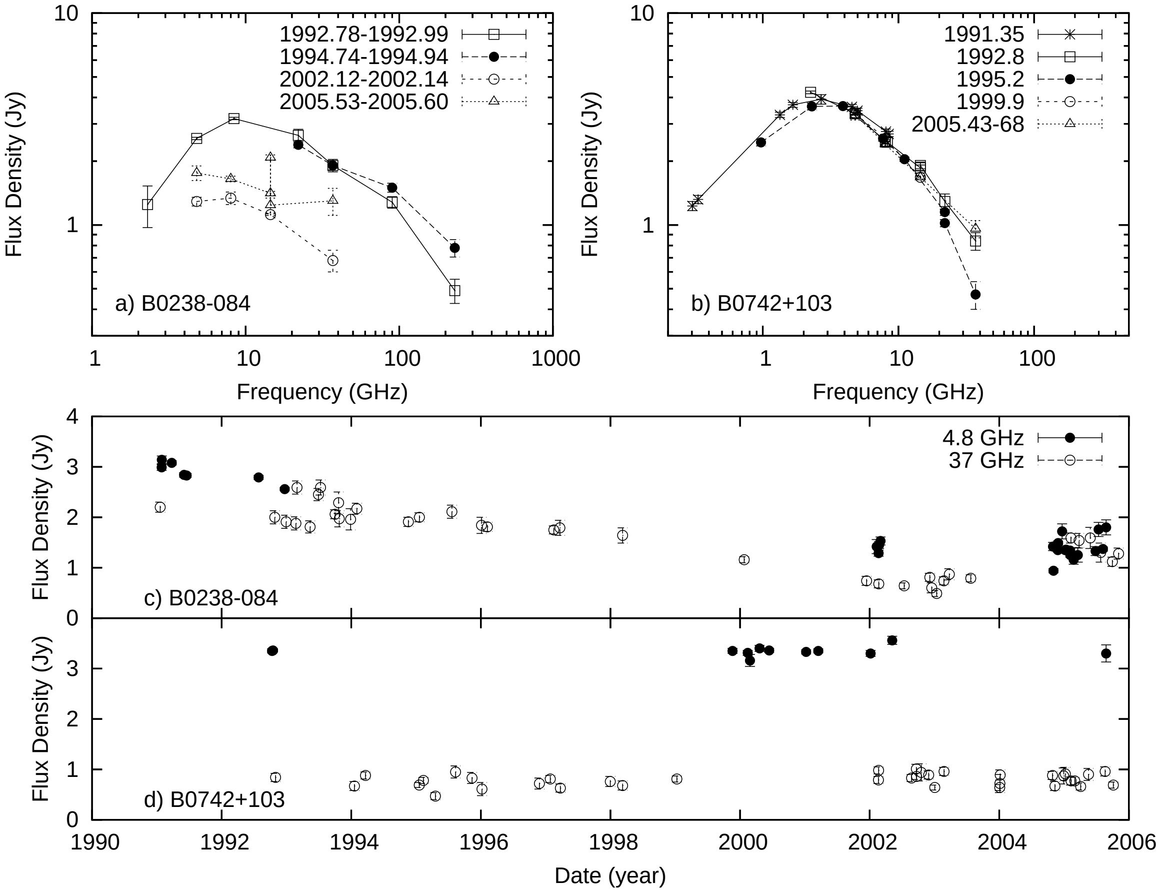


Figure 4.1: The semisimultaneous spectra of two sources identified in the literature as GPS sources. The bottom panels show the light curves of the sources at two different frequencies. Figure from Paper IV.

4.3 Planck satellite and GPS sources

Planck satellite[1] is a mission of European Space Agency (ESA) to explore the anisotropies in the cosmic microwave background (CMB) at frequencies 30 - 857 GHz. It will be launched in 2008 together with the Herschel satellite. Besides its important task in studying the CMB and cosmological issues, Planck will detect galactic and extragalactic sources in the foreground. These sources must be extracted from the CMB maps, and as a by-product of this clean-up, astronomers will get at least two all-sky surveys at frequencies that have never been used before for all-sky surveys.

Most of the common steep-spectrum AGNs are too faint to be detected by Planck at high frequencies, but flat- and convex-spectrum sources will contribute to the CMB

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[1] http://www.rssd.esa.int/Planck

maps. O'Dea & Baum (1997) noticed that the rest-frame turnover frequencies of some high-z GPS sources extended up to 15 GHz and noted that if there is a population of such high-peaking sources also at low redshifts, they would contribute to measurements of the CMB.

Our group has an important role in the Planck Extragalactic Point Source Working Group, which is responsible for the extragalactic contribution to the Planck foreground science. Our task is to make predictions of how many and how bright AGNs Planck will detect. This was one of the main motivators to start studying the GPS sources. In the beginning, we expected to find new high-peaking GPS sources, but after noticing the high level of contamination of GPS samples by variable sources with temporarily GPS-type spectrum (Papers I and II), we have concentrated on studying the level of contamination in other GPS samples (Papers IV and VI).

The highest radio frequencies at which all-sky surveys have been conducted are 4.85 GHz (Green Bank survey, Bennett et al. 1986; Langston et al. 1990; Griffith et al. 1990, 1991; Gregory et al. 1996) and 8.4 GHz (CRATES flat-spectrum source survey, Healey et al. 2007). Considering only the common steep-spectrum sources, the effect of AGNs on the Planck CMB maps would be simple: the flux densities at the Planck frequencies would be easily calculated by using the known flux density at the survey frequency and the spectral index. Also the GPS sources, according to the classical view of low variability and the turnover at ~1 GHz, would be easy to extract from the maps, since the turnover is below the survey frequencies and the optically thin slope is known. However, the complicated picture of temporarily GPS-type spectra of variable sources, the unpredictably high variability of the genuine GPS sources and the possibly unobserved population of extremely high-peaking GPS sources make the predictions challenging.

With the neural network analyses in Paper VI we hoped to clarify the picture of the GPS zoo, and to find some distinctive groups of sources that could help the predictions. Indeed, we found that there are different groups of genuine GPS sources, some with low turnover frequencies and intermediate radio powers and others with high turnover frequencies and high radio powers. There seems to be some level of variability in all of them.

5 Conclusions

In this thesis work, GPS sources and candidates have been studied using multifrequency radio monitoring data from Metsähovi Radio Observatory, the SEST telescope, and UMRAO AGN variability programme, complemented with new observations and data from the literature. We have constructed an extended database of GPS source observations, which allows us to study the shape of the spectrum and the variability of these sources.

The studies presented in this thesis have shown that the majority of the previously identified GPS sources have been misclassified (Papers I, II, IV and VI). The spectra by which the sources have been classified in the literature have been constructed either from few non-simultaneous datapoints from different catalogues, or the classification relies on one or few epochs of simultaneous multifrequency observations. As major outbursts happen in AGNs on the average every six years (Paper V) and the outbursts typically last for a couple of years, a solid classification requires long term monitoring at several frequencies. The misclassified sources have mostly been variable flat-spectrum sources that have temporarily had peaked spectra associated with a radio flare. In Paper III simultaneous multifrequency observations of a blazar, SWIFT J0746.3+2548, have been presented. Using combined flux density measurements from the literature and the campaign, it would have been classified as a high-peaking GPS source, eventhough closer examination reveals it to be a flaring flat-spectrum radio quasar.

One major outcome of this thesis is the observed high variability of the sources which maintain their GPS type spectra. GPS sources have been considered the least variable class of extragalactic radio sources, but we have found variability ranging from 30% to $\sim$ 300% in the confirmed GPS sources, which is approximately 4 to 40 times greater than originally suggested. The variability of the quasar-type GPS sources is somewhat higher than that of the GPS galaxies, but this may be due to smaller number of observations of galaxy-type sources. The presumption of GPS galaxies often having CSO morphologies is confirmed but the core-jet nature of the confirmed GPS quasars seems to be false (Paper VI). GPS quasars have been suggested to be intrinsically large sources seen with a small angle between the jet and the line of sight and therefore they appear to be compact. Our results imply that most of these core-jet GPS quasars indeed are foreshortened large-scale sources, not GPS sources at all. The nature of the compact symmetric GPS quasars remains unknown.

All the previous GPS studies have concentrated on moderate-sized samples of sources and only on one or few properties, or on a single source with wider range of properties, but more extensive approaches have not been used. Also, it must be stressed that the contamination by the variable sources have skewed the results presented in the literature with a major impact. We have compiled a sample of 206 GPS sources identified in the literature and collected a wide range of parameters for them to analyse the clustering of the sources into possibly different populations. We have used self-organizing neural maps (SOMs) to form clusters of similar sources. The results of the cluster analysis support our earlier results of high degree of contamination of GPS samples. The blazar-type sources form clusters clearly separate from the clusters of genuine GPS sources. However, the population of genuine GPS sources is not uniform, but there are several clusters of different objects. There is a cluster of young and small low-redshift galaxies with CSO morphology, but for some reason the turnover frequencies of these sources are very low, in contrast with the expectations from the size - turnover frequency anticorrelation. There is a cluster of high-peaking quasars and galaxies, with CSO and CD morphologies, which also could be young sources. There is also a cluster with some evidence of free-free absorption.

Based on the results of this thesis, the population of GPS sources presented in the literature is very heterogeneous, and a great fraction of sources are not true GPS sources. Moreover, the genuine GPS sources, even when separating the quasar- and galaxy-type sources, do not form a homogeneous population either, but there seem to be many types of sources exhibiting a GPS-type spectrum.

6 Summary of the papers

6.1 Observations of GPS sources and sources with temporarily inverted spectra

Paper I: *Radio spectra and variability of gigahertz-peaked spectrum radio sources and candidates*
by Tornikoski, M., **Jussila, I.**, Johansson, P., Lainela, M., Valtaoja, E.

Paper II: *Long term variability of gigahertz-peaked spectrum sources and candidates*
by **Torniainen, I.**, Tornikoski, M., Teräsranta, H., Aller, M.F. and Aller, H.D.

Paper III: *Discovery of an Extreme MeV Blazar with the Swift Burst Alert Telescope*
by Sambruna, R. M., Markwardt, C. B., Mushotzky, R. F., Tueller, J., Hartman, R., Brandt, W. N., Schneider, D. P., Falcone, A., Cucciara, A., Aller, M.F., Aller, H.D., **Torniainen, I.**, Tavecchio, F., Maraschi, L., Gliozzi, M., Takahashi, T.

Paper IV: *Radio continuum spectra of gigahertz-peaked spectrum galaxies*
by **Torniainen, I.**, Tornikoski, M., Lähteenmäki, A., Aller, M.F., Aller, H.D. and Mingaliev, M.G.

The first four papers in this thesis present new observations of GPS sources and candidates, as well as sources that temporarily have a convex radio spectrum.

In Paper I, we used data from our observing programmes with the SEST, complemented with data from the literature, to study equatorial and southern, mostly quasar-type, AGNs with convex spectra. We identified 12 new sources with GPS-type spectra, and eight other sources having an inverted feature at gigahertz-frequencies. Because we found strong variability in the mm-domain in most of our new candidates, we wanted to study the overall spectral shape and variability of known GPS sources and candidates. We investigated the ’bona fide’ GPS sources observed at SEST and found remarkable variability also among them. After combining all the data from our observations with the data from the literature, we found that some of the known GPS sources actually were flat spectrum sources that had been classified as GPS sources using insufficient data.

Inspired by the results of Paper I, we wanted to repeat the investigation on the northern hemisphere in Paper II using the data from Metsähovi monitoring programme and UMRAO variability programme. From the literature, we collected all GPS sources that had been sometimes observed in Metsähovi, and also picked up promising GPS candidates from the monitoring programme for further studies. We made new observations of the sources and collected data from the literature. We expected to find some new high-peaking GPS sources but, instead, we found that most of the GPS sources identified in the literature were strongly variable and that only a small fraction (5 out of 44) of them kept their original GPS classification. Others were too flat, too variable, or they showed convex shape in the spectrum only during outbursts. None of our new candidates turned out to be a genuine GPS source. Instead of presenting new high-peaking GPS sources we ended up smashing the classifications of previously identified sources. Evidently, the classifications had been made with too sparse data sets and ”masquerading” blazars (Lister 2003) had been mistaken as GPS sources.

Out of 60 sources in the entire sample of previously identified convex spectrum sources and our candidates in Paper II, there were only four sources optically identified with a galaxy. The rest were quasars and blazars. Thus, the contamination was evident only for the quasar-type GPS sources. In Paper IV we studied the variability and shape of the spectrum of galaxy-type GPS and HFP sources. We collected a sample of 96 sources from the literature, gathered data from the literature using the CATS database (Verkhodanov et al. 1997), the archives of Metsähovi and UMRAO monitoring programmes, and made new observations with Metsähovi and RATAN-600 telescopes. Our presumption that the GPS galaxy sample would be fairly uncontaminated proved to be misconceived. Only a third of the sources were clearly to be classified as GPS sources, a third were candidate GPS sources with too sparse data sets for a solid classification, but nothing contradicting a possible GPS identification. The rest of the sample were either too flat, too variable or their turnover frequencies were too low (< 500 MHz) to be gigahertz-peaked. Thus, the galaxy-type GPS sources proved to be less contaminated than the quasar-type sample but yet there is a remarkable share of misclassified objects in the galaxy sample.

In Paper III a new extreme MeV blazar is presented. The source SWIFT J0746.3+2548 was detected in hard X-rays by the Burst Alert Telescope (BAT) onboard Swift satellite. It was one of the brightest objects detected during the first three months of the BAT sky survey, and a multifrequency campaign was launched to study its spectral energy distribution across the electromagnetic spectrum.

SWIFT J0746.3+2548 is an example of a blazar, or more precisely a flat-spectrum radio source, which could have easily been misclassified as a GPS source if the flux density data from the observations and the literature were combined. The source has been monitored at 2.5 and 8.2 GHz by Lazio et al. (2001) in 1988 - 1995. The flux density was not observed to vary at all at 2.5 GHz, and if the 2.5 GHz data were combined with the radio observations of the multifrequency campaign, the source would have been classified as a GPS source. The 8.2 GHz flux density varied substantially but for most of the time the result would have been the same.

6.2 Long-term variability of AGNs

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

The amount of monitoring data has more than tripled since the variability time scale study by Lainela & Valtaoja in 1993. They studied the typical variability time scales of the Metsähovi monitoring sample at frequencies 22 GHz and 37 GHz using the structure function. Following their approach, we have used the structure function, and also the discrete correlation function and the Lomb-Scargle periodogram to study the radio light curves obtained during over 30 years of monitoring in UMRAO and Metsähovi. The frequencies studied were 4.8, 8.0, 14.5, 22, 37, 90 and 230 GHz.

In the perspective of this thesis, the most important outcome of Paper V is that smaller outbursts occur in AGNs typically on timescales of 1 - 2 years and major outbursts with intervals of ~6 years, and that, in some cases, even monitoring of 10 years is not enough to reveal the true variability behaviour of an AGN. The differences between the various source types (low and high polarization quasars, galaxies and Bl Lac objects) were insignificant. In the sample of 80 sources, there were 11 sources classified as GPS sources in the literature out of which there were two sources with a confirmed GPS-type spectrum according to our studies. The timescales of these sources did not differ from the other sources in the sample.

6.3 Cluster analysis of GPS sources

Paper VI: *Cluster analyses of gigahertz-peaked spectrum sources with self-organizing maps*
by **Torniainen, I.**, Tornikoski, M., Turunen, M., Lainela, M., Lähteenmäki, A., Aller, M.F., Aller, H.D. and Mingaliev, M.G.

From the studies presented in the literature it was obvious that there are many different types of GPS sources. Furthermore, our studies showed that among the GPS sources presented in the literature there were many sources belonging to other source populations, and there was no clear parameter or parameter combination combining the genuine GPS sources. All the previous GPS studies have concentrated either on one or very few individual sources, or on a sample of sources but only with few source properties. We wanted to study the whole population of previously classified GPS sources through all possible parameters to find out if there were distinctive, physically fundamentally different source populations of genuine GPS sources.

For this purpose we collected a sample of 206 GPS sources and HFPs identified in the literature. For these sources, we gathered a database of different source parameters (for example, the redshift, the size, the morphology, the spectral indices) and performed analyses using self-organizing neural maps (SOMs). The SOM algorithm is used for visualizing multidimensional data and clustering similar sources without prior knowledge of their classification.

The results of Paper VI confirm that there is a population of sources with typical blazar properties contaminating the GPS samples. These sources are mostly quasars, they are foreshortened by projection, and therefore their emission is beamed and variable. Temporarily, their spectra show GPS-like features as new shock components emerge and fade away. In the cluster analysis, these sources form clusters clearly separathe from the genuine GPS sources. Also the sources with genuine GPS-type spectra form discrete clusters of differing sources. There are galaxy-type sources with low turnover frequencies and intermediate radio powers, yet they are small and young sources confirmed by kinematic and spectral age estimates. There is also a mixed cluster of galaxies and quasars, mostly with CSO and CD morphologies, which also could be young sources. They have high turnover frequencies and high radio powers and the sizes of the sources with linear size information are small. There is also, for example, a cluster of sources with some evidence of free-free absorption. The main outcome of this paper is that the population of genuine GPS sources is not homogeneous even if the quasar- and galaxy-type sources are considered separately.

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