TURUN YLIOPISTON JULKAISUJA
ANNALES UNIVERSITATIS TURKUENSIS

SARJA - SER. A I OSA - TOM. 416

ASTRONOMICA - CHEMICA - PHYSICA - MATHEMATICA

VARIABILITY IN ACTIVE GALACTIC NUCLEI: UNDERSTANDING EMISSION MECHANISMS AND UNIFICATION MODELS

by

Carolin Villforth

TURUN YLIOPISTO
UNIVERSITY OF TURKU
Turku 2011

From the Department of Physics and Astronomy
University of Turku
Turku, Finland

Supervised by

Dr. Kari Nilsson
Tuorla Observatory
University of Turku
Turku, Finland

Reviewed by

Prof. Dr. Juri Poutanen
Astronomy Division
Department of Physics
University of Oulu
PO BOX 3000
90014 Oulu, Finland

and

Dr. Denise Gabuzda
Department of Physics
National University of Ireland
University College Cork
Cork, Ireland

Opponent

Dr. Paolo Padovani
European Southern Observatory (ESO)
Germany

ISBN 978-951-29-4569-6 (PRINT)
ISBN 978-951-29-4570-2 (PDF)
ISSN 0082-7002
Painosalama Oy - Turku, Finland 2011

Weshalb ist das Erkennen, das Element des Forschers und Philosophen, mit Lust verknüpft? Erstens und vor Allem, weil man sich dabei seiner Kraft bewusst wird, also aus dem selben Grunde, aus dem gymnastische Übungen auch ohne Zuschauer lustvoll sind. Zweitens, weil man, im Verlauf der Erkenntniss, über ältere Vorstellungen und deren Vertreter, hinauskommt, Sieger wird oder wenigstens es zu sein glaubt. Drittens, weil wir uns durch eine noch so kleine neue Erkenntniss über Alle erhaben und uns als die Einzigen fühlen, welche hierin das Richtige wissen.

Friedrich Wilhelm Nietzsche

Acknowledgments

Knowing that this is the part of the thesis that will be read by most people, I feel some pressure to make this the best part of thesis. But it seems that I can only come up with the usual list of thank yous.

I would like to thank all the people that have made this thesis possible. Foremost, I would like to thank my supervisor Dr. Kari Nilsson for his support throughout the last four years. I would also like to thank Dr. Anton Koekemoer for giving me the possibility to work at the Space Telescope Science Institute and for his support during my stay there.

During the four years of my thesis, I had the pleasure to work abroad at the Nordic Optical Telescope and the Space Telescope Science Institute. I would like to thank all my colleagues at the Nordic Optical Telescope for the great time I had there, I learned a lot from all of you and also thoroughly enjoyed my time on La Palma, even the staff meetings. I would also like to thank the Space Telescope Science Institute for the scientifically stimulating environment, I greatly enjoyed all the talks and heated scientific discussions.

Of course, no PhD student can survive without money. I would like to thank the following persons and organisations for their financial support: The Nordic Optical Telescope for support during my NOT studentship, Dr. Anton Koekemoer for financial support through the STScI graduate research assistantship program, The Emil Aaltonen Foundation and Dr. Elina Lindfors.

My gratitude also goes to the following persons (and things): Sami-Matias Niemi for especially critical proof-reading of good and not so good drafts, controversial scientific discussions and being a wonderful husband, my sister Teresa for bravely attempting to read some of my articles and being a great little sister, Ricardo Cardenes for converting me to Python programming and performing go-to-exorcism, Tapio Pursimo for turning me into a Stokes-plane fundamentalist, Jarkko Niemelä for being my fellow polarimetry-nerd at the NOT and of course OJ287 for being an extremely annoying blazar.

Special thanks also goes to my reviewers Prof. Juri Poutanen and Dr. Denise Gabuzda, whose comments have improved the thesis, as well as Dr. Paolo Padovani who has agreed to be my opponent.

Carolin Villforth

Contents

Acknowledgments **4**

List of publications **6**

1 Introduction **7**

2 Active Galactic Nuclei **9**
- 2.1 A short history of AGN 9
- 2.2 The AGN Zoo 10
- 2.3 AGN Unification Models 16
- 2.4 AGN in Cosmology 26

3 AGN Physics **29**
- 3.1 Accretion 29
- 3.2 Jets 33
- 3.3 Narrow and Broad Line Regions 42
- 3.4 Obscuration 44

4 Variability as a key to understanding AGN **47**
- 4.1 Where are the radio-quiet blazars? 47
- 4.2 What are the physical conditions in blazar jets? 48
- 4.3 Finding low-luminosity AGN at high redshifts 51
- 4.4 Where are the supermassive binary black holes? 52

Bibliography **55**

Original papers **75**

List of publications

I *Intranight polarization variability in radio-loud and radio-quiet AGN*
Villforth C., Nilsson K., Østensen R., Heidt J., Niemi S.-M., Pforr J.
MNRAS **397**, 1893 (2009)

II *Variability and stability in blazar jets on time scales of years: Optical polarization monitoring of OJ287 in 2005-2009*
Villforth C., Nilsson K., Heidt J., Takalo L.O., Pursimo T., Berdyugin A., Lindfors E., Pasanen M., Winiarski M., Drozdz M., Ogloza W., Kurpinska-Winiarska M., Siwak M., Koziel-Wierzbowska D., Porowski C., Kuzmicz A., Krzesinski J., Kundera T., Wu J.-H., Zhou X., Efimov Y., Sadakane K., Kamada M., Ohlert J., Hentunen V.-P., Nissinen M., Dietrich M., Assef R.J., Atlee D. W., Bird J., DePoy D. L., Eastman J., Peeples M. S., Prieto J., Watson L., Yee J. C., Liakos A., Niarchos P., Gazeas K., Dogru S., Donmez A., Marchev D., Coggins-Hill S. A., Mattingly A., Keel W. C., Haque S.. Aungwerojwit A., Bergvall, N.
MNRAS **402**, 2087 (2010)

III *A new extensive catalog of optically variable AGN in the GOODS Fields and a new statistical approach to variability selection*
Villforth C., Koekemoer A. M., Grogin N. A.
The Astrophysical Journal **723**, 737 (2010)

IV *A change in the optical polarization associated with a γ-ray flare in the blazar 3C279*
Fermi-LAT Collaboration & Members of 3c279 multi-wavelength campaign
Nature **463**, 919 (2010)

CHAPTER 1
Introduction

Active Galactic Nuclei (AGN) are amongst the most luminous objects in the Universe. They produce incredible amounts of radiation in a volume only a few light years across. Only 50 years after the first discovery of these interesting objects, we have a good idea of the basic building blocks of Active Galactic Nuclei (Antonucci 1993; Urry & Padovani 1995). A supermassive black hole is at the centre of the AGN. Plasma is accreting onto the black hole in a hot accretion disk. Gas in the vicinity of the black hole is ionised by the accretion disks emission. Part of the gas moves in the gravitational potential of the black hole and emits extremely broad line emission. Further out, the gas moving in the gravitational potential of the galaxy emits narrow line emission. A thick dusty torus surrounds those elements obscuring the emission for certain viewing angles. In some sources, plasma is ejected in highly relativistic well-collimated jets that can span over several hundred thousands lightyears.

Studying the detailed physical conditions in AGN can be extremely challenging. The sizes of centres of AGN are only on the order of light years. Only with the advent of near-infrared interferometry in the last years has it become possible to marginally resolve the dust torus in a few nearby AGN (NGC 1068 and Circinius, see Jaffe et al. 2007; Tristram et al. 2007; Raban et al. 2009). Therefore, to understand what is going on in the centres of AGN, indirect methods have to be used. Due to the fact that practically all AGN show variability throughout the electromagnetic spectrum (Ulrich et al. 1997; Koo et al. 1986; Wagner & Witzel 1995; Paper I), variability studies have made a great contribution to our understanding of AGN.

Monitoring the echo of accretion disk bursts in the broad line emitting gas has taught us about the geometry and size of the broad line region (Kaspi et al. 2007). By connecting these studies to independent black hole mass estimates, it has become possible to estimate the black hole masses for a large number of AGN using only simple spectroscopic data (Vestergaard & Peterson 2006; Vestergaard et al. 2008). Our knowledge about AGN jets is based mostly on monitoring campaigns in different wavelength ranges (D'Arcangelo et al. 2009; Marscher et al. 2008, Paper IV). Over the years, the understanding of shock fronts travelling down the jet has been growing (Marscher & Gear 1985), thanks to research of the variability in jets. This has led to the understanding of the building blocks of jets even down to scales that cannot be resolved with even the most high-resolution imaging methods.

The purpose of this thesis is to summarise how variability studies can be used to help understand the physical conditions in AGN as well as the role that AGN play in cosmology.

In Paper I, we address the open question if all AGN have relativistic jets. While relativistic jets are clearly detected in many radio-loud AGN, radio-quiet AGN, the most commonly observed AGN, mostly do not show relativistic jets. One of the clearest sign of a relativistic jet is the fast variability on time-scales of hours and below that is observed in many highly beamed objects. In Paper I, we use optical polarization variability data of different types of AGN on timescales of hours to try to assess if the variability observed is due to a relativistic jet. Our data indicate that the variations on time-scale of hours and below reported for some sources are either extremely rare or not due to jet emission.

Paper II and IV are both aimed at constraining the physical conditions in the unresolved parts of AGN jets. While jet emission in the radio is nowadays rather well understood due to the superb resolution available in the radio using interferometry, only a handful AGN jets can be resolved in the optical. In Paper II we use optical polarization monitoring to study the little understood conditions in the collimation zone of AGN jets. We find a stable source of polarized emission, indicating the presence of a stable magnetic field in the part of the jet that emits the optical radiation. We also find that shock fronts are likely not the main source of polarized emission and variability in the optical jets. Paper IV uses monitoring data in multiple wavelength to constrain the origin of the highest energy radiation observed in jets. The data indicate that the highest energy emission is emitted cospatial with the optical emission.

Paper III focuses on the evolution of AGN through cosmic times. In the last years, it has become clear that the properties of AGN likely change through cosmic times and that those changes can be used to better understand AGN physics and unification models. However, many high-redshift AGN samples are heavily affected by selection biases and especially little is known about the locally abundant class of low-luminosity AGN. In Paper III we use variability to select AGN candidates up to high redshifts. We developed a new method that allows us to control for underestimated errors. We show that it is possible to select highly interesting low-luminosity AGN up to redshifts higher than three using this method.

In Paper II, we additionally address the question if and how variability studies can be used to find supermassive binary black holes. While supermassive binary black holes are expected to be formed when two massive galaxies merge, no close supermassive binary black hole has been confirmed so far. In Paper II, we study the binary black hole candidate OJ 287, an object that has been studied over decades as a possible close binary black hole due to its pseudo-periodic outbursts (deviations from strict periodicity by over a year are observed). Collecting all available data, we conclude that at this point, all proposed binary black hole models have clear conflicts with some of the data, indicating that OJ 287 possibly does not host a close binary black hole.

CHAPTER 2
Active Galactic Nuclei

2.1 A short history of AGN

> "...quasi-stellar radio-sources have been eyed by observational cosmologists as potentially very useful standard candles..."
>
> Jack A. Baldwin

Active Galactic Nuclei first entered the astronomical history in the 1950s. The first AGN were detected in the radio wavelength and were lacking optical counterparts. A catalogue of those objects was published in the 1960s, the Third Cambridge Catalogue or 3C Catalog (Bennett 1962). Objects from this catalogue still belong to the most widely studied AGN, including such famous sources as 3C 273 or 3C 279. In the 1960s, the first optical counterparts to the 3C sources were detected. Amongst the first sources with identified optical counterparts were 3C 48, 3C 196 and 3C 286 (Matthews & Sandage 1963). Their optical counterparts were faint, point-like sources with highly peculiar extremely blue spectral indices (Matthews & Sandage 1963). This gave the first AGN identified by humans the odd name 'quasi-stellar radio source' or simply 'Quasar'.

The first spectroscopic observations of quasars in the optical brought more surprises: the objects showed extremely broad emission lines at wavelengths at which no atomic emission lines were known (Matthews & Sandage 1963). Other authors soon realised that those lines could be identified with known atomic lines when extreme redshifts were assumed. The first redshifts were derived for 3C 48, showing a redshift of 0.367 (Greenstein & Matthews 1963) and 3C 273, showing a redshift of 0.158 (Schmidt 1963). Those values correspond to extremely high recession speeds of about 47 000 km/s for 3C 273 and as much as 110 000 km/s for 3C 48. This raised the question if quasars are nearby, fast moving objects or if the redshift is of cosmological origin. However, it soon became clear that it is not possible to explain speeds as extreme as indicated by observations of the first quasars unless the redshift is of cosmological origin. Evidence for this explanation has grown over decades. Quasars have been observed up to redshifts as high as 7 (Fan et al. 2001), also, observations of high-redshift quasars lensed by lower-redshift galaxies (McGreer et al. 2010) confirm a cosmological origin of the quasar redshifts.

On the other hand, the extreme luminosities required for the redshifts to be of cosmological origin puzzled astronomers. Quasars often outshine the most luminous galaxies by several orders of magnitudes. Clearly, the process powering these objects must be different from emission mechanisms known at this point. On top of that, those extreme luminosities are emitted in a volume of only a few lightyears across. The transformation of gravitational energy into radiation was found to be the source behind the extreme luminosities observed in AGN.

It was also discovered that some objects undetected in the radio still show similar properties as the original sample of quasars. This led to the name QSO (Quasi-Stellar Object) for 'quasars' with no or only weak radio emission and the beginning of a flood of detections of Active Galaxies with different properties and in the aftermath to a rather confusing AGN Zoo with a vast number of names. Only as late as the beginning of the 1990s did a unified model of AGN emerge (Antonucci 1993; Urry & Padovani 1995) and it became possible to explain a large variety of AGN with very different properties. The unified model postulated that all AGN are intrinsically similar and that most observed differences are due to orientation effects.

Once the basic properties of AGN were understood, it was recognised that AGN can be used as laboratories for the most extreme physical conditions such as hot plasma, extreme magnetic fields, black holes and relativistic motion. Hence, the study of AGN can open possibilities to study extreme physics far beyond the current possibilities of laboratories.

2.2 The AGN Zoo

"...orientation effects have been the source of much confusion."

Roberto Antonucci

Before we continue to the properties of AGN and the physical processes inside AGN, it is a good idea to take a step back and consider what an AGN actually is. In the simplest interpretation one could say that AGN are central unresolved point-sources in galaxies, emitting a non-stellar spectrum. But what are the observables of those sources and how can they be identified?

• **Point-like appearance** was one of the first striking properties of the first observed AGN, resulting in the name quasar. The first quasars looked point-like. Until now, the centres of AGN remain unresolved. The point-like appearance of the first AGN was mostly caused be the fact that the nucleus in those sources was so bright that it overshadowed the hosting galaxy. Thus, the point-like appearance of AGN heavily depends on the ratio of nucleus to galaxy luminosity, but also on the deepness of the studied image and the redshift of the object. It even depends on the wavelength at which the object is studied as the luminosity of both the nucleus and the host galaxy are strongly wavelength dependent. Many nearby as well as high-redshift but low-luminosity AGN show clear extended emission from the hosting galaxy. Thus, the fact that this feature is regarded one of the most prominent of AGN is due to the fact that the first AGN to be detected in the optical were high-redshift[1], radio-loud, sources dominated by nuclear emission.

[1] The definition of what is high redshift has considerable evolved over time, while redshifts of far below

• **High luminosity:** The luminosities of AGN span a very wide range, from 10^{42} up to as much as 10^{48} erg/s. For comparison, a typical galaxy has a luminosity of about 10^{44} erg/s. However, this might be a biased view of AGN. For example, much fainter AGN might exist, but those would be extremely hard to detect against the background host galaxy. On the other hand, the influence of obscuration is still not understood. Some AGN are believed to be surrounded by heavy dust tori obscuring most of the central emission. Such obscuration can result in most of the bolometric luminosity to be emitted as thermal emission of hot dust heated by the AGN in the infrared or in the X-ray, which can still pierce thick layers of dust.

• **Emission over the whole electromagnetic spectrum:** Many AGN emit radiation over the whole electromagnetic spectrum, from radio through optical to X- and even to γ and TeV rays. However, not all parts of the electromagnetic spectrum are prominent in all types of AGN. Considerable radio emission is only seen in about a tenth of all AGN. Similarly, hard-X-ray and γ-ray emission is not present in all AGN. Optical and soft-X-ray emission on the other hand is observed in practically all AGN.

• **Line emission** is observed in two different flavours in AGN: broad and narrow line emission. A line is labeled broad if its velocity dispersion is greater than $\sim$ 1 000-2 000 km/s, but line widths up to as much as $\sim$ 10 000 km/s are observed in some AGN (Boroson & Green 1992). A notable feature is created by the numerous FeII lines in the optical: those lines are merged due to their extreme broadness and, together with the Balmer continuum, form a 'little blue bump' near 5000 Å(Netzer 1985). Broad lines are not visible in all AGN and their strength compared to the narrow lines can change considerably between objects (Krolik 1999). Narrow lines on the other hand are present in practically all AGN. The width of the narrow lines can differ but is generally very close to the velocity dispersion of the underlying galaxy (Nelson & Whittle 1995; Nelson & Whittle 1996). While broad line emission is a clear sign of an AGN, narrow lines also appear in 'normal' galaxies, especially in starbursting objects (Veilleux & Osterbrock 1987). Emission line diagnostics of the narrow line ratios can be used to distinguish AGN from 'normal' starforming galaxies (Baldwin et al. 1981; Veilleux & Osterbrock 1987; Heckman 1980a).

• **Variability** is found in practically all AGN when observed over a long enough period of time (Koo et al. 1986). Variability reaches down to timescales of hours in some objects (Wagner & Witzel 1995; Paper I). Variability by several orders of magnitudes is observed on timescales of decades in some objects (e.g. Hufnagel & Bregman 1992; Ulrich et al. 1997; Fernandes et al. 2000; de Vries et al. 2005; Emmanoulopoulos et al. 2010, Paper II). Variability is observed throughout the wavelength range from radio (e.g. Valtaoja et al. 1992) through optical (e.g. Koo et al. 1986; di Clemente et al. 1996; Wold et al. 2007) up to X-rays (e.g. Vaughan et al. 2003; Paolillo et al. 2004) and even γ-rays (e.g. Maraschi et al. 1992; Ghisellini 2009). The variability can usually

1 were considered high when first observed in Quasars, nowadays only redshifts beyond 6 are considered high.

be described as so-called 'red noise' with a slope of about -2 (e.g. Trevese et al. 1994; Ulrich et al. 1997; Vaughan et al. 2003). It is yet unclear if breaks in the power spectrum, which would be associated with a characteristic time scale of the variability, are present or if detections of such breaks are due to the uneven and limited time-sampling of the light-curves (Emmanoulopoulos et al. 2010). Some authors also successfully used other statistical prescriptions such as for example damped random walks to describe AGN light-curves (e.g. Kelly et al. 2009; Fernandes et al. 2000), but it is generally recognised that AGN variability is 'random'. For reviews on AGN variability, see e.g. Wagner & Witzel (1995), Ulrich et al. (1997) or Uttley & Mchardy (2004).

• **Radio jets** can be seen in a minority of AGN. In some cases, they are extremely compact, showing an unresolved core with only weak extended emission (Wardle et al. 1984) on parsec scales. Other AGN show clearly extended jets that can reach Mpc scales and extend beyond the hosting galaxy into the halo (Fanaroff & Riley 1974; Laing & Bridle 1987; Bridle et al. 1994). The jets are usually highly relativistic at least on parsec scales, and in some cases on kpc scales (Blandford & Konigl 1979).

• **Polarization** is observed in some AGN and comes in two flavours: polarization due to synchrotron emission and reflection polarization. Synchrotron-based polarization is most prominent in high-luminosity objects (Angel & Stockman 1980). The most extreme optical polarization is observed in blazars and can sometimes reach values greater than 40% in the optical, while being lower in the radio (Rudnick et al. 1978; Jorstad et al. 2007; Paper II). Reflection polarization on the other hand is more prominent in low-luminosity AGN. It can reach up to $\approx 15\%$ and is usually not strongly wavelength dependent in the optical (Antonucci 1993). For a review of optical and near-infrared polarization properties of AGN, see Angel & Stockman (1980).

However, no AGN is observed to show all of the above features and the appearances of AGN are complex. This led astronomers to create a multitude of AGN 'classes' containing a certain subset of AGN showing a certain set of observables. The first classification system for AGN (along with a simple attempt to describing the differences) was presented by Lawrence (1987). These AGN classes can be excessively confusing. Most of them were created on purely phenomenological standards and later it was realised that many classes show significant overlap. Therefore, before continuing, I will introduce the most commonly used labels for AGN and their definition. Additionally, a simple flow chart for the classification of AGN is shown in Fig. 2.1. The abbreviations used in this Figure are described in the following paragraphs.

• **Radio-Loud quasars (RLQ) and Radio-Quiet Quasars (RQQ)** are AGN that have a ratio of B-band to radio luminosity greater (RLQ) or smaller (RQQ) than 10, respectively (Kellermann et al. 1989). In general, in accordance with Veron-Cetty & Veron (2006) only objects with an absolute B-band magnitude brighter than -23 are considered quasars, all fainter objects are considered Seyfert galaxies. About 10% of optically selected quasars are found to be radio-loud (Kellermann et al. 1989) though the fraction increases with both optical (Padovani 1993; Franca et al. 1994) and X-ray

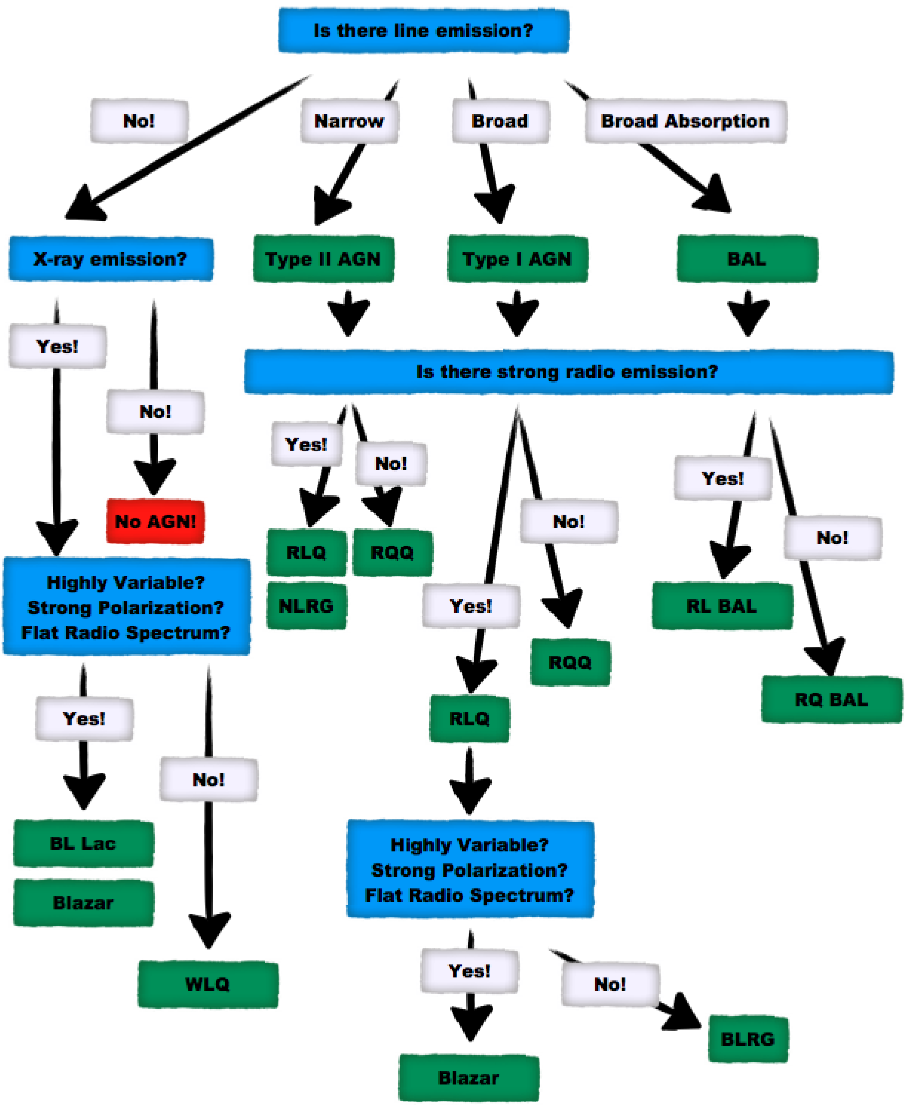

Figure 2.1: *A simple flow chart for the classification of AGN.*

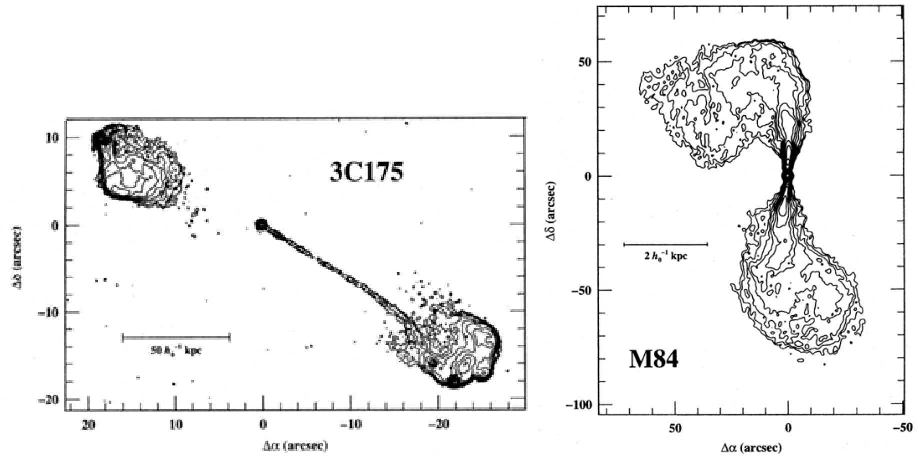

Figure 2.2: *Comparison of radio morphology for different types of Fanaroff-Riley Radio Galaxies. The left picture shows 3C175 (From Bridle et al. 1994), a FRII radio galaxies, gigantic luminous lobes are clearly visible. The right picture shows M84 (Laing & Bridle 1987), a FRI radio galaxy.*

luminosity (della Ceca et al. 1994).

• **Seyfert 1 and 2 Galaxies** are low-luminosity AGN ($M_B > -23$), they are divided into subclasses according to the appearance of their emission lines. In the most simply subdivision, objects showing broad emission lines are labeled Seyfert 1 galaxies while objects without broad lines are labeled Seyfert 2 galaxies. Lines are considered broad if they have an velocity dispersion of $> 1000 - 2000$ km/s (Krolik 1999). More precise subclasses (Seyfert 1.0, 1.2, 1.8, 1.9, 2.0), depending on the exact appearance of the broad lines are sometimes used (Krolik 1999).

• **Type I and Type II Quasars** are the bright counterparts of Seyfert 1s and 2s. The Type I objects have broad emission lines while the Type II objects do not. To my knowledge the decimal numbered subclasses are generally not used for quasars.

• **Narrow Line Radio Galaxies (NLRG)** are galaxies with resolvable radio jets that show only optical narrow line emission. Sometimes, also low-luminosity AGN that are radio-loud (i.e. radio-loud Seyferts) are labeled radio galaxies (e.g. Urry & Padovani 1995 use this convention). This makes NLRGs radio-loud Seyfert 2s.

• **Broad Line Radio Galaxies (BLRG)** are galaxies with resolvable radio jets that show broad optical emission lines. Sometimes, also low-luminosity AGN that are radio-loud (i.e. radio-loud Seyferts) are referred to as radio galaxies (e.g. Urry & Padovani 1995 use this convention). This makes BLRGs radio-loud Seyfert 1s.

• **Fanaroff Riley Type I and II Radio Galaxies**: Fanaroff & Riley (1974) studied a sample of radio galaxies and found that their radio morphologies show two distinct classes, which were thereafter labeled Fanaroff-Riley I and II radio galaxies (commonly abbreviated as FRI / FRII, respectively). FRI galaxies are commonly described as edge-darkened: their jets are most luminous near the centre and fade further from the core, ending in gigantic radio lobes or plumes. The jet decelerates to sub-relativistic speeds on kpc scales (Bicknell 1985). FR II galaxies on the other hand are edge brightened, the jets are rather faint near the bright radio core and end in gigantic hot spots, located at the tips of radio lobes. The jets are relativistic up to Mpc scales (Bicknell 1985). FR I and II radio galaxies are also found to differ in their radio luminosity with FRIs being of low and FRIIs of high luminosity (Bicknell 1985). For example images of both types, see Fig. 2.2.

• **BL Lac objects** have been named after BL Lacertae. The defining criterion is a emission line equivalent width of less than 5Å(Urry & Padovani 1995). Additionally, violent variability and high optical polarization are required. All of those requirements are somewhat arbitrary and can be confusing. For example, the BL Lac prototype BL Lacertae itself sometimes has too strong line emission to be a BL Lac object (Vermeulen et al. 1995).

• **Optically Violently Variable (OVV)** are objects that show violent (i.e. both fast and strong) variability in the optical.

• **High Polarization Quasar (HPQ)** are objects that show high polarization in the optical, usually $P > 3 - 5\%$ is adopted as a limit Urry & Padovani (1995). Note that the polarization in most, if not all, highly polarized objects is also variable. Similarly, sometimes objects with lower degrees of polarization are labelled Low Polarization Quasars (LPQs).

• **Flat Spectrum Radio Quasars (FSRQ)** are quasars with a flat radio spectrum with a slope α_r of $-0.5 < \alpha_r < 0.5$ (Urry & Padovani 1995). It is nowadays established that a great majority of FSRQs are highly beamed sources (Urry & Padovani 1995). It is commonly believed that the flat spectrum is caused by synchrotron emission from a combination of emission zones with different self-absorption frequencies.

• **Steep Spectrum Radio Quasars (SSRQ)** are quasars with a steep radio spectrum $\alpha_r > 0.5$ or < -0.5 (Urry & Padovani 1995).

• **Blazars** is a rather new class which is used to unite BL Lac objects and FSRQs. It has been found that the FSRQ, HPQ and OVV classes are all virtually identical (Fugmann 1988; Impey et al. 1991; Valtaoja et al. 1992). BL Lac objects also belong to this class (Urry & Padovani 1995). Since it has been proven that practically all objects in this class are highly beamed (Antonucci 1993; Urry & Padovani 1995), the word blazar is commonly used to refer to all highly beamed AGN. Usually, all objects with weak line emission are labeled BL Lacs while all others are referred to as FSRQs.

• **Weak-lined Quasars (WLQs)** is a very new class describing objects that show weak or absent optical line emission, but are not BL Lacs (i.e. no high optical polarization, violent variability or flat radio spectrum). This subclass of AGN has only lately been discovered (Shemmer et al. 2009; Diamond-Stanic et al. 2009) and the origin of those sources is still a mystery.

• **Broad Absorption Line (BAL) Quasars** are quasars that show broad absorption lines (Turnshek & Grillmair 1986) near the systemic redshift. A special subclass of this class is build by FeLoBALs, BALs showing low-ionisation iron lines in absorption (e.g. Farrah et al. 2007). Roughly 10% of radio-quiet AGN are BALs (Turnshek 1984). Radio-loud BALs are extremely rare (Becker et al. 1997; Wills et al. 1999).

• **LINERs** are narrow-lines, low-ionisation AGN, identified through optical emission line ratios (Heckman 1980a; Heckman 1980b). LINERs are commonly believed to be the lowest luminosity AGN, they commonly also show very high starformation rates.

• **Compton-Thick AGN** are a subclass of extremely heavily obscured AGN, usually a cut-off for the H column density at $N_H > 10^{24}\mathrm{cm}^{-2}$ is adopted. Compton-thick AGN are detected in the very hard X-ray ($>$ 6 keV) only (Daddi et al. 2007). It is yet unclear how common they are, but those sources are suspected to contribute significantly to the X-ray background emission (Treister et al. 2009).

It should be noted that these classifications are not exclusive, objects can belong to several of these classes. It should also be noted that these labels are not always used consistently and different authors use different definitions. Therefore, it is wise to be aware how a given label is defined in a certain study and how the studied objects where selected.

2.3 AGN Unification Models

> "...All idealisation makes life poorer. To beautify it is to take away its character of complexity – it is to destroy it. Leave that to the moralists, my boy."
>
> Joseph Conrad, *The Secret Agent*

With the multitude of different AGN types described in the last Section, it becomes clear that to understand AGN, one needs to understand what causes the diversity in their appearances. From the discovery of AGN in the 60s and 70s, it took till the early 90s to get an understanding of the nature of AGN.

The most pressing question in the early days of AGN research concerned the broad emission lines seen in some AGN. It seemed that AGN were divided into two distinct classes: AGN with and without broad emission lines. The question that needed to be answered was: are Type II AGN missing broad-line emitting gas or is the broad-line emitting gas 'hidden' from our line of sight by some kind of obscuring material? As described in the previous Section, objects showing broad emission lines are known as Type I Quasars or Seyfert 1s (depending on their luminosity) and those without broad lines are known as Type II Quasars or Seyfert 2s. To avoid unnecessary confusion, in the further discussion both low-luminosity Seyferts and high-luminosity Quasars will be refereed to as Type I and Type II AGN, respectively.

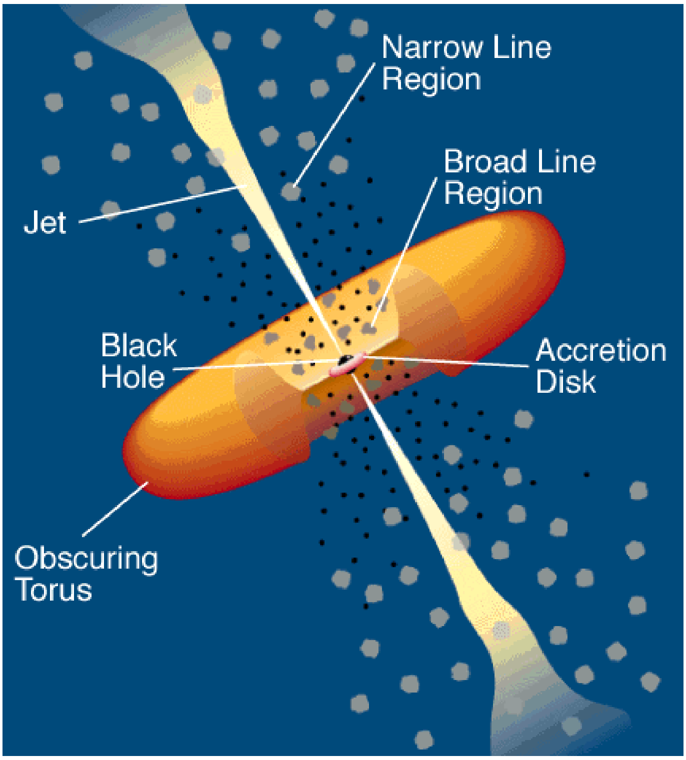

Figure 2.3: *The notorious AGN cartoon from Urry & Padovani 1995. The components of the model are not too scale.*

By the mid-90s, numerous observations had pointed to the direction that orientation causes the bulk of the differences between different types of AGN. Antonucci (1993) collected all evidence available at that time and discussed what he referred to as the 'straw person model' for AGN: there are (intrinsically) two different types of AGN, radio-loud ones and radio-quiet ones. Both types occur with a certain range of intrinsic luminosities, but all other apparent differences are due to orientation effects. The radio-loudness of some objects in this model is caused by an additional source of emission that is unrelated to the other properties of the AGN, i.e. the jets emitting in the radio do not show correlations with the other building blocks of the AGN.

From this basic straw person model (SPM), one can derive a unified model of AGN which describes the basic building blocks of AGN: a supermassive black hole in the centre of the AGN, surrounded by a flow of accreting gas. The emission from the accretion ionises clouds of gas moving in the potential well of the central black hole, forming the broad-line region. A doughnut shaped torus of obscuring dust surrounds the broad line region and accretion disk. Above the torus, gas clouds in the potential well of the galaxy are also ionised by the soft X-ray and UV emission from the accretion disk, emitting the strong narrow lines observed in all AGN. Outflows are present in all AGN, but are weak for radio-quiets and well collimated and strong for radio-louds. The famous cartoon showing this 'Unified Model of AGN' is shown in Fig. 2.3.

The SPM is the rather undisputed core of the Unified Model of AGN. Urry & Padovani (1995) in another review paper with a similar scope as the Antonucci (1993) review, came to the same conclusions about the basis of the Unification Model. However, they limited their discussion to radio-loud AGN and at the same time went a step further than Antonucci (1993) by dividing the radio-loud AGN into two subclasses, defined by their Fanaroff-Riley morphology. Urry & Padovani (1995) suggested that when beamed, FRI radio galaxies become BL Lacs and FRII radio galaxies become FSRQs. This notion was also discussed by Antonucci (1993), but was rejected due to a lack of evidence. Indeed, this part of the Unified Model according to Urry & Padovani (1995) is still under debate and observations suggest that such a clear dichotomy does not exist (e.g. Antonucci & Ulvestad 1985; Kharb et al. 2010).

I will therefore first discuss evidence that shows that the SPM or the core unification model (as described by both Antonucci 1993 and Urry & Padovani 1995) is correct to first order. In the next paragraph, I will discuss open questions and problems, including the Fanaroff-Riley-Blazar Unification suggested by Urry & Padovani (1995).

2.3.1 The unified model is right: Mirrors & Screens

Mirrors: A conclusive evidence for the SPM would be to see the BLR in Type II AGN. This would prove that the BLR is present, but obscured from our line of sight. While this may seem like an absurd plan, it has actually been achieved. The idea behind this is the following: if broad line regions exist inside an obscuring structure of unknown shape, the emission from those regions will be partially absorbed by the obscuring material and partially reflected. The reflected emission will be extremely weak. However, as reflection introduces linear polarization, the broad emission lines should be visible in polarized light. Spectropolarimetric observations can therefore help to detect the gas that is obscured from our line of sight (Antonucci 1993). Indeed, broad emission lines in polarized light have been detected in numerous Type II AGN (Antonucci 1982; McLean et al. 1983; Miller & Antonucci 1983; Antonucci & Miller 1985; Miller & Goodrich 1990; Tran et al. 1992). The first detection of hidden BLRs in Type II AGN was in NGC 1068, the prototype Type II Seyfert (Miller & Goodrich 1990). The spectrum of NGC 1068 with the hidden BLR emission is shown in Fig. 2.4. Without any doubt this is the single most conclusive evidence for hidden broad-line regions in most Seyferts 2s.

Ionisation cones: If the central part of the AGN is obscured on some lines of sight and not on others, one should be able to see the light 'escape' from the centre even if the emission is not directly observable. Such 'ionisation cones' are seen in several AGN. They are aligned with both the radio structure (Ulvestad et al. 1981) and the NLR (Tadhunter & Tsvetanov 1989; Evans et al. 1991). The edges of the cones are surprisingly sharp (Tadhunter & Tsvetanov 1989; Evans et al. 1991), which is expected if

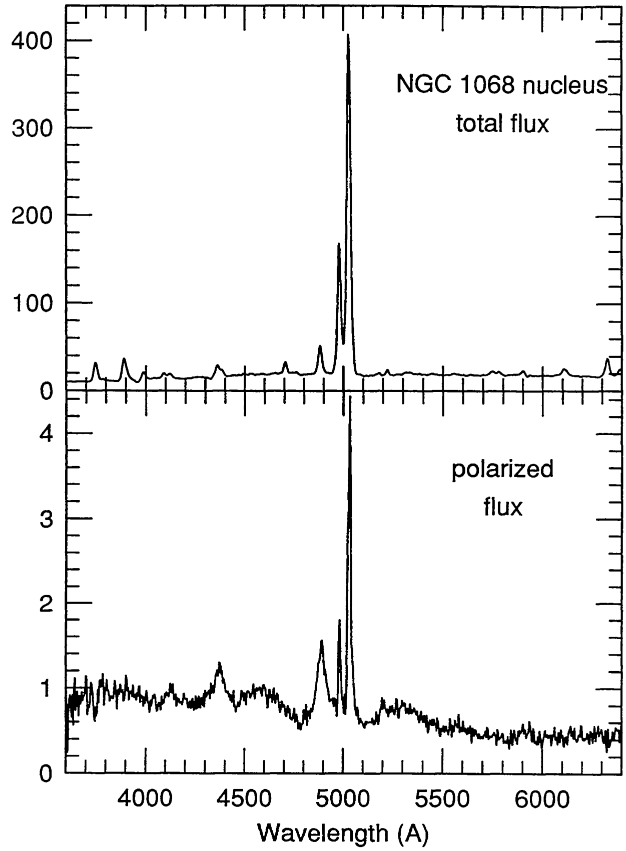

Figure 2.4: *Spectropolarimetry of NGC 1068 taken from Antonucci (1993). The top panel shows the flux and the bottom panel shows the polarized flux. Clear broad emission lines show in the polarized emission while only narrow lines are visible in the total flux. The broad component of Hβ at 486.1nm is clearly visible.*

they are indeed caused by ionising photons escaping from the central region, constricted by the obscuring structure. Therefore, ionisation cones are yet another indication for the validity of the unified model (Pogge 1988; Haniff et al. 1988; Ulvestad et al. 1981; Evans et al. 1991; Antonucci 1993).

X-ray emission and obscuration: Another way to test the SPM is through X-ray emission. As X-ray emission originates from very close to the AGN core, it should be obscured similar to the BLR. Dust obscuration is however stronger in the optical than in the X-ray (Antonucci 1993). If we imagine 'tilting an AGN' from very high to lower inclination angles, the X-ray will start shining through the obscuring material before the BLR becomes visible. Indeed, this has been observed in several AGN (Warwick et al. 1989; Awaki et al. 1990; Awaki et al. 1991).

Blazars: The unified model predicts a very rare subclass of AGN: those almost exactly aligned with our line of sight. Blazars are believed to be those rare objects (Urry & Padovani 1995). The most convincing arguments for blazars being the beamed counterparts of normal AGN are the superluminal motion observed in blazars and their ultrafast variability observed throughout the electromagnetic spectrum. Superluminal motion was predicted by Rees (1966), it has since been observed in a number of sources (e.g. Witzel et al. 1988; Gabuzda et al. 1989; Jorstad et al. 2001; Lister et al. 2009; Marscher 2009) and can only be explained through beaming from a relativistic source moving close to the line of sight (see Section 3.2 for a closer description of superluminal motion). Rapid variability down to time-scales as short as a few minutes is observed in many blazars throughout the electro-magnetic spectrum, but preferably at optical and higher energy wavelengths (e.g. Maraschi et al. 1992; Wagner & Witzel 1995; Ulrich et al. 1997; Gupta et al. 2008; Foschini et al. 2010; Rieger & Volpe 2010; Tavecchio et al. 2010). Such variability is hard to explain using any other mechanisms, since light-time travel arguments set an upper limit on the variability timescales. Beaming can make observed variability timescales much shorter. In support of the theory that blazars are beamed sources, it can be shown that the large scale radio emission and jet length in blazars are consistent with the assumption that they are the beamed counterparts of 'normal' jets (Schilizzi & de Bruyn 1983; Antonucci et al. 1987; Barthel 1989; Antonucci 1993).

Jet asymmetries, i.e. asymmetries between the two sides of the jet, can also be used to test the blazar unification. It is found that jets of high-luminosity AGN are often one-sided (Bridle & Perley 1984; Parma et al. 1987 see also the example FRII radio galaxy in Fig. 2.2). Asymmetries between the stronger and weaker side (Bridle 1992) and the detection of weak counter-jets in apparently one-sided sources (Axon et al. 1989; Stiavelli et al. 1992; Sparks et al. 1992) suggest that those asymmetries are due to beaming. Another way to prove that the jet asymmetries are due to beaming is through depolarization measurements. If beaming is the source of the asymmetries, emission from the weaker counter-jet has to travel through more host galaxy medium and therefore the depolarization is stronger for the weaker (de-beamed) side of the jet. Indeed, it has been found that such depolarization is consistent with beaming as a source for the asymmetry in many sources (Laing 1988; Garrington & Conway 1991; Tribble 1992), while in a few cases the depolarization is not due to beaming but foreground processes (Taylor et al. 1990; Fernini et al. 1991; Clarke et al. 1992). However, it is recognised that beaming is the major cause of jet asymmetries (Antonucci 1993; Urry & Padovani 1995).

2.3.2 The unified model is wrong: Open questions, incomplete AGN and the blazar unification

Antonucci (1993) already pointed out that the unification model is only correct to first order. In this Section, I will discuss open questions and problems of the core unification model as well as the Fanarof-Riley-Blazar-Unification suggested by Urry & Padovani (1995).

A question that came up early in the discussion about possible unification models is if 'true Type II AGN' exist (Antonucci 1993). While it is proven that *many* Type II AGN have hidden BLRs (Antonucci & Miller 1985; Miller & Goodrich 1990; Tran et al. 1992), this clearly does not imply that *all* Type II AGN do. Therefore, the question remains if there is a bimodality in the Type II population. Some authors argued that evidence for such a bimodality exists (Hutchings & Neff 1991; Neff & Hutchings 1992), while others have argued against such a bimodality (Antonucci 1993). Most FRI radio galaxies have cores which do not show BLRs (Baum et al. 1995), however, those objects also show little signs of an accretion disk and NLRs that seem to be ionised by the host galaxy light (Baum et al. 1995), making them something different than 'true Type II AGN'. Another candidate sample for 'true Type II AGN' are weak-lined AGN (McDowell et al. 1995; Londish et al. 2004; Leighly et al. 2007; Leighly et al. 2007; Shemmer et al. 2009; Diamond-Stanic et al. 2009). However, most of those objects do show weak broad emission lines. The detection of a rather large number of these objects at redshifts greater than two (Shemmer et al. 2009; Diamond-Stanic et al. 2009), has caused interest amongst researchers. However, research about their nature is still ongoing. Section 3.3 will show that certain models for the origin of the BLR clearly predict that BLR cannot form under certain conditions and therefore true Type II AGN must exist (see e.g. Czerny et al. 2004 and Section 3.3).

Another open question is how the cores of FRIs and FRIIs compare, i.e. are the differences in jet morphology related to intrinsic differences in the accretion flow or broad-line emitting region? It has been noted that most FRIIs show strong line emission, while most FRIs show significantly weaker line emission (Baum & Heckman 1989; Rawlings et al. 1989; Zirbel & Baum 1995). Baum et al. (1995) showed that the cores of FRI AGN show properties that cannot be explained by obscuration. The lack of broad emission lines and the properties of the narrow emission lines can however be well explained when assuming that the AGN in the centres of FRI radio galaxies accrete through radiatively inefficient Advection Dominated Accretion Flows (ADAFs) (Narayan & Yi 1994) (for more on accretion flows, see Section 3.1). However, other authors have shown that some FRIIs have low-excitation emission lines similar to those found in many FRIs (Hine & Longair 1979; Laing et al. 1994). A similar trend seems to be indicated by the findings of Owen & White (1991) and Owen & Ledlow (1994), who found the radio luminosity at which the FRI/FRII break takes place to depend on optical luminosity. All this indicates that while there is no clear dichotomy in the properties of Fanaroff-Rileys, the two types of sources show on average different properties in their accretion flows and line emitting regions. Apart from their optical properties, FRIs and FRIIs might also live in different environments, with FRIs residing in massive cluster ellipticals while FRIIs tend to avoid dense environments (Prestage & Peacock 1988; Hill & Lilly 1991; Zirbel 1997). Other authors (Owen & Ledlow 1994) however have not found such a correlation between the Fanaroff-Riley type and the environment.

Additionally, it is still not understood how the different FR types appear when observed as highly-beamed blazars. The first attempts to pin down the parent populations of BL Lacs were made by Browne (1983) and Wardle et al. (1984). Both suggested that BL Lac objects are the beamed counterparts of FRI radio galaxies. This explanation was included as a part of the unified model by Urry & Padovani (1995). Antonucci (1993) on the other hand pointed out that the evidence for FRIs being the parent population of BL Lacs is less obvious. Kollgaard et al. (1992) studied the extended radio morphology of 17 BL Lac objects and found a majority, but not all of them, to belong to the FRI class. Similar properties of the extended emission were found by Kharb et al. (2010). However, if we take a step back and think about what defines a BL Lac and what defines a FRI, part of this contradiction resolves. FRIs are defined by the morphology of their extended radio emission (Fanaroff & Riley 1974), while BL Lacs are defined by the weakness or absence of their line emission (Urry & Padovani 1995). It has been found that the radio power (and therefore FR type) does correlate with line emission strength (Baum & Heckman 1989; Rawlings et al. 1989; Zirbel & Baum 1995), however this does not mean that all FRII have stronger line emission than FRIs. It only follows that FRIIs have on average stronger line emission. Actually, if blazars are the beamed counterparts of a mixed sample of FRI and FRII radio galaxies, one would only expect the BL Lacs to be *on average* the beamed counterparts of FRIs and FSRQs to be *on average* the beamed counterparts of FRIIs. Therefore, findings such as those by (Kollgaard et al. 1992; Kharb et al. 2010) are not a severe problem for unification, but simply show that AGN classification can be complicated.

Still, more research is necessary to how the beamed counterparts of FRI and FRII jets relate to FSRQs and BL Lacs. Some studies comparing the properties of FSRQs and BL Lacs exist. Xu et al. (2009) compared host galaxy properties of BL Lacs and FSRQs and found results consistent with those of FRIs and FRIIs (Owen & Ledlow 1994), but no clear dichotomy in the properties was found and the results only indicate that the unification is true on average. Ghisellini et al. (2009) studied the γ-ray properties of a sample of FSRQs and BL Lacs and found them to show distinct differences implying that FSRQs accrete through normal thin disks and BL Lacs through radiatively inefficient accretion flows, in agreement with Baum et al. (1995) and Urry & Padovani (1995). In Paper II we found indications that FSRQ jets are on average much more turbulent than BL Lac jets. However, further research will be needed to understand the differences between FSRQs and BL Lacs and to see how blazars can be united with FR radio galaxies.

Part of the solution will include better classification of objects into the two blazar-subclasses. It has been argued that the dividing line at 5Å is arbitrary and does not reflect any physical separation . Some blazars show strong variations in their emission line strength. For example, 3C 279 is a transition object that is sometimes a BL Lac and sometimes a FSRQ (Koratkar et al. 1998). Amusingly, even the BL Lac prototype BL Laceratae sometimes exhibits such strong emission lines that it is technically no longer a BL Lac (Vermeulen et al. 1995). Studies of both the emission line strength (Vermeulen et al. 1995; Koratkar et al. 1998; Benitez et al. 2009) and the strength of the blue bump (Fiorucci et al. 2004) are needed to understand how the optical line emission and accretion properties of blazars relate to their jet properties.

Broad-Absorption Line (BAL) AGN (Turnshek & Grillmair 1986) are a subclass of AGN that pose a problem for the SPM: they show extremely broad absorption lines that are believed to be related to outflowing gas (Turnshek & Grillmair 1986). Soon after their discovery, it was noted that most if not all BAL objects are radio-quiet (Turnshek 1988; Stocke et al. 1992), indicating that the source if the broad-absorption lines is specific to radio-quiet AGN. The search for radio-loud BAL objects has recently shown some success (Becker et al. 1997; Wills et al. 1999), but it is still clear that most BALs are radio-quiet, though some data seems to indicate that the problem is smaller than initially believed (Becker et al. 2000). Observations of broad-absorption line systems could be explained as a sign of slow uncollimated outflows (instead of fast, collimated jets) being present in some or all radio-quiet AGN (Antonucci 1993), but the origin of the BALs remains a puzzle. Understanding this open question would require answering the question if radio-quiet AGN have relativistic jets at all, and if not, what type of outflows they have. There is evidence for relativistic jets in some radio-quiet AGN (Blundell et al. 2003), as well as indications from fast optical variability observed in radio-quiet AGN (de Diego et al. 1998; Gopal-Krishna et al. 2003). But the question of the nature of radio-quiet jets or outflows remains unanswered. Our Paper I addressed this question by studying fast optical polarization variability in radio-loud and radio-quiet AGN. However, no evidence for relativistic jets was found (see also Section 4.1).

2.3.3 The next level of unification?

As we have seen, the unification model is clearly very successful to the first order. Some problems exist, but none are significant enough to raise any doubt in the fact that most differences in appearances of AGN are due to orientation effects. As has been shown, the problems in the Fanaroff-Riley-Blazar-Unification can possibly be resolved by addressing some of the inaccuracies in the naming scheme commonly used and hence these problems most likely do not pose a serious problem to unification.

Other problems can be resolved by using more physical models for the origin of the main building blocks of AGN. In general, a next level of unification is needed to account for intrinsic differences in the AGN, such as in the accretion flow (Baum et al. 1995; Ghisellini et al. 2009), emission line strengths (Zirbel & Baum 1995) or jet properties (Kharb et al. 2010; Paper II).

The clear differences between the two types of radio galaxies need to be understood. Attempts have been made in that direction. Some authors have suggested that environmental effects cause the differences (Young 1993; Gopal-Krishna & Wiita 2000). Those authors suggest that the jets of FRI and FRII radio galaxies start out identically, but the environment 'brakes' the FRI jets while leaving the FRII jets intact. Gopal-Krishna & Wiita (2000) pointed out that a small population of hybrid FRI-FRII sources exist (i.e. one side of the jet is FRI-like, while the other is FRII-like). This can clearly only be

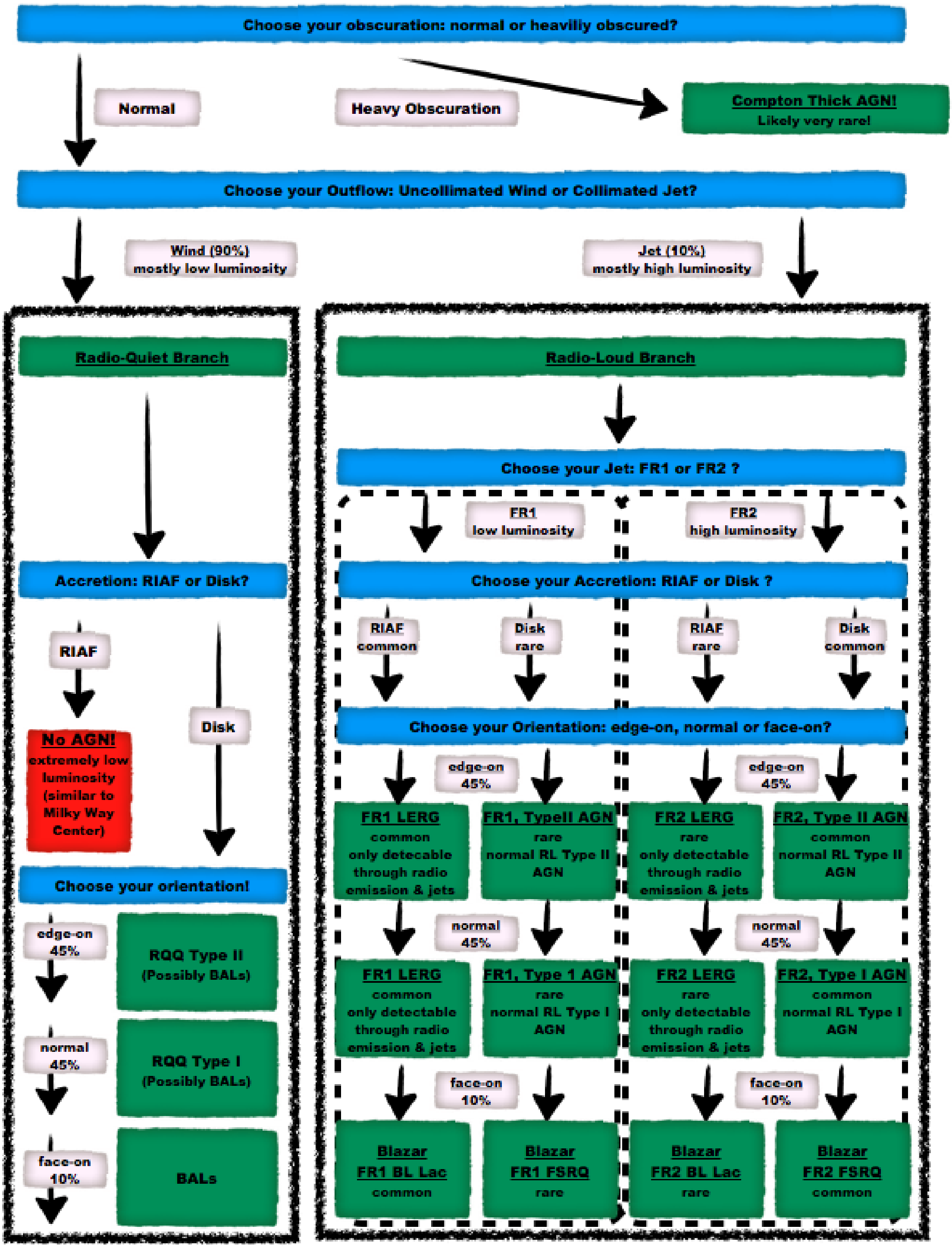

Figure 2.5: *A simple flow chart for 'building' an AGN. The chart makes some simplifications, for example, poorly understood classes such as weak-lined quasars or true Type II AGN are not included. Percentage values in the white 'decision' boxes give the approximate percentage of objects with the given value.*

explained by environmental effects. Other authors have suggested intrinsic differences. Celotti & Fabian (1993) suggested that the content of the jets is different, with FRI jets having $e^+ - e^-$ content (i.e. pair plasma) and FRIIs having $e^- - p$ content (i.e. normal plasma). Ghisellini & Celotti (2001) suggested a 'switch' between FRI and FRII jets at a certain black hole mass, with heavier black holes producing the stronger, FRII-type jets. They speculated that this 'switch' might be related to a critical mass accretion rate at which the accretion flow properties might change. Their interpretation is consistent with the findings of Baum et al. (1995): FRIs and FRIIs accrete differently. Another suggestion is that the black hole spin decides the jet power and morphology (Meier 1999), with slowly spinning black holes creating FRI-type jets and faster spinning black holes producing FRII jets. Meier (1999) showed that there might be a rather sudden 'switch' acting, explaining the clear dichotomy of radio morphologies.

A similar approach as the one by Meier (1999) was taken by Garofalo et al. (2010). However, they not only explained the differences in jet power and morphology but proposed a model that can explain most of the intrinsic differences between different types of radio-loud AGN as well as their evolution through cosmic times using simple physical prescriptions. They based their analysis on simple physical prescriptions of jet launching mechanisms (For a more detailed discussion of the physics of AGN jets, see Section 3.2). They combined the two most renowned jet launching mechanisms, the Blandford-Znajek and the Blandford-Payne process and showed how the jet power evolves if one assumes that both processes act simultaneously. Garofalo et al. (2010) showed that the jet strength depends on the spin of the black hole as well as the alignment of the accretion disk rotation with respect to the black hole spin. They showed that such a simple model can explain the differences in emission line strength between FRIs and FRIIs (Zirbel & Baum 1995) as well as their evolution with redshift (Stocke 2001; Garofalo et al. 2010 and references therein). This model partially explains some earlier findings and can explain many differences between the two FR classes. As we will see later, the two different jet launching mechanisms are very likely to influence the content of the jet, therefore, the model described by Garofalo et al. (2010) might well explain the differences in the jet content suggested by Celotti & Fabian (1993). Additionally, the Garofalo et al. (2010) model also predicts differences in accretion flows, similar to the ones found by Baum et al. (1995). Garofalo et al. (2010) clearly put forward an extremely interesting suggestion for the second round of unification.

Another open question is how radio-loud and radio-quiet objects are related. Earlier research suggested a quite clear dichotomy between the radio-loud and radio-quiet objects. However, recent observations have shown that a population of radio-intermediate sources exist (Falcke et al. 1996). It is not yet understood what distinguishes the outflows in RQQs and RLQs. The fact that practically all BALs are RQQs (Turnshek 1984), seems to indicate that the BALs are signs of an outflow type unique to RQQs. However, RQQs with relativistic jets are known (Blundell et al. 2003), moreover, it is unclear which physical conditions might cause an AGN to either show well collimated jets or weakly collimated winds. The fact that RQQs are predominantly located in spiral galaxies while

RLQs are predominantly located in ellipticals (e.g. Hamilton et al. 2002; Dunlop et al. 2003) might indicate environmental effects. On the other hand, simple assumptions that low spins might cause objects to show uncollimated outflows and therefore be radio-quiet are questioned by the fact that the spins measured so far in radio-quiet Seyferts are high (e.g. Brenneman & Reynolds 2006; Schmoll et al. 2009). However, modelling uncertainties in such studies are generally high. More research about the launching of jets is needed to resolve these questions. Paper I addressed this question by using polarization variability data (see Section 4.1).

Clearly, the next level of unification will have to concentrate on understanding the physics within jets and how accretion, line emitting regions and jets interact in AGN and influence each other. We need to understand how the different parts of AGN form and which conditions influence the properties of AGN. The first steps made in this direction are promising and likely the next few years will bring researchers much closer to a second round of unification.

As an amusement to the reader, 2.5 shows a simple flowchart that can be used to build an AGN and see how it would appear to an observer.

2.4 AGN in Cosmology

> "...a radio star must not emit very much light and should be situated in an interstellar cloud. This would explain why it is so difficult to find astronomical objects associable with radio stars. "
>
> Hans Alfven & N. Herlofson

AGN moved to the centre of attention outside the AGN community in the mid-90s when several studies found that the masses of black holes in the centres of local giant elliptical galaxies correlate with the properties of their hosts (Gebhardt et al. 2000; Graham et al. 2001; Marconi & Hunt 2003; Novak et al. 2006; Graham 2007). These findings have puzzled researchers ever since. It was recognised early on that the gravitational influence of the central black hole is significant only in the very centre of the galaxy. It has therefore been suggested that some kind of conspiracy between the black hole and its hosting galaxy is required to achieve strong correlations between the masses of black holes and properties of the hosting galaxy. Additionally, detailed studies of local radio galaxies have shown that AGN strongly influence the hot gas in their halo. AGN jets inflate giant bubbles in the cluster gas and heat the gas through shocks (Churazov et al. 2002). These effects are especially well studied in the local FRI radio galaxy M 87 (Bohringer et al. 1995; Forman et al. 2007).

These findings have sparked the idea that AGN feedback, i.e. the influence of AGN activity on the entire galaxy or even on the cluster, plays a major role in galaxy evolution. The idea of AGN influencing the star formation in their hosting galaxies was first suggested by Silk & Rees (1998). AGN feedback has found great resonance amongst researchers studying the evolution of galaxies through semi-analytical models (Granato et al. 2004; Matteo et al. 2005; Croton et al. 2006). Indeed, AGN feedback in such codes has been shown to be an effective way to avoid the overproduction of massive galaxies in N-body simulations (e.g. Somerville et al. 2008). However, the mechanism that produces this AGN feedback is still not understood and strong feedback such as in M 87, is only observed in a small number of galaxies. But those codes also include a second, more mysterious type of AGN feedback: this mode relies only on the radiation from the accretion process (Silk & Rees 1998), it is usually referred to as 'quasar mode feedback' and has so far only been observed in a single source (Feruglio et al. 2010).

Lately, it has been suggested that AGN feedback is at least not necessary to produce the correlations found between central black holes and the properties of their hosting galaxies at low redshifts (Peng 2007). Both Hirschmann et al. (2010) and Jahnke & Maccio (2010) showed, by using simulations, that such correlations occur naturally through merging from completely uncorrelated seeds of galaxies and black holes. Such studies have raised some doubt in the notion that AGN feedback plays a pivotal role in galaxy evolution. Still, more data about AGN throughout cosmic times is needed to answer the question if (and how) AGN influence the formation and evolution of galaxies.

Our knowledge about the evolution of AGN over redshift is however sparse. Commonly used selection techniques are heavily influenced by Malmquist bias, causing a strong artificial correlation between the redshift and absolute luminosity. At redshifts of one and higher, practically all AGN we know of are extremely luminous (Fan et al. 2001), making it impossible to study the evolution of the entire AGN population as a function of redshift.

The little we know about the evolution of the AGN population over redshift indicates that higher redshift quasars are on average much more luminous than their low-redshift counterparts (Dunlop & Peacock 1990; Hartwick & Schade 1990). However, as mentioned before, selection effects can be very severe. This has brought up the question if different selection techniques could be used at high redshifts to detect low-luminosity AGN that would otherwise be missed. Sarajedini et al. (2003) suggested to detect high-redshift AGN through their variability. This technique was also applied in Paper III and we showed that it can indeed be used to find low-luminosity AGN up to high redshifts (see Section 4.3).

A new selection technique might also help to detect possible populations of peculiar AGN at high redshift. Several uncommon AGN have so far been found in high-redshift quasar samples. Jiang et al. (2010) studied a sample of $z > 6$ AGN and found that some of them did not show emission from hot dust, indicating that the obscuring torus is not present in those sources. Shemmer et al. (2009) found another sample of peculiar high-redshift AGN, those objects show extremely weak emission lines and were initially thought to belong to the population of missing high-redshift BL Lac objects (Stocke 2001). Due to their high beaming, BL Lac objects are extremely luminous and should therefore be detectable up to high redshifts (Urry & Padovani 1995). The fact that no BL Lacs have been found beyond redshifts of about one is known as the missing high-redshift BL Lac problem (Stocke 2001). However, as Diamond-Stanic et al. (2009) showed, the objects found by Shemmer et al. (2009) are not high redshift BL Lacs but a rare populations of weakly-lined AGN that have only very few low-redshift counterparts (McDowell et al. 1995; Londish et al. 2004; Leighly et al. 2007; Leighly et al. 2007).

Such findings show how little we understand about high-redshift AGN. New selection techniques will be needed to understand the populations of high-redshift AGN. As indicated by Garofalo et al. (2010), evolution of AGN populations over redshift might well be expected in a new level of unification. Therefore, high-redshift AGN are the key for understanding unification and environmental effects for AGN properties.

Another interesting way in which AGN can help to understand the evolution of galaxies is through supermassive binary black holes. Merging is thought to play a rather major role in the evolution of galaxies (Bell et al. 2005) but constraining the merger rates can be extremely challenging. Merger rates can either be derived by using close pairs or disturbed appearances. The first method has two major problems, firstly, the two galaxies might have a considerable difference in the line-of-sight direction. Secondly, even if they are actual 'neighbours' this might still not mean that they will eventually merge. Disturbed appearances on the other hand are hard to detect and it is unclear how long they will be visible, some authors suggested that signs of mergers might be visible for only about 500 million years after the merger took place (Mihos 1995), but poor resolution or shallow imaging will surely make the mergers visible for even shorter. As it is assumed that all massive galaxies host supermassive black holes, merging will also mean that the new galaxy will host two supermassive black holes that will eventually merge. And in at least some cases, both black holes should be active. If we could detect those, we could get an additional handle on merger rates. In section 4.4 we show how variability studies can be used to find close supermassive binary black holes and review our work from Paper II in which we tested binary black hole models for the blazar OJ 287 and came to the conclusion that this particular source most likely does not host a close binary black hole.

CHAPTER 3

AGN Physics

So far, we have learned how the wide variety of observed AGN types can be explained. Now we need to understand the physical conditions and processes in AGN and the electromagnetic signatures we see. In this chapter, I will summarise some basic physics of importance for AGN research. The chapter will be divided in four sections, symbolising the major building blocks of AGN: accretion flow, jets and outflows, line emitting regions and obscuring material.

3.1 Accretion

> "Nature's affinity for cosmic disk structures was noted in the earliest surveys of the night sky."
>
> Steven Balbus & John Hawley

While accretion processes are in general extremely complicated, some simple analytical approximations and solutions to the accretion problem exist. In this section, some basics of accretion theory are introduced. Afterwards, I discuss observational constraints to the accretion process.

3.1.1 Some simple formulae for accretion

The most simple analytical solution to the accretion problem was presented by Bondi (1952). The solution describes spherically symmetric accretion onto a compact object and is often referred to as Bondi-accretion. The Bondi-accretion rate is:

$$\dot{M} = \frac{4\pi\rho G^2 M^2}{c_s^2}, \tag{3.1}$$

where ρ is the density in the surrounding medium, G is the gravitational constant, M is the mass of the central objects and c_s in the sound speed in the accreting medium. While the Bondi-accretion is a simple approximation that is unlikely to appear in reality, it is useful as an estimate for accretion rates.

A question that is of great concern for all accretion processes, especially for those in AGN, is how the radiation we observe influences the accretion process. Radiation from the central object will exert a force on the gas. While this force cannot be calculated in detail, if one assumes that the accreting material is fully ionised, one can write the radiation force exerted as:

$$F_{radiation} = \sigma_{Thomson} n_e \int \mathrm{d}\nu \frac{L_\nu}{4\pi c r^2}, \tag{3.2}$$

where $\sigma_{Thompson}$ is the Thomson cross section, n_e is the electron density, ν is the frequency of the radiation and L_ν is the luminosity at a given frequency. This means that the outward acceleration due to radiation decreases as radius squared, just as the gravity. Therefore, if the radiation pressure exceeds the gravity at any radius, it will do so at all points. From this equation, one can derive the Eddington luminosity L_E:

$$L_E = \frac{4\pi c G M \mu_e}{\sigma_{Thomson}} = 1.51 \times 10^{38} \frac{M}{M_\odot} \frac{erg}{s} \tag{3.3}$$

where μ_e is the mass per electron. If the luminosity exceeds this value, radiation pressure overpowers gravity and the accretion flow cannot be sustained. From this argument, one can estimate the black hole masses for standard AGN: with luminosities between typically $10^{43} - 10^{47}$ erg/s, we get minimum black hole masses between $10^5 - 10^9 M_\odot$.

Now, if we assume that the accretion process itself emits light with a given efficiency, we can write the Eddington accretion rate as:

$$\dot{M}_E = \frac{L_E}{c^2 \eta} = 3 \frac{M}{10^8 M_\odot} \left(\frac{\eta}{0.1}\right)^{-1} \frac{M_\odot}{yr} \tag{3.4}$$

where η is the radiative efficiency, commonly assumed to be $\eta \approx 0.1$ (Krolik 1999). It should be noted here that the luminosity of the accretion is *not* directly related to the accretion rate. Firstly, the formula for the Eddington luminosity assumes full ionisation in the accreting gas. Secondly, the formula for the Eddington accretion rate takes the radiative efficiency as an input parameter. Associating a certain accretion luminosity to an accretion rate is therefore not straightforward, since the radiative efficiency has to be known to make that connection. This should especially be kept in mind as Eddington ratios are often used in observational astronomy and frequently interpreted as estimates for the accretion rates.

Another basic property of the accretion flow is its inner edge. In general, orbits around a black hole are stable, however, at the innermost stable circular orbit (ISCO), all orbits become unstable. At the ISCO, it is no longer possible for particles to shrink their orbits slowly through energy loss, instead, they plunge into the black hole. The location of the innermost stable circular orbit is at 3 Schwarzschild radii for a non-spinning black hole (Beskin 2010), but can be much smaller for spinning black holes (Krolik & Hawley 2002).

The ISCO is of importance in methods that can be used to determine the spin of a black hole (Zhang et al. 1997; Shafee et al. 2006; McClintock et al. 2006). Those methods model the emission of accretion disks in the X-ray and use either the break-off of the spectrum or the shape of X-ray iron lines. Those methods assume that no photons reach the observer from within the ISCO. However, this relies on the assumption of zero torque at the ISCO. Lately, there has been discussion if this assumption really holds (Krolik & Hawley 2002). Such considerations have also been applied to the case of measuring black hole spins (Shafee et al. 2008) but the effects have been shown to be mild.

3.1.2 Real accretion: thin disks and radiatively inefficient accretion flows

The most basic limitation to accretion is angular momentum. A disk-like structure for the accretion process follows directly from the presence of angular momentum in the accreting material. For accretion to take place, the angular momentum has to be transported outwards. In an influential paper, Shakura & Syunyaev (1973) noted this problem and as they were unable to establish a physical prescription for the angular momentum transport introduced a parameter α that describes the viscosity. α can be understood as the efficiency of the hydrodynamic stress tensor. This α-disk model is popular as it allows calculating accretion processes without understanding the torque that transports angular momentum outwards. Shakura & Syunyaev (1973) also showed that $0 \leq \alpha \leq 1$. If α exceeds 1 at any point, rapid heating of the plasma will reduce α to ≤ 1. They also showed that α changes with the distance from the central black hole.

The origin of the torque is however still a mystery. Shakura & Syunyaev (1973) discussed several possible explanations for the torque. Molecular, atomic and radiation viscosity are all too weak to enable sufficient transport of angular momentum (Shakura & Syunyaev 1973; Krolik 1999). Electromagnetic stresses and turbulence are good candidates for carrying out angular momentum and can be expressed in the α-formalism (Shakura & Syunyaev 1973). Interestingly, it has also been found that the launching of jets through the extraction of angular momentum and energy from the accretion disk is an effective way of loosing angular momentum and therefore enabling accretion (Blandford & Payne 1982; Sakurai 1987; Krolik 1999).

Balbus & Hawley (1998) discussed a different process for creating torque. They showed that while disks are stable when treated as fluids, they are not when treated as MHD-flows. They were able to show that small radial perturbations of poloidal magnetic field lines are unstable and can grow extremely fast, creating loops. This process creates torque and therefore enables accretion. Interestingly, this instability is most effective for a weak initial poloidal field. This mechanism is quite different from viscous processes. It does not produce heat proportional to the torque and all torque is created by magnetic fields and not diffusion (Krolik 1999).

Luckily, even though the source of the torque is unknown, the α-disk model can be used to describe properties of the accretion flow (Shakura & Syunyaev 1973). Some basic predictions for disk structure and emission where made by Shakura & Syunyaev (1973). One can derive simply estimations for the dependence of temperature and pressure on disk radius, the overall spectrum and other properties. A number of useful formulae describing disks can be found in Shakura & Syunyaev (1973). All in all, the α-disk model predicts strong UV thermal emission, sharp features at the Lyman edge and rather substantial optical polarization perpendicular to the accretion disk surface due to scattering (Antonucci 2002). Later theoretical models incorporated much more physics and are able to model disk emission more accurately (see e.g. Laor & Netzer 1989; Laor 1990; Laor et al. 1990; Agol & Blaes 1996).

Another interesting feature of accretion disks is their variability. It can therefore be of interest to be able to estimate timescales of variability in α-disks. The simplest timescale is the dynamical timescale, it corresponds to the Keplerian frequency at a given radius and can be written as follows (Czerny 2006):

$$t_{dyn} = \sqrt{\frac{GM}{r^{3]}}} = 10^4 \left(\frac{r}{3R_{schwarzschild}}\right)^{3/2} \left(\frac{M_{BH}}{10^8 M_\odot}\right) seconds \tag{3.5}$$

where r is the radius, $R_{schwarzschild}$ is the Schwarzschild-Radius and M_{BH} is the mass of the central black hole. Another timescale of interested is the thermal timescale, i.e. the timescale on which cooling and heating takes place, it can be estimated as (Czerny 2006):

$$t_{the} = 10^5 \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{r}{3R_{schwarzschild}}\right)^{3/2} \left(\frac{M_{BH}}{10^8 M_\odot}\right) seconds \tag{3.6}$$

As we have learned earlier, viscosity is the driving force of the accretion process, therefore, it is of interest to understand on what timescale the viscosity works at a certain radius, the viscous timescale is (Czerny 2006):

$$t_{vis} = 10^7 \left(\frac{\alpha}{0.1}\right)^{-1} \left(\frac{r}{10h_d}\right)^{2} \left(\frac{r}{3R_{schwarzschild}}\right)^{3/2} \left(\frac{M_{BH}}{10^8 M_\odot}\right) seconds \tag{3.7}$$

Where h_d is the disk heights and, a typical value for r/h_d is 0.1.

A general rule of accretion disks is that only efficiently radiating disks are thin. If the disk cannot radiate efficiently, cooling is impossible and the flow will become geometrically thick. This can be important at both extremely low and extremely high accretion rates. When the accretion rate is low, the density is too low to allow for effective cooling and the heat is advected along with the accretion flow. If the accretion rate is extremely high, the photon diffusion time is large compared to an inflow time, the photons get trapped in the flow and accrete along with the material (Krolik 1999). This class of radiatively inefficient geometrically thick accretion flows has been described in literature (see e.g. Abramowicz et al. 1988; Narayan & Yi 1994; Igumenshchev 2004). They are known under several names, such as radiatively inefficient accretion flow (RIAF), advection dominated accretion flow (ADAF), adiabatic inflow-outflow solutions (ADIOS) or convection dominated Bondi flows (CDBF) (see Igumenshchev 2004 for a summary of different analytical models). Such flows are of interest for both extremely quiescent supermassive black holes such as the centre of the Milky Way (Mahadevan 1998) and powerful radio galaxies showing no signs of accretion (Baum et al. 1995; Ghisellini et al. 2009). It has also been shown that such flows are able to produce powerful outflows given certain magnetic field configurations in the accreting material (Igumenshchev et al. 2003). It is also recognised that most accretion flows might become radiatively inefficient close to the ISCO (Czerny et al. 2004). However, in some cases, the whole flow might be radiatively inefficient and therefore almost no emission from the accretion flow might be observable.

3.2 Jets

> "...we do not know why jets exist."
>
> Julian Krolik

So far, the idea of jets has been treated as if it were perfectly obvious what they actually are. However, when they were first detected, their nature was a puzzle to astronomers. When radio maps of the first lobed radio galaxies were first published, many scientists suggested that those were the remnants of balls of plasma being ejected by the central source (see the introduction of Blandford & Rees 1974 for a summary of different arguments and propositions). But it soon became clear that it is almost impossible to supply the incredible amounts of energy required to explain the observations in a single event. Blandford & Rees (1974) were the first to suggest that constant flows or 'exhausts' could be the engines driving those radio lobes and the idea of jets was born. Nowadays, it is clearly established that jets are collimated constant flows of plasma or electromagnetic energy. Jets have also been observed in a variety of other astronomical sources such as neutron stars, stellar mass black holes and young stars (Blandford et al. 2002).

3.2.1 Jet Launching, Collimation and Basic Jet Properties

In 1976, both Blandford (1976) and Lovelace (1976) showed that jets are naturally launched in presence of a rotating accretion disk with an embedded magnetic field. It was also found that collimation of such outflows occurs naturally, both through MHD effects and centrifugal forces in the outflow (Blandford & Payne 1982; Sakurai 1987). Interestingly, such processes for jet launching and collimation also remove angular momentum and can therefore allow accretion even if no viscosity is present in the disk (Blandford 1976; Blandford & Payne 1982; Sakurai 1987). This process of removing angular momentum is sometimes referred to as 'magnetic braking' (Blandford 1976).

There are two major physical processes for the launching of jets, the Blandford-Znajek (Blandford & Znajek 1977) and the Blandford-Payne process (Blandford & Payne 1982). The difference between those two processes is that in the Blandford-Znajek process energy is extracted from the rotating Kerr black hole while in the Blandford-Payne process energy is extracted from the accretion disk. Both are believed to act in combination in real sources (Beskin 2010; Garofalo et al. 2010).

In the Blandford-Znajek (BZ) process, energy is extracted from a rotating black hole. Technically, no accretion is needed in this process but material is required to be present around the black hole to supply the magnetic field. In this process, rotation energy is extracted from within the event horizon. This happens through the production of pair plasma in the black hole magnetosphere. As a result, a poloidal magnetic field trapped near the black hole is created and builds the basis of the outflow (Blandford & Znajek 1977). The content of a jet launched in this manner is pair plasma created in the black hole magnetosphere. For a more detailed description of this process and the physics of black hole magnetospheres, see for example Beskin (2010). The luminosity that can be created through the Blandford-Znajek process is:

$$W_{BZ} \approx 10^{45} erg/s \left(\frac{a}{M}\right)^2 \left(\frac{B_0}{10^4 G}\right)^2 \left(\frac{M}{10^9 M_\odot}\right)^2 \tag{3.8}$$

where a is the black hole spin, M is the mass of the black hole and B_0 is the magnetic field embedded in the accretion disk (Beskin 2010). If the black hole is spinning fast and B_0 is close to the Eddington magnetic field (the magnetic field for which the magnetic field density in the disk is comparable with the energy density of the plasma emitting the Eddington luminosity) then W_{BZ} is about the Eddington luminosity. Indeed, Paggi et al. (2009) showed the the Blandford-Znajek process alone can explain the jet powers in some BL Lac objects, indicating that this process might be the dominating jet launching mechanism in those objects.

The Blandford-Payne process on the other hand launches the jets purely from the accretion disk (Blandford & Payne 1982). Poloidal magnetic field lines frozen into the accretion process are wound up through the rotation of the disk, accretion disk matter can travel along those lines and be ejected from the disk. This process produces a toroidal component in the jet magnetic field which grows stronger further down the jet. The toroidal field might even be able to further collimate the jet through 'hoop' stresses. Usually about one-third of the energy is carried away in the form of kinetic energy and the other two thirds are associated with the Poynting flux (Blandford & Payne 1982).

As we saw, collimation is already an intrinsic property of the Blandford-Payne process (Blandford & Payne 1982) and it can be shown that collimation is a generally acting on jets, even if no toroidal magnetic field is present (Sakurai 1987).

Such analytical models have shown impressively that jets can be launched in the presence of accretion disks around massive objects as well as Kerr black holes embedded in matter carrying magnetic field lines. But the problem of jet launching and collimation is extremely complex. Analytical models can describe the overall picture, but are not suitable to derive detailed solutions. With the increased computer power available, simulations have started to play a major role in our understanding of jets (e.g. Cerqueira

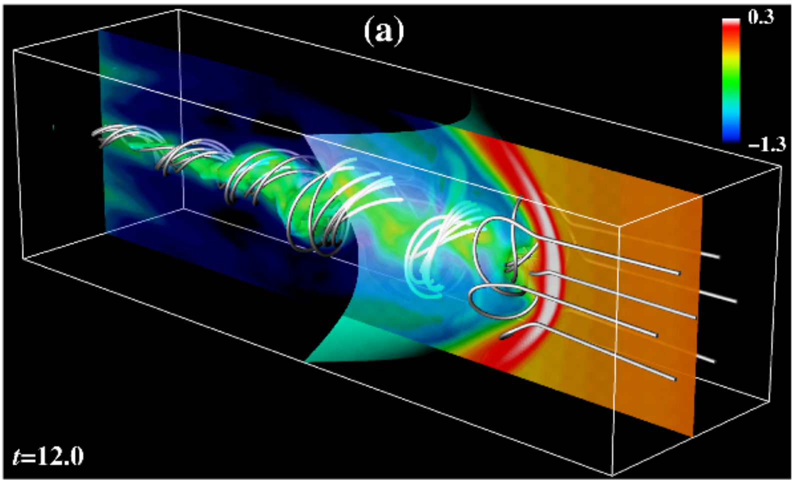

Figure 3.1: *The magnetic field in a simulated jet, from Nakamura 2001. The simulation clearly shows the helical structure of the jet magnetic field.*

& de Gouveia Dal Pino 2001; Nakamura et al. 2001; Casse & Keppens 2002; Nakamura & Meier 2004; Leismann et al. 2005).

Simulations of jets have so far shown how instabilities in the jet move along the jet and how the helical magnetic field evolves in interaction with the surrounding medium (Nakamura et al. 2001; Nakamura & Meier 2004), how the configuration of the magnetic field affects properties of the jet (Cerqueira & de Gouveia Dal Pino 2001; Leismann et al. 2005), how jets get launched from a disk (Casse & Keppens 2002). Such models are now beginning to be compared with observations of nearby jets and seem to show good results (e.g. Asada et al. 2008; Asada et al. 2009). In Fig. 3.1, we show the structure of the jet magnetic field from a MHD simulation.

An important open question concerning jets is their content. From the BZ process, one would expect the content to be pair plasma while for the BP process, the content should be 'normal' matter. It is however extremely difficult to observationally constrain the jet content. Technically, annihilation photons should be observable from pair plasma jets, but the predicted fluxes are well below the current observational upper limits (Krolik 1999; Marscher 2009). Celotti & Fabian (1993) were able to constrain the content of some jets arguing that they must be heavy (i.e. contain normal plasma), but the amount of data available to constrain this question is still sparse.

As we have learned, magnetic fields play a pivotal role in jet launching and collimation. Therefore, it is of interest to be able to estimate the strength of the magnetic field in the jet. Measuring the magnetic field is however extremely challenging. No direct ways to derive the magnetic field strength exist, but for both optically thick and optically thin emission, one can derive estimates making certain assumptions (Krolik 1999). For the optically thin regime one can estimate the magnetic field strength that minimises the total energy. Assuming equipartition, one can then find an estimate for the magnetic field strength (Krolik 1999):

$$B_m \simeq 2.4 \times 10^{-6} \left(\frac{L_{43GhZ}}{r_{100}^3}\right)^{2/7} \left(\frac{\nu_l}{1GhZ}\right)^{(1-2\alpha)/7} G \tag{3.9}$$

where L_{43} is the monochromatic luminosity at 1 GHz in units of 10^{43} erg/s, ν_l is the lowest frequency observed, α is the slope of the radio spectrum and r_{100} is the length of the source in units of 100 kpc. One should note that this is only a very rough estimate, there is no good reason to believe that the magnetic field in the jet is the one that minimises the total energy.

The case is easier for optically thick emission, for example the opaque radio core. For those, we can estimate the magnetic field strength without excessive amounts of previous assumptions (Krolik 1999):

$$B = 5.8 \times 10^{-4} \frac{\nu_t}{1GHz} \left(\frac{T_{bt}}{10^{12}K}\right)^{-2} G \tag{3.10}$$

where ν_t is the peak frequency and T_{bt} is the brightness temperature. The main limitations to be kept in mind using this formula are that the measured brightness temperature is only an upper limit and that resolution issues might play a role.

In reality, the magnetic field has been estimated for a few sources only. Stawarz et al. (2005) managed to derive an estimate of the magnetic field strength in the FRI radio galaxy M 87 on kiloparsec scales, and found a value of $B \geq 300\mu$G $\geq B_{eq}$ and an upper limit of $B \leq 1000\mu$G. The magnetic field strength on parsec scales has been derived for a few sources by Croke, O'Sullivan & Gabuzda (2010) and O'Sullivan & Gabuzda (2009) using a combination of VLBI maps at different wavelengths, both studies found magnetic field strength $\sim 10 - 100$ mG on parsec scales.

Another problem in understanding AGN jets is the extreme loss of energy that shows in strong synchrotron and self-Compton emission. Given the energy loss observed, jets should not be able to sustain their emission for the long time span observed (Ferrari 1998). Reacceleration of the emitting electrons must take place throughout the jet to sustain the emission over the whole jet length (Ferrari 1998; Krolik 1999). The mechanism behind this reacceleration is still a mystery, but shock fronts might play a role.

3.2.2 Shock fronts

Shock fronts, either through the collision of the jet plasma with slower gas clouds or through internal instabilities have been proposed early as a source of variability in AGN jets (Blandford & Konigl 1979). Indeed, shocks occur naturally in plasma. For MHD waves, small disturbances lead to a steepening of the wave and ultimately to a shock.

MHD equations break down in the shock region but conservation laws can be used to calculate the conditions up- and downstream the shock. For a description of basic principles of plasma physics and MHD formulations for astrophysical applications, see the textbook by Kulsrud (2005).

The importance of shocks was early recognised as a source of variability in AGN, especially in blazars (Blandford & Konigl 1979). Astronomers started modelling strong outbursts in blazar jets as shock fronts with good success (Marscher & Gear 1985; Hughes et al. 1985) and numerous monitoring projects since then have studied strong outbursts in jets and used shock front models to constrain physical conditions in the jet (see e.g. Chatterjee et al. 2008; Marscher et al. 2008; D'Arcangelo et al. 2009).

In an influential paper, Marscher & Gear (1985) studied an outburst in the famous blazar 3C 273. They argued that an adiabatically expanding source can well explain all the observed features of the flare such as the changes in the spectral shape, but that shock fronts provide a much more natural explanation for most typical characteristics of major outbursts. Marscher & Gear (1985) were also able to derive basic physical properties in the shock front. This model has been used numerous times since then and is surprisingly successful in modelling outbursts in blazars. One of the prominent characteristic of shock fronts is a swinging motion observed in the optical polarization during outburst (e.g. D'Arcangelo et al. 2009), which can be explained as a sign of accelerating plasma down the jet. However, as we have shown in Paper II this simple diagnostics might fail in cases in which several components are producing polarized emission. As we showed in Paper II, underlying sources of polarized emission can cause a lot of confusion when trying to detect signatures of shock front. On the other hand such signatures might also help us reveal new interesting properties of blazar jets. In Section 4.2, we discuss how diagnostics of monitoring data can reveal interesting facts about the physical conditions in blazar jets not related to shock fronts.

3.2.3 Jet Emission

One of the best established facts about jets is that they mostly emit synchrotron radiation. This has been established due to the high degrees of polarization observed in jets. The other emission mechanism of interest is Compton scattering. In this section, the physics of those emission mechanisms will be shortly described.

Synchrotron radiation is emitted by relativistic charged particles moving in a magnetic field. The spectrum emitted by a highly relativistic particle per unit frequency is (Rybicki & Lightman 1986):

$$P(\nu) = \frac{\sqrt{3}}{2\pi} \frac{q^3 B \sin\theta}{mc^2} F\left(\frac{\nu}{\nu_c}\right) \tag{3.11}$$

where the critical frequency ν_c is:

$$\nu_c = \frac{3\gamma^2 q B \sin\theta}{4\pi mc} \tag{3.12}$$

and θ is the pitch angle (the angle between the trajectory of the particle and the magnetic field). The function F can be approximated for very small and very large values of $x = \nu/\nu_c$ in the following manner:

$$F(x) \sim \frac{4\pi}{\sqrt{3}\Gamma(1/3)} \left(\frac{x}{2}\right)^{1/3} \quad \text{for} \quad x \ll 1 \tag{3.13}$$

$$F(x) \sim \left(\frac{\pi}{2}\right)^{1/2} e^{-x} x^{1/2} \quad \text{for} \quad x \gg 1 \tag{3.14}$$

Full formulas for F can for example be found in the textbooks Rybicki & Lightman (1986) or Krolik (1999).

However, we are seldomly interested in the emission of electrons with a single energy. Often, we are interested in an ensemble of electrons with a certain distribution of energies. Power laws are rather common in nature and most distributions can locally be approximated by a power law. For an electron ensemble with the energy distributions of

$$N(E) \propto E^{-p} \tag{3.15}$$

it can be shown the the spectrum emitted by the electrons goes as

$$P_{tot}(\nu) \propto \nu^{-\left(\frac{p-1}{2}\right)} \tag{3.16}$$

and therefore the spectral index s for an electron ensemble with index p is $s = \frac{p-1}{2}$ (Rybicki & Lightman 1986). Therefore, from a spectral slope we can infer the distribution of the energies for the emitting electrons.

Polarization was the property of AGN jet emission that lead astronomers to believe that synchrotron emission is the main emission mechanisms in AGN jets. A single electron with a given pitch angle emits an elliptically polarized electromagnetic wave (for a basic introduction into polarization properties and notations, see e.g. Degl'Innocenti 2002), but averaging over an ensemble of electrons with different pitch angles will cancel out the circular polarization and therefore result in linear polarization. This linear polarization can be calculated, but the resulting formulas are rather complicated, so we refer the reader to Rybicki & Lightman (1986) or Krolik (1999). The degree of polarization integrated over all frequencies is about 75% (Rybicki & Lightman 1986). The degree of polarization for $\nu/\nu_c \ll 1$ is about 50% while the degree of polarization for $\nu \gg \nu_c$ is around 100% (Krolik 1999). Those values are however only valid for a set of electrons with the same energy, if the distribution of electron energies is less narrow, those values will change. For particles with a power law distribution, the degree of polarization integrated over all wavelengths is (Rybicki & Lightman 1986):

$$P = \frac{p+1}{p+\frac{7}{3}} \tag{3.17}$$

So far, we have not taken into account absorption, i.e., we have assumed that the synchrotron emission is optically thin. While this is likely the case for most of the extended emission, it might not be true for compact regions which might well be opaque. A full description of synchrotron self absorption can be found in Rybicki & Lightman (1986) or Krolik (1999). An important property of synchrotron self-absorption is that it declines very rapidly with increasing frequency, i.e. synchrotron self-absorption is much more important in the radio than it is in the optical (Krolik 1999). Assuming equipartition, one can make an estimate of the optical depth in a region of size r:

$$\tau_{equipartition} \sim \frac{\pi^2}{36}(p+2)\frac{r}{c}\left(\frac{eB_m}{2\pi m_e c}\right)^4 \nu_l^{-3}\left(\frac{\nu}{\nu_l}\right)^{(4+p)/2} \tag{3.18}$$

where p $\simeq 2-3$ is the index describing the energy distribution of the electrons (as defined in equation 3.15) and ν_l is the lowest frequency observed (Krolik 1999). The self-absorbed synchrotron intensity is (Krolik 1999):

$$I_\nu \propto \frac{1}{4\pi}\frac{e^2B^2}{m_e c^2}\left(\frac{2\pi m_e c\nu}{eB}\right)^{5/2} \tag{3.19}$$

One would therefore expect a self-absorbed synchrotron emission to show a spectral slope around $\propto \nu^{5/2}$. However, the compact, presumably opaque cores seldomly show that steep spectral slopes! Instead, the spectra are usually relatively flat. This can easily be understood as follows: as shown earlier, the optical depth strongly depends on the peak frequency. Therefore, one can imagine the spectrum from an opaque region to be a superposition of countless spectra with different peak intensities and different optical depths. Such a superposition can produce flat spectra over a wide range of frequencies.

The other physical process for emission in blazar jets is inverse Compton scattering. Compton scattering is scattering between moving electrons and photons in which energy is transferred from the photon to the electron. Inverse Compton scattering is scattering between electrons and photons where the photon gains and the electron loses energy (Rybicki & Lightman 1986). In some AGN jets, the jet emission itself undergoes scattering with the electrons in the jet. This is commonly referred to as Synchrotron Self Compton Scattering (SSC) (Ghisellini et al. 1985), in this case, the synchrotron radio to optical spectrum scatters of the relativistic electrons and produces a high-energy hump observed in some blazar spectra (Ghisellini et al. 1985; Krolik 1999). Simple inverse Compton scattering is the source of the high energy bump in other sources. This model of blazar jet emission is able to explain the multi-wavelength SEDs of blazars, as seen in Fig. 3.2.

One property of the synchrotron and Compton emission in jets is that it is emitted in a highly non-isotropic fashion. Blazars are the subclass of AGN with jets close to the line of sight and therefore, beaming effects play an important role in those sources. For a summary of formulae for beamed synchrotron emission, see Blandford & Konigl (1979). Beaming means that radiation, even when emitted isotopically in the rest-frame of the

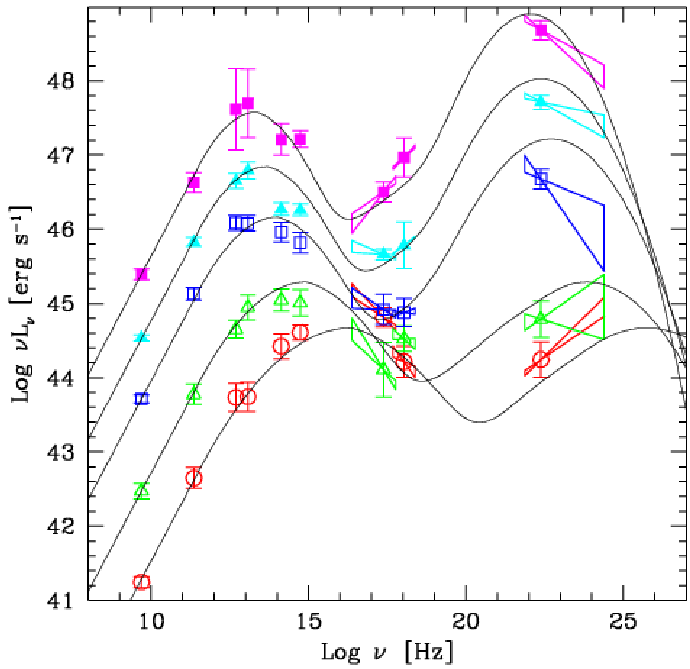

Figure 3.2: *Multi-wavelength SEDs of a number of blazars, from Donato et al. 2001. The low energy bump is due to synchrotron emission and the high energy bump is due to inverse Compton scattering.*

emission will be beamed into a small angle. It can be shown that for $\Gamma \gg 1$ (where Γ is the Lorentz factor), half of the photons are emitted in a narrow angle $\theta \sim \frac{1}{\Gamma}$ (Rybicki & Lightman 1986). Another effect of beaming is the relativistic Doppler effect. A photon emitted with a frequency ν' will be have an observed frequency

$$\nu = \frac{\nu'}{\Gamma(1 - \frac{v}{c}cos\theta)} \tag{3.20}$$

The relativistic Doppler effect has two parts, the factor Γ in the denominator is a purely relativistic effect, while the second part of the denominator is the 'normal' Doppler effect.

Rees (1966) predicted an important observational appearance of beamed sources: superluminal motion. And indeed, superluminal motion was observed soon after in seven quasars, namely 3C 120, BL Lac, 3C 273, 3C 279, 3C 345, 3C 179 and NRAO 140 (for a review and summary of earliest observations see Porcas 1983) and later in countless other sources. Superluminal motion can be explained as follows: let us imagine a blob of matter emitting radiation, which is moving with speed β at an angle θ with respect to the line of sight. When the moving blobs first emits a photon, the signal arrives after $\frac{D}{c}$. When the blob moves along its trajectory with speed β (where $\beta = v/c$) and emits another photon after Δt. The second photons will arrive after a time $t = \Delta t + \frac{D}{c} - \beta \Delta t cos\theta$, therefore the apparent speed of the blob is

$$\beta_{apparent} = \frac{\beta sin\theta}{(1 - \beta cos\theta)}. \tag{3.21}$$

When $\theta \ll 1$ and β is close to one, superluminal motion is observed. In some blazars, $\beta_{apparent}$ is up to about 20 (e.g. Gabuzda et al. 1989; Jorstad et al. 2001). Many more effects of beaming are known, for a nice collection of different formulae see for example Blandford & Konigl (1979) or the textbooks Rybicki & Lightman (1986) and Krolik (1999).

3.2.4 Outflows and Winds

So far, we have only dealt with highly-collimated relativistic jets, but sub-relativistic weakly collimated winds are most likely present in many low-luminosity AGN. In this section, we will shortly deal with outflows and winds. The shortness of this paragraph compared to the treatment of jets is mostly due to the fact that much less observational constraints are known to uncollimated outflows than there are for jets.

Uncollimated outflows and winds can appear in three different flavours: thermal winds, radiation pressure driven winds and magnetically driven winds (Krolik 1999). Thermal winds happen when gas in the center is so hot that the thermal energy exceeds the gravitational potential. The gas can escape the galaxy in a wind. Radiation pressure driven winds appear when strong radiation transfers part of its momentum to gas, for example through scattering. The gas is then accelerated and if the radiation pressure is strong enough, can be expelled from the galaxy. Since interaction between the radiation field of the AGN is clearly observed in both BALs and the broad-line region, radiation pressure driven winds might well play a role. Note that both of these mechanisms are in no way specific to AGN. They only require hot gas or strong radiation, both of which might well be caused by other astronomical phenomena such as for example starbursts. Magnetically driven winds are similar to the jets we described earlier, but simply much less collimated. Such winds might well appear in radio-quiet AGN. As we saw earlier, rotating disks easily create wound-up magnetic field lines that can carry away material from the disk. This poses the question why the collimation is very successful in some sources while it is not in others. For the Blandford-Payne process, both the strength of the field in the disk and is rotation speed contribute to the properties of the flow and might therefore determine the collimation. As shown, one can easily think of several rather natural ways of creating uncollimated winds and outflows, but what are the observational constraints for winds and outflows in AGN?

Strong winds are observed in some AGN (Nesvadba et al. 2008), but also in starbursting galaxies such as M 82 (Strickland & Heckman 2007). Interestingly, many clear cases of detections of AGN winds (Nesvadba et al. 2008) are at high redshifts where star formation rates are typically very high (e.g. Madau et al. 1998; Reddy et al. 2006; Bouwens et al. 2010). This raises the question if those AGN winds are driven by the AGN or by a central starbursts. Clearly, much work is needed in this field. We need to better understand the specifications of winds in AGN and therefore be able to tell how exactly they are driven. This also touches the question of the starburst-AGN link, i.e. are most strong starburst also hosting a weak AGN (e.g. Ptak et al. 2003) and are the winds we see in low-luminosity AGN due to the starburst or the AGN itself.

3.3 Narrow and Broad Line Regions

> "The emission lines in the brightest diffuse nebulae in other extragalactic objects do not appear to have wide emission lines similar to those found in the nuclei of emission spirals. "
>
> Carl Seyfert

As mentioned in Section 2.2, both narrow and broad line emission is observed in AGN. A line is normally defined as broad if its velocity dispersion is $> 1000 - 2000$ km/s (Krolik 1999). Quasars showing broad emission lines usually show broad components in all of the following lines: Lyα, Hα, Hβ, Paα, Paβ, Brα, HeII 4686, HeI 5876, HeI 10830, CIII] 1909, CIV 1548,1551, NV 1239,1243, OVI 1032,1038, OIV] 1400, OI1305, OI 8446, SiIV 1394,1403, MgII 2796,2804 as well as a number FeII multiplets (in wavelength ranges 2200-2600Å, 3000-3400Å, 4500-4600Åand 5250-5350Å) (Krolik 1999). This list is somewhat biased due to the fact that most spectroscopy of AGN is performed in the optical. Without a doubt more lines of HI and other elements can be observed in other wavelength ranges. Due to the extreme broadening of the lines, close doublets usually merge to a single line. The most prominent merged doublets and the wavelength ascribed to them are CIV (1549Å), NV (1240Å), OIV (1034Å), SiIV (1400Å) and MgII (2800Å). The line strength ratios are not identical when comparing different objects, but generally a few rules of thumb apply: Lyα, CIV and Hα are typically strongest, followed by CIII] 1909 and MgII 2800, the rest of the lines are weaker (Krolik 1999). The FeII multiplets are generally poorly understood as both the observational characterisation and the physical modelling are difficult (Wills et al. 1985; Netzer 1985). It is unclear if the broad line ratios correlate with any other properties of the AGN (see e.g. Boroson & Green 1992; Baldwin et al. 1989). The equivalent width of the broad lines however is found to negatively correlate with the quasar luminosity, this is known as the Baldwin effect (Baldwin et al. 1989). The profile shapes show low levels of asymmetry and usually all lines in a single object show similar asymmetries (Brotherton et al. 1994).

Narrow emission lines are all lines with velocity dispersions smaller than $\approx 1000 - 2000$ km/s. The line widths of the narrow lines are usually comparable to the velocity dispersion of the host galaxy bulge (Nelson & Whittle 1995; Nelson & Whittle

1996). The most prominent narrow emission lines are [OIII] 4959,5007, [OII] 3727, [NII] 6548,6583, [OI] 6300 and [SII] 6716, 6731. Additionally, the Lyman and Balmer series as well as CIV 1549 have narrow components (Krolik 1999). [OIII] 5007 and Lyα are typically the strongest narrow lines. The strengths of the narrow lines are clearly negatively correlated with the objects absolute luminosity, making narrow lines practically undetectable in high-luminosity AGN (Wills et al. 1993). The line ratios between different narrow lines can be used for diagnostics to separate AGN from star forming galaxies (Baldwin et al. 1981; Veilleux & Osterbrock 1987). Line ratios are also used to identify LINERs, extremely low-luminosity AGN on the border to star forming galaxies (Heckman 1980a; Heckman 1980b). From the unification models we know that the BLR is located in the center of the AGN and is obscured towards most lines of sight (Antonucci 1993). The NLR region is found to be located in the biconical photoionisation cone, aligned with the radio jet axes (Ulvestad et al. 1981; Tadhunter & Tsvetanov 1989; Evans et al. 1991). See Figure 2.3 for an descriptive cartoon of a prototype AGN.

It is believed that photoionisation is the main physical process behind line emission. The total energy release of the AGN correlates well with the line equivalent width, suggesting that the former causes the latter. Additionally, typical temperatures inferred from line ratios are not high enough to explain the high excitation states observed. And observations of ionisation cones (Tadhunter & Tsvetanov 1989; Evans et al. 1991, see also Section 2.3) also point towards photoionisation as the physical process behind the narrow line emission. Shocks might also contribute to the excitation in some sources.

The physics behind photoionisation processes is extremely complex. As line emission has played only a minor role in this thesis, we will refer the reader to the review by Davidson & Netzer (1979) or Krolik (1999) for a full description of photoionisation physics. Additionally, simulation codes are publicly available, those can help to simulate line strengths and ratios for different physical conditions. Some well-known codes for photoionisation calculations are CLOUDY (Ferland et al. 1998) and XSTAR (Bautista & Kallman 2001).

An open question is the origin of the BLR. The unified model (Antonucci 1993; Urry & Padovani 1995) only states the existence of the BLR and makes no statement about its origin. Elvis (2000) addressed this question and suggested that the BLR is embedded in an outflow from the accretion disk. Similar models have been proposed by other authors (Nicastro et al. 2003; Laor 2003; Tran 2003), all suggesting that the BLR originates from the disk. Laor (2003) and Tran (2003) both suggested that such an origin of the BLR might explain true Type II AGN, in a sense that in some objects the conditions for producing a BLR are not met. Czerny et al. (2004) showed that this is indeed true and that formation of an BLR is impossible at low Eddington ratios.

Broad line emission has been found to be highly variable (for a review, see Peterson 1988). This variability has been used to understand the structure and dynamics of the line emitting regions through a technique that is known as reverberation mapping. The idea of this method is rather simple: the accretion disk emits photons that ionise the BLR. If the accretion disk emission varies in strength, one can observe echoes of those variations in the emission lines (for a description of the methodology see Welsh & Horne 1991 and references therein). From such measurements, one can infer the size and the geometry of the broad line emitting regions (Welsh & Horne 1991). The BLR has been found to be anywhere between a few and around 100 light days (Peterson 1993).

But reverberation mapping has been used to address scientific questions far beyond constraining the broad line region geometry: to measure the mass of the central black hole. The idea is rather simple again: if the broad line clouds move in the potential of the central black hole, their speeds are determined only by the mass of the central black hole and the radius of the emitting material, therefore, one can infer the black hole mass (e.g. Kaspi et al. 2007; Wandel et al. 1999). Going even a step further, one can derive relations between the line width and continuum flux measured in a single spectrum and the black hole mass (Vestergaard & Peterson 2006). This method can be easily applied to simple spectroscopic data and thereby enables determining black hole masses up to very high redshifts for large numbers of AGN (see e.g. Vestergaard et al. 2008; Villforth et al. 2008; Kelly et al. 2010). This method is a powerful tool for understanding the evolution of black hole masses and AGN through cosmic times. However, it has been pointed out that the basic assumption that the origin of the BLR motion is purely the gravitational potential of the black hole might not be valid and therefore the method might not work (Krolik 2001).

3.4 Obscuration

"I will show you fear in a handful of dust. "

T. S. Eliot

The existence of obscuring material around the centres of Type II Seyferts has been shown through spectropolarimetric observations (Antonucci & Miller 1985, see also 2.3). Additionally, thermal emission humps in the infrared observed in most Seyferts can easily be interpreted as re-radiation of the central AGN emission (Miley et al. 1985; Edelson et al. 1987). A torus-like structure for the obscuring material was first suggested by Krolik & Begelman (1988). They studied the case of NGC 1068 (Antonucci & Miller 1985) and discussed basic physical properties of the obscuration. The obscuring structure is found to be oriented perpendicular to the radio jet in most Seyferts (Antonucci 1993).

Some basic properties of the torus can be easily inferred from basic physical considerations. Due to the fact that most of the optical and X-ray emission is completely absorbed, the torus must be optically thick from optical to X-ray. Therefore, the covering factor of clouds along the equatorial plane must either be large, or the individual clouds must be optically thick. Comparison between the number of Type I and Type II objects lead to a simple estimate for the opening angle of the torus, yielding about 40° (Krolik 1999).

Generally, dust in the universe consist of about 53% silicates and 47% graphite (Elitzur 2008) and grain sizes on average follow a power-law from 0.005 μm to 0.25 μm (Mathis et al. 1977). The temperature of the dust is determined by its interaction with radiation and is typically around a few hundred Kelvin in the tori of AGN (Elitzur 2008). The dust sublimation temperature is around 1200 K, meaning that at higher temperatures, dust will evaporate (Elitzur 2008). This also means that no dust emission bluewards of $\sim 2\mu$m is expected.

Estimating the size of the torus is challenging, given that only very lately and in a few cases has it become possible to actually resolve the torus using optical interferometry (Jaffe et al. 2007; Tristram et al. 2007; Raban et al. 2009). Earliest calculations (Pier & Krolik 1992) estimated the outer radius of the torus at about 5-10 pc. The same authors in a later paper (Pier & Krolik 1993) speculated that this torus might be embedded in a larger structure with a radius of about 30-100 pc. Granato & Danese (1994), using similar methods estimated the torus to have an outer radius of greater than 300-1000 pc, while in a later paper, Granato et al. (1997) lowered their estimate to about a few hundred parsec. This shows that the complicated physics involved make calculations extremely difficult. However, a value for the radius of the dust torus of a few hundred parsecs is now a commonly accepted estimate (Elitzur 2008). In distinct disagreement with those values, first interferometric observations of nearby AGN found torus sizes well below 10 pc (Jaffe et al. 2007; Tristram et al. 2007; Raban et al. 2009)!

Another property of dust tori that is commonly accepted, is the fact that the torus is not smooth, but consists of smaller clouds (e.g. Elitzur 2008). Even the first interferometric observations of dust-tori in nearby AGN found indication of a clumpy torus structure (Tristram et al. 2007). Calculations of physical properties of clumpy system can be rather challenging (see e.g. Nenkova et al. 2002; Conway et al. 2005 for physical prescriptions, for a review see Elitzur 2008) and the treatment of this problem exceeds the scope of this thesis.

While early work did not consider the origin of the dust torus but its properties (Krolik & Begelman 1988), later studies started discussing the origin of the torus. Emmering et al. (1992) suggested that the dust torus might be produced through the wind driven by the AGN (see also e.g. Konigl & Kartje 1994). Such a view is also supported by the fact that very low-luminosity AGN do not show dust emission or obscuration (Chiaberge et al. 1999). But can AGN really be the sources that produce the dust that enshrouds them? Commonly considered sources of dust in the Universe are Asymptotic Giant Branch (AGB) stars (Sedlmayr 1997) and supernovae (Bianchi & Schneider 2007). Generally, the production of dust requires certain physical conditions: a chemically enriched medium of sufficiently low temperature and high density. When these conditions are met, dust condensation occurs. These conditions generally occur in the winds of AGB stars and supernovae, but as Elvis et al. (2002) pointed out are also very likely to occur in the winds of AGN accretion disks. Interestingly, in AGN, the region in which broad absorption line clouds in AGN appear is approximately identical to the dust sublimation radius (Clavel et al. 1989). While the origin of dust has so far received little attention amongst AGN researches, the fact that AGN are now found up to very high redshifts (Fan et al. 2001) at which the Universe is too young to have produced any dust through AGB stars (Jiang et al. 2010) has started to raise the question how dust is produced at high redshifts. Indeed, Jiang et al. (2010) have found some high-redshift AGN without dust emission. Further research on this topic will have to show how dust is produced and if AGN indeed produce their own dust as for example suggested by Jiang et al. (2010) and Elvis et al. (2002).

CHAPTER 4

Variability as a key to understanding AGN

"AGN do not vary."

Meg Urry

As we have seen, a basic unified model of AGN has been established, but countless open questions concerning the physical conditions in AGN remain. In this section, we will show how variability studies can be used to help answer those open questions. Those will be the question of the nature of outflows in radio-quiet AGN (Section 4.1 and Paper I), the question of the physical conditions in blazar jets (Section 4.2 and Papers II and IV), the search for new samples of high-redshift AGN (Section 4.3 and Paper III) and finally the search for supermassive binary black holes (Section 4.4 and Paper II).

4.1 Where are the radio-quiet blazars?

As we have learned, all AGN are believed to produce some kind of outflows, with RLQs producing powerful relativistic jets and RQQs showing weaker and slower jets or outflows (Antonucci 1993). The exact difference in the outflow is still very poorly understood, and some RQQs indeed do show fast relativistic outflows (Blundell et al. 2003). In any case, if RQQs have jets then radio-quiet blazars, the beamed counterparts of RQQs, must exist. However, most blazars known are radio-loud (Urry & Padovani 1995). The search for radio-quiet blazars has shown some success (Rector et al. 2000; Collinge et al. 2005; Anderson et al. 2007; Plotkin et al. 2008), but still few radio-quiet blazars are known and their properties are poorly understood.

One of the defining properties of blazars is their rapid variability (Wagner & Witzel 1995; Ulrich et al. 1997) and high polarization (Angel & Stockman 1980). Very fast variability has been found in numerous AGN, both radio-loud and radio-quiet (Gopal-Krishna et al. 1993; Jang & Miller 1995; de Diego et al. 1998; Gopal-Krishna et al. 2003; Stalin et al. 2004; Stalin et al. 2005; Jang 2005; Carini et al. 2007; Goyal et al. 2007) but the origin of this variability is still a puzzle and might require beaming in the emitting region. Other authors have claimed that fast variability detection might be due to problems in the data reduction process (Cellone et al. 2007). Variability can originate from different kind of processes, while polarization variability indicates synchrotron emission and is therefore a much better diagnostic for jet emission. This raises the question if the fast variability observed in some RQQs is a sign of a hidden jet or processes in the accretion disk. Studying polarization instead of flux variability can answer this question.

In Paper I, we studied intranight polarization variability in blazars and radio-quiet AGN to examine if the intranight variability observed in many AGN is due to jet emission. Intranight polarization variability has been observed in numerous radio-loud blazars (Andruchow et al. 2005; Paper I) but so far has not been detected in any radio-quiet AGN (Paper I). We found no indications of hidden jet emission as a cause of the intranight variability in radio-quiet AGN. However, we did not find extremely fast variability in the polarization in any of the observed sources, indicating that the fastest variations in blazar jets are either extremely rare or not related to jet emission. Indeed, the only extremely fast and violent variability in polarization known to us was reported by Sasada et al. (2008).

4.2 What are the physical conditions in blazar jets?

As we have seen in Section 3.2, AGN jets are extremely complicated and still poorly understood. Simulations are now giving us an idea of the physical conditions in AGN jets, but it is difficult to derive observational constraints. Only few AGN jets are so nearby that they can be resolved easily and studied in detail. The best case for a nearby AGN jet is M 87, an object that has been studied excessively and whose jet can be resolved even in the optical (e.g. Biretta et al. 1995; Biretta et al. 1991; Asada et al. 2009). However, M 87 is a rare example of a radio galaxy close enough to study the detailed conditions in AGN jets close to the black hole. Therefore, many studies regarding the physics of AGN jets have concentrated on blazars, in which the jet emission is highly beamed.

Given the extreme variability and powerful outbursts observed in blazars, a question that moved blazar researchers for long time was to understand the physics behind these outbursts. Blandford & Konigl (1979) was the first to suggest that shock fronts in the jet plasma might be causing the massive outbursts observed. Marscher & Gear (1985) were able to model an outburst in 3C 273 as a shock front. Since then, such shock front models have been used to model numerous outburst in different blazars and were shown to be extremely successful (see e.g. Hughes et al. 1989; D'Arcangelo et al. 2009; Chatterjee et al. 2008; Marscher et al. 2008; Anderhub et al. 2009, Paper IV). For a summary of the physics behind shock fronts, see Section 3.2.

However, such outburst tell us little about the underlying jet structure. The model proposed by Marscher & Gear (1985) assumes that the magnetic field in the jet is unordered and only gets aligned through shock fronts. This means that polarization occurs only when a shock front passes through the jet. Therefore, high degrees of polarization and high fluxes should strongly correlate, such a behaviour is however not observed (Jones et al. 1985; Jannuzi et al. 1994 and Paper II). This shows that while shock fronts are present in jets, they are not the sole source of polarized emission.

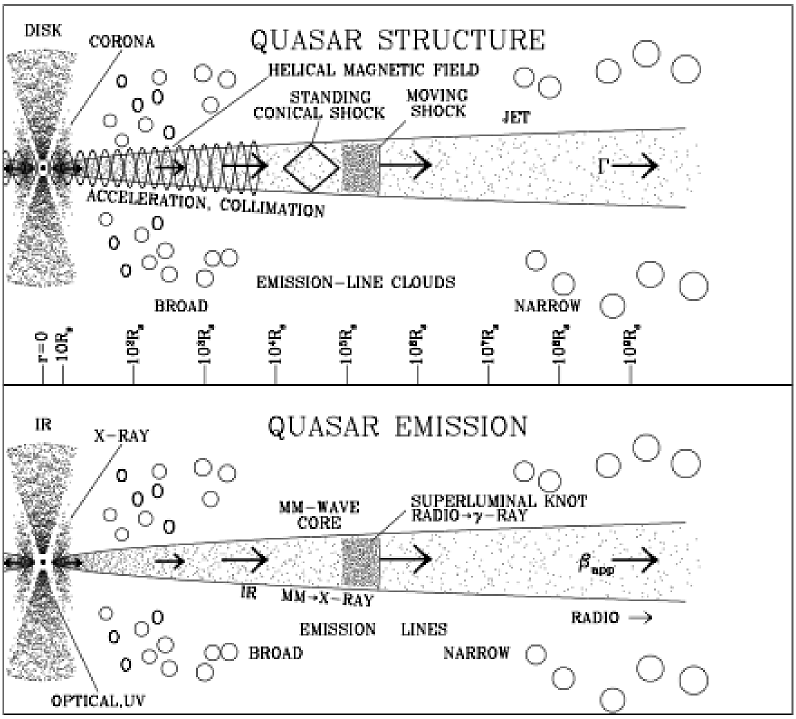

Figure 4.1: *A sketch of the current picture of blazar jets, taken from Marscher 2009.*

As the launching of the jet is usually associated with wound-up magnetic field lines from the accretion disk (Nakamura et al. 2001), the simple picture of the chaotic magnetic field in the jet is indeed unlikely. The current picture of AGN jets therefore assumes a helical magnetic field at least in some parts of the jet (Marscher 2009, see also Fig. 4.1). In this model of AGN jets, the collimation zone is dominated by a helical magnetic field, which ends in a standing shock front, after which the magnetic field breaks up. This is similar to the picture from simulations (Nakamura et al. 2001).

In the radio, VLBI maps can be used to study the magnetic field in blazar jets and to address the question of the underlying magnetic field configuration. Gabuzda (2003) studied VLBI maps of blazars and found evidence that not all polarization is produced in shock fronts but that an underlying magnetic field is present in the jets. In some cases, helical structures in the jet magnetic field have been found (Gabuzda et al. 2004; Asada et al. 2008). Lyutikov et al. (2005) calculated expected polarization properties for blazar jets assuming a helical magnetic field. Those predictions agree rather well with observations of blazar jets.

In the AGN jet model as presented by Marscher (2009) (see Fig. 4.1), it is also assumed that different parts of the jet emit at different wavelengths, with shorter wavelength being emitted closer to the black hole and longer wavelengths being emitted further downstream. In this picture, the optical emission originates in the collimation zone where an ordered helical magnetic field is present and the radio wavelength are emitted mostly downstream of the standing shock front where the helical magnetic field breaks up.

If this is true, we would expect outbursts to start in the optical and then move to longer wavelengths while the shock front travels down the jet. This is indeed observed, (Marscher & Gear 1985; D'Arcangelo et al. 2009) but can also be well explained as a sign of shock fronts (Marscher & Gear 1985). Secondly, one would expect a qualitative difference between radio and optical polarization properties as those are emitted in areas with different magnetic field configurations. Gabuzda et al. (2006) studied the correlations between radio and optical polarization in a set of blazars. After they corrected the radio polarization data for Faraday rotation, they found the polarization vectors to be well aligned with each other for most objects. They concluded from this that the bulk of the emission at the both radio and optical wavelength must originate from a similar region in the jet. However, such observations can also be explained if the magnetic field is similar throughout the jet and therefore a preferred direction for the polarization exists. In a similar study, Jorstad et al. (2007) compared polarization properties at different wavelengths from radio through mm to optical and where able to constrain the configuration of the magnetic field in different areas of the jet. Yuan et al. (2001) studied the optical polarization of a sample of BL Lacs and high polarization quasars (HPQs). They found clear signs of aligned magnetic fields in all BL Lacs (similar to findings by Jannuzi et al. 1994 and Paper II). On the other hand, they found no evidence for an aligned magnetic field in HPQs.

Another open question in this context is if there is a bimodality in the jet properties, as would be expected to correlate directly with the line strength (Urry & Padovani 1995) or the extended radio emission (Antonucci 1993). If blazars are beamed counterparts of FRI and FRII jets, should we see two different types of blazar jet behaviours? Little research has been done on this field. In Paper II we discussed earlier results from optical polarimetric monitoring and found indications that the optical jets of FSRQ type blazars are on average more turbulent than those of BL Lacs.

An interesting open question in this context is where the highest energy photons in blazar jets originate. Since the launch of *Fermi*, our knowledge of the highest energy emission in blazar jets has grown considerably (e.g. Ghisellini et al. 2009; Pushkarev et al. 2010), but it is still unclear where the emission originates. Pushkarev et al. (2010) found that the γ-ray emission usually leads the radio emission, indicating that it is produced upstream in the jet. In Paper IV, it was found that the gamma-ray outburst happened simultaneously to a strong change in optical polarization, indicating that the optical and gamma-ray emission are produced in the same region.

4.3 Finding low-luminosity AGN at high redshifts

As has been pointed out in Sections 2.3 and 2.4, finding new samples of faint AGN at high redshifts is of outmost importance. Here, I will shortly explain how AGN are generally 'found' and then describe the method we used in Paper III.

The most reliable way to identify AGN is through their UV-NIR spectra. Broad emission lines are clear evidence for AGN activity (Urry & Padovani 1995). For narrow-line AGN, line ratios can be used to distinguish them from star-forming galaxies (Baldwin et al. 1981; Veilleux & Osterbrock 1987). However, taking spectra of a large number of objects is observationally extremely costly and becomes close to impossible for extremely faint high-redshift objects. Therefore, preselected samples are needed.

Optical colours are commonly used to select AGN from large samples. These methods dates back to the early times of AGN research. Markarian (1967) selected nearby UV-excess galaxies and found numerous low-luminosity AGN. Schmidt & Green (1983) selected UV-excess objects from a much larger sample and created the Palomar Green Bright Quasar Catalog (known under the abbreviations BQS and PG). However, young stars also create massive amounts of UV emission. Therefore, contamination by star forming galaxies is a serious problem in samples selected in such a manner. More sophisticated methods using multiple colours and rejecting all extended objects are therefore more appropriate to select AGN candidates from large samples (Warren et al. 1991) and are for example used to create quasar catalogues for the Sloan Digital Sky Survey (SDSS) (Fan et al. 2001). Such methods rely on training sets of known AGN and are therefore only suitable for detecting objects similar to those in the training set. For example, low-luminosity AGN or other types of AGN resembling normal or starforming galaxies will be missed.

Radio emission can also be used to select AGN. However, given that only about 10% of all optically selected AGN show strong radio emission (Smith & Wright 1980), this method is not suitable to detect the bulk of radio-quiet AGN. Some star forming galaxies also show excess radio emission. Additionally, radio surveys are generally shallow or suffer from poor resolution. X-ray emission is more specific to AGN. However, strong emission from hot gas in the dark matter haloes of large clusters also makes some clusters X-ray sources (e.g. Bohringer et al. 1995). X-ray emission from hot halo gas in such objects is however weak compared to AGN and not detectable up to high redshifts. X-ray selected AGN samples should therefore not be contaminated. However, observations in the X-ray can be challenging and only few deep surveys in the X-rays (e.g. the Chandra Deep Field South, Giacconi et al. 2002) exist. And even in such deep surveys, it can be challenging to detect less luminous AGN at higher redshifts (e.g. Comastri et al. 2011).

The properties of infra-red dust emission can also be used to select AGN candidates (e.g. Klesman & Sarajedini 2007). The IR emission is thought to originate from the hot dusty torus (Sanders et al. 1989) and is believed to be distinguishable from star forming UltraLuminous InfraRed Galaxies (ULIRGs) (Genzel et al. 1998) through the IR slope. This makes assumptions about the properties of the radiation field heating the dust and given that ULIRGs are extremely common at redshifts around two or three (Madau et al. 1998; Reddy et al. 2006; Bouwens et al. 2010), contamination from 'normal' starforming galaxies is expected.

While all of the selection methods above are suitable for detecting certain types of AGN, all have a similar weakness: they have little power for detecting low-luminosity AGN in which the host galaxy light contributes considerably to the overall spectral energy distribution. Sarajedini et al. (2003) suggested and first applied a method for selecting AGN that has practically no contamination from other sources and is especially effective to detect low-luminosity AGN: variability selection. It is known that practically all AGN vary on all timescales from hours to decades (Koo et al. 1986; Wagner & Witzel 1995; Ulrich et al. 1997). Due to light-travel time arguments, galaxies cannot produce variability on human-observable timescales. It has also been found that low-luminosity AGN are more variable than their luminous counterparts (excluding blazars) (Trevese et al. 1994; Cristiani et al. 1996; di Clemente et al. 1996; de Vries et al. 2005; Wold et al. 2007). This makes variability selection especially sensitive to low-luminosity AGN that are hard to detect using other methods. Contamination is only expected from stars and supernovae. Most surveys, such as the GOODS Deep Fields (Dickinson et al. 2003) are taken in several epochs and can therefore be used for variability selection.

Variability selection is therefore theoretically an extremely powerful method to select AGN. In practice, it can be extremely difficult. In general, there is a choice between using well-calibrated robust statistical estimator but having to rely on the errors (which might simply be wrong) or determining some arbitrary measure of variability from a large sample and then setting an arbitrary cut-off over which all objects are considered variable. This raises the problem that one has no control over false positive rates. Samples derived in that way therefore contain unknown numbers of false positives. In Paper III we address this problem and derive a method that is robust, has high power and is able to pick up problems with error estimates. We applied this method to the GOODS Deep Field and found low-luminosity AGN beyond redshifts of 2.5.

4.4 Where are the supermassive binary black holes?

Supermassive Binary Black Holes (SMBBH) have received a lot of attention lately. Those objects should be formed when two sufficiently massive galaxies merge. However, given the vast amount of merging observed in the universe, our knowledge about SMBBH is surprisingly limited (Volonteri et al. 2009). Some double AGN sources are known, in those sources the two AGN are separated by several kpc (Comerford et al. 2009). However, there are no reliably identified close SMBBHs. Given that the final stage of the merger should last rather long as shrinking the binary becomes extremely difficult (Merritt & Milosavljević 2005), this is rather surprising. With the advent of gravitational wave detectors such as LISA that are also looking to find mergers of SMBBHs (Stavridis et al. 2009), finding close SMBBHs has become of interest.

However, it still remains a mystery what would be the signature of a SMBBH close to merging.

The stages of approach and merging of the two black holes after their host galaxies have merged are reasonably well understood. In the earliest stage, when the two black holes have just ended up in the same galaxy, they will carry, in most cases, significant angular momentum that needs to be lost to allow the black holes to move towards the center. Dynamical friction with stars and gas in the hosting galaxy plays the leading role in this process. Once the two black holes have sank to the center, they will form a binary system. The shrinking of the orbits from this stage used to be mysterious. There were worries that the shrinking would halt once all nearby stars were ejected, but later research showed that this is likely not the case (Gergely & Biermann 2008 and references therein). In the late stages of merging, it is likely that the spins of both two black holes align with the rotation of the accretion disk (Dotti et al. 2007) or that a spin-flip takes place (Gergely & Biermann 2008). Once the orbits are very close, gravitational waves will start to play a role and can radiate angular momentum as well as energy. This inspiral phase ends with a merger and after the two black holes have merged, the ring-down starts, i.e. the newly formed black hole will radiate all 'excess' information of its formation apart from its mass, spin, and charge (which is very likely zero).

OJ 287 is possibly the first candidate for a supermassive close binary black hole. Sillanpää et al. (1988) first noted this objects due to its extreme rapid variability. At that point, blazars were still unknown, so the BL Lac object OJ 287 naturally was noticed as a peculiar source. Sillanpää et al. (1988) searched archives of photo-plates and were able to construct a light-curve back to 1900. They noticed what looked like periodic outbursts of extreme strength and suggested that OJ 287 might host a SMBBH. Later on, Sillanpää et al. (1996) found the bursts to be double-peaked. The object was further monitored, and indeed, it seemed to continue to show periodic double-peaked bursts. However, the latest outburst has showed significant deviation from periodicity (Paper II).

After the periodicity was 'confirmed' in 1985, several authors started suggesting binary black hole models. The first of all binary black hole models for OJ 287 was proposed by Lehto & Valtonen (1996). In this model, the central black hole is much more massive than the secondary black hole. The secondary black hole induces disturbances in the accretion disk of the primary black hole (the secondary does not sustain a disk in this model), causing massive thermal flares. This model has since been adjusted to fit the newest observations (Valtonen et al. 2006; Valtonen 2007; Valtonen et al. 2008; Valtonen et al. 2009).

Other models have also been suggested to describe OJ 287 (Katz 1997; Villata et al. 1998; Valtaoja et al. 2000). Katz (1997) suggested that a binary black hole induces precession in the jet axes, resulting in a wobbling of the jet and thereby changing the beaming. Double-peaked bursts are then observed when the jet sweeps through the line of sight. In a similar model, Villata et al. (1998) suggested that both black holes produce jets, those sweep through the line of sight in regular intervals, causing the outbursts. Valtaoja et al. (2000) suggested a model similar to the original Lehto & Valtonen (1996) model. They found that only some of the outbursts observed in OJ 287 show radio counterparts and therefore suggested a model in which the secondary first hits the disk, which causes the first flare, this disturbance then travels down the jet, causing the second flare. None of these models seems to be able to explain all the observations (see Paper II for a discussion).

Interestingly, it has been found that a high percentage of well observed AGN show 'pseudo-periodicities' on multiple timescales (see Rieger 2007 for a list of such sources). Such periodicities have been suggested to be a sign of a close supermassive binary black hole by several authors (for example Qian et al. 2007; Rieger 2007; Rieger & Volpe 2010). However, given that the usual timescales of the periodicity are on the order of years and only few blazars have been observed for decades, it often happens that periodicities 'disappear' when observers try to follow an upcoming outburst (such has happened to some extent in the case of OJ 287 (where the outburst happend over a year earlier than expected, see Paper II) as well as AO 0235+16 (where the periodicity disappeared altogether, see Rieger 2007)). Such observations, as well as the fact that pseudo-periodicity over a short number of cycles is detected in a high percentage of well monitored blazars raises the question if regularly appearing outburst in blazars are simply a common feature of blazar light-curves and not a sign of binary black holes. Several authors have suggested methods that can cause periodic outbursts in blazar emission without the presence of a binary black hole (e.g. Ouyed et al. 1997; Liu et al. 2006; Paper II). More well designed follow-up observations such as performed for OJ 287 might be able to help constrain if binary black holes can really explain such observations.

Other AGN have been suspected to be close supermassive binary black holes. For example, some AGN (Boroson & Lauer 2009; Bogdanović et al. 2009; Dotti et al. 2009) show double-lined emission, this has sometimes been interpreted as a sign of a close pair of supermassive black holes that each 'carry' a broad line region. However, this theory can easily be tested through long term spectroscopic monitoring. None of the proposed double-lined AGN has passed the tests, and it has been repeatedly pointed out that accretion disks can explain the same kind of double-lined spectrum (e.g. Gaskell 1988). For example, Chornock et al. (2009) showed that the binary black hole claimed by Boroson & Lauer (2009) is indeed a normal double-line emitter. And Heckman et al. (2009) argued that the binary black hole candidate found by Dotti et al. (2009) is indeed an interacting system.

Another possibility to solve this mystery would be to try to detect SMBBH after they have merged. Schnittman & Krolik (2008) described emission expected from circumbinary accretion disks (i.e. disk located around both of the black holes). They modelled the emission in the circumbinary disk due to excess energy deposited in the disk from gravitational waves. The model proposed by Schnittman & Krolik (2008) predicts a long infrared afterglow after the merging.

Due to the complicated physical processes involved in this process and the fact that we do not even fully understand the circumstances under which a single black hole is active, more theoretical work is needed to better be able to understand if a certain observation is a sign of a binary black hole. For example, it has been shown that in a close binary black hole system, both black holes might form accretion disk and additionally a circumbinary disk further out (Hayasaki et al. 2007). Dotti et al. (2007) performed simulations of binary black hole systems embedded in an accretion disk and found similar structures to those described by (Hayasaki et al. 2007). They also suggested that activity might be present during coalescence, however possible heavily obscured due to star formation in the surrounding region. Once LISA becomes operational, detections of merging SMBBHs (Stavridis et al. 2009) might lead us to the host galaxies of those events and help us understand how close SMBBHs can be observed.

Bibliography

Abramowicz M. A., Czerny B., Lasota J. P., Szuszkiewicz E., 1988, Astrophysical Journal, 332, 646

Agol E., Blaes O., 1996, Monthly Notices of the Royal Astronomical Society, 282, 965

Anderhub H., Antonelli L. A., Antoranz P., Backes M., Baixeras C., Balestra S., Barrio J. A., Bastieri D., et al. 2009, The Astrophysical Journal, 704, L129

Anderson S. F., Margon B., Voges W., Plotkin R. M., Syphers D., Haggard D., Collinge M. J., Meyer J., Strauss M. A., Agüeros M. A., Hall P. B., Homer L., Željko Ivezić Richards G. T., Richmond M. W., Schneider D. P., Stinson G., Berk D. E. V., York D. G., 2007, The Astronomical Journal, 133, 313

Andruchow I., Romero G. E., Cellone S. A., 2005, Astronomy and Astrophysics, 442, 97

Angel J. R. P., Stockman H. S., 1980, Annual Review of Astronomy and Astrophysics, 18, 321

Antonucci R., 1993, Annual Review of Astronomy and Astrophysics, 31, 473

Antonucci R., 2002, in Proceedings of the XII Canary Islands Winter School of Astrophysics, Puerto de la Cruz, Tenerife, Spain, November 13 - 24, 2000, edited by J. Trujillo-Bueno, F. Moreno-Insertis, and F. Sánchez. Polarization insights for active galactic nuclei. Cambridge University Press, pp 151–175

Antonucci R. R. J., 1982, Nature, 299, 605

Antonucci R. R. J., Hickson P., Miller J. S., Olszewski E. W., 1987, The Astronomical Journal, 93, 785

Antonucci R. R. J., Miller J. S., 1985, The Astrophysical Journal, 297, 621

Antonucci R. R. J., Ulvestad J. S., 1985, The Astrophysical Journal, 294, 158

Asada K., Doi A., Kino M., Nagai H., Nakamura M., Kameno S., Group V. S. W., 2009, in Approaching Micro-Arcsecond Resolution with VSOP-2: Astrophysics and Technologies ASP Conference Series, Vol. 402, proceedings of the conference held 3-7 December, 2007, at ISAS/JAXA, Sagamihara, Kanagawa, Japan.

Edited by Yoshiaki Hagiwara, Ed Fomalont, Masato Tsuboi, and Yasuhiro Murata. Vol. 402, VSOP-2 observations of m 87: A proposal for a VSOP-2 key science program. p. 262

Asada K., Inoue M., Nakamura M., Kameno S., Nagai H., 2008, 0806.4233

Awaki H., Koyama K., Inoue H., Halpern J. P., 1991, Publications of the Astronomical Society of Japan, 43, 195

Awaki H., Koyama K., Kunieda H., Tawara Y., 1990, Nature, 346, 544

Axon D. J., Pedlar A., Unger S. W., Meurs E. J. A., Whittle D. M., 1989, Nature, 341, 631

Balbus S. A., Hawley J. F., 1998, Reviews of Modern Physics, 70, 1

Baldwin J. A., Phillips M. M., Terlevich R., 1981, Publications of the Astronomical Society of the Pacific, 93, 5

Baldwin J. A., Wampler E. J., Gaskell C. M., 1989, The Astrophysical Journal, 338, 630

Barthel P. D., 1989, The Astrophysical Journal, 336, 606

Baum S. A., Heckman T., 1989, The Astrophysical Journal, 336, 681

Baum S. A., Zirbel E. L., O'Dea C. P., 1995, Astrophysical Journal, 451, 88

Bautista M. A., Kallman T. R., 2001, The Astrophysical Journal Supplement Series, 134, 139

Becker R. H., Gregg M. D., Hook I. M., McMahon R. G., White R. L., Helfand D. J., 1997, The Astrophysical Journal, 479, L93

Becker R. H., White R. L., Gregg M. D., Brotherton M. S., Laurent-Muehleisen S. A., Arav N., 2000, The Astrophysical Journal, 538, 72

Bell E. F., Papovich C., Wolf C., Floc'h E. L., Caldwell J. A. R., Barden M., Egami E., McIntosh D. H., Meisenheimer K., Pérez-González P. G., Rieke G. H., Rieke M. J., Rigby J. R., Rix H., 2005, The Astrophysical Journal, 625, 23

Benitez E., Chavushyan V. H., Raiteri C. M., Villata M., Dultzin D., Martinez O., Perez-Camargo B., Torrealba J., 2009, ArXiv astro-ph 0910.0437

Bennett A. S., 1962, Memoirs of the Royal Astronomical Society, 68, 163

Beskin V. S., 2010, MHD Flows in compact astrophysical objects: accretion, winds and jets. A&A Library, Springer

Bianchi S., Schneider R., 2007, Monthly Notices of the Royal Astronomical Society, 378, 973

Bicknell G. V., 1985, Proceedings of the Astronomical Society of Australia, 6, 130

Biretta J. A., Stern C. P., Harris D. E., 1991, The Astronomical Journal, 101, 1632

Biretta J. A., Zhou F., Owen F. N., 1995, The Astrophysical Journal, 447, 582

Blandford R., Agol E., Broderick A., Heyl J., Koopmans L., Lee H., 2002, in Proceedings of the XII Canary Islands Winter School of Astrophysics, Puerto de la Cruz, Tenerife, Spain, November 13 - 24, 2000, edited by J. Trujillo-Bueno, F. Moreno-Insertis, and F. Sánchez. Compact objects and accretion disks. Cambridge University Press, pp 177–223

Blandford R. D., 1976, Monthly Notices of the Royal Astronomical Society, 176, 465

Blandford R. D., Konigl A., 1979, Astrophysical Journal, 232, 34

Blandford R. D., Payne D. G., 1982, Monthly Notices of the Royal Astronomical Society, 199, 883

Blandford R. D., Rees M. J., 1974, Monthly Notices of the Royal Astronomical Society, 169, 395

Blandford R. D., Znajek R. L., 1977, Monthly Notices of the Royal Astronomical Society, 179, 433

Blundell K. M., Beasley A. J., Bicknell G. V., 2003, Astrophysical Journal, 591, L103

Bogdanović T., Eracleous M., Sigurdsson S., 2009, The Astrophysical Journal, 697, 288

Bohringer H., Nulsen P. E. J., Braun R., Fabian A. C., 1995, Monthly Notices of the Royal Astronomical Society, 274, L67

Bondi H., 1952, Monthly Notices of the Royal Astronomical Society, 112, 195

Boroson T. A., Green R. F., 1992, Astrophysical Journal Supplement Series, 80, 109

Boroson T. A., Lauer T. R., 2009, Nature, 458, 53

Bouwens R. J., Illingworth G. D., Oesch P. A., Stiavelli M., van Dokkum P., Trenti M., Magee D., Labbé I., Franx M., Carollo C. M., Gonzalez V., 2010, The Astrophysical Journal, 709, L133

Brenneman L. W., Reynolds C. S., 2006, The Astrophysical Journal, 652, 1028

Bridle A. H., 1992, in Testing the AGN paradigm; Proceedings of the 2nd Annual Topical Astrophysics Conference, Univ. of Maryland, College Park, Oct. 14-16, 1991 (A93-29801 11-90) Vol. 254, Jets on large scales. pp 386–397

Bridle A. H., Hough D. H., Lonsdale C. J., Burns J. O., Laing R. A., 1994, The Astronomical Journal, 108, 766

Bridle A. H., Perley R. A., 1984, Annual Review of Astronomy and Astrophysics, 22, 319

Brotherton M. S., Wills B. J., Steidel C. C., Sargent W. L. W., 1994, The Astrophysical Journal, 423, 131

Browne I. W. A., 1983, Monthly Notices of the Royal Astronomical Society, 204, 23P

Carini M. T., Noble J. C., Taylor R., Culler R., 2007, Astronomical Journal, 133, 303

Casse F., Keppens R., 2002, The Astrophysical Journal, 581, 988

Cellone S. A., Romero G. E., Araudo A. T., 2007, Monthly Notices of the Royal Astronomical Society, 374, 357

Celotti A., Fabian A. C., 1993, Monthly Notices of the Royal Astronomical Society, 264, 228

Cerqueira A. H., de Gouveia Dal Pino E. M., 2001, The Astrophysical Journal, 560, 779

Chatterjee R., Jorstad S. G., Marscher A. P., Oh H., McHardy I. M., Aller M. F., Aller H. D., Balonek T. J., Miller H. R., Ryle W. T., Tosti G., Kurtanidze O., Nikolashvili M., Larionov V. M., Hagen-Thorn V. A., 2008, The Astrophysical Journal, 689, 79

Chiaberge M., Capetti A., Celotti A., 1999, Astronomy and Astrophysics, 349, 77

Chornock R., Bloom J. S., Cenko S. B., Silverman J. M., Filippenko A. V., Hicks M. D., Lawrence K. J., Chang P., Comerford J. M., George M. R., Modjaz M., Oishi J. S., Quataert E., Strubbe L. E., 2009, The Astronomer's Telegram, 1955, 1

Churazov E., Sunyaev R., Forman W., Böhringer H., 2002, Monthly Notices of the Royal Astronomical Society, 332, 729

Clarke D. A., Burns J. O., Norman M. L., 1992, The Astrophysical Journal, 395, 444

Clavel J., Wamsteker W., Glass I. S., 1989, The Astrophysical Journal, 337, 236

Collinge M. J., Strauss M. A., Hall P. B., Željko Ivezić Munn J. A., Schlegel D. J., Zakamska N. L., Anderson S. F., Harris H. C., Richards G. T., Schneider D. P., Voges W., York D. G., Margon B., Brinkmann J., 2005, The Astronomical Journal, 129, 2542

Comastri A., Ranalli P., Iwasawa K., Vignali C., Gilli R., Georgantopoulos I., Barcons X., Brandt W. N., et al. 2011, Astronomy and Astrophysics, 526, L9

Comerford J. M., Griffith R. L., Gerke B. F., Cooper M. C., Newman J. A., Davis M., Stern D., 2009, The Astrophysical Journal, 702, L82

Conway J., Elitzur M., Parra R., 2005, Astrophysics and Space Science, 295, 319

Cristiani S., Trentini S., Franca F. L., Aretxaga I., Andreani P., Vio R., Gemmo A., 1996, Astronomy and Astrophysics, 306, 395

Croke S. M., O'Sullivan S. P., Gabuzda D. C., 2010, 402, 259

Croton D. J., Springel V., White S. D. M., Lucia G. D., Frenk C. S., Gao L., Jenkins A., Kauffmann G., Navarro J. F., Yoshida N., 2006, Monthly Notices of the Royal Astronomical Society, 365, 11

Czerny B., 2006, in AGN Variability from X-Rays to Radio Waves: Proceedings of the conference held 14-16 June, 2004 at the Crimean Astrophysical Observatory in Crimea, Ukraine. Edited by C. Martin Gaskell, Ian M. McHardy, Bradley M. Peterson and Sergey G. Sergeev. Vol. 360, The role of the accretion disk in AGN variability. p. 265

Czerny B., Rózańska A., Kuraszkiewicz J., 2004, Astronomy and Astrophysics, 428, 39

Daddi E., Alexander D. M., Dickinson M., Gilli R., Renzini A., Elbaz D., Cimatti A., Chary R., Frayer D., Bauer F. E., Brandt W. N., Giavalisco M., Grogin N. A., Huynh M., Kurk J., Mignoli M., Morrison G., Pope A., Ravindranath S., 2007, The Astrophysical Journal, 670, 173

D'Arcangelo F. D., Marscher A. P., Jorstad S. G., Smith P. S., Larionov V. M., Hagen-Thorn V. A., Williams G. G., Gear W. K., Clemens D. P., Sarcia D., Grabau A., Tollestrup E. V., Buie M. W., Taylor B., Dunham E., 2009, Astrophysical Journal, 697, 985

Davidson K., Netzer H., 1979, Reviews of Modern Physics, 51, 715

de Diego J. A., Dultzin-Hacyan D., Ramirez A., Benitez E., 1998, Astrophysical Journal, 501, 69

de Vries W. H., Becker R. H., White R. L., Loomis C., 2005, Astronomical Journal, 129, 615

Degl'Innocenti E. L., 2002, in Proceedings of the XII Canary Islands Winter School of Astrophysics, Puerto de la Cruz, Tenerife, Spain, November 13 - 24, 2000, edited by J. Trujillo-Bueno, F. Moreno-Insertis, and F. Sánchez. Cambridge, UK: Cambridge University Press, ISBN 0-521-80998-3, 2002, p. 1 - 53 The physics of polarization. Cambridge University Press, pp 1–53

della Ceca R., Lamorani G., Maccacaro T., Wolter A., Griffiths R., Stocke J. T., Setti G., 1994, The Astrophysical Journal, 430, 533 di Clemente A., Giallongo E., Natali G., Trevese D., Vagnetti F., 1996, Astrophysical Journal, 463, 466

Diamond-Stanic A. M., Fan X., Brandt W. N., Shemmer O., Strauss M. A., Anderson S. F., Carilli C. L., Gibson R. R., Jiang L., Kim J. S., Richards G. T., Schmidt G. D., Schneider D. P., Shen Y., Smith P. S., Vestergaard M., Young J. E., 2009, The Astrophysical Journal, 699, 782

Dickinson M., Giavalisco M., Team G., 2003, in Proceedings of the European Southern Observatory and Universitäts-Sternwarte München Workshop Held in Venice, Italy, 24-26 October 2001 The great observatories origins deep survey. Springer, p. 324

Dotti M., Colpi M., Haardt F., Mayer L., 2007, Monthly Notices of the Royal Astronomical Society, 379, 956

Dotti M., Montuori C., Decarli R., Volonteri M., Colpi M., Haardt F., 2009, Monthly Notices of the Royal Astronomical Society, 398, L73

Dunlop J. S., McLure R. J., Kukula M. J., Baum S. A., O'Dea C. P., Hughes D. H., 2003, Monthly Notices of the Royal Astronomical Society, 340, 1095

Dunlop J. S., Peacock J. A., 1990, Monthly Notices of the Royal Astronomical Society, 247, 19

Edelson R. A., Malkan M. A., Rieke G. H., 1987, The Astrophysical Journal, 321, 233

Elitzur M., 2008, New Astronomy Review, 52, 274

Elvis M., 2000, The Astrophysical Journal, 545, 63

Elvis M., Marengo M., Karovska M., 2002, The Astrophysical Journal, 567, L107

Emmanoulopoulos D., McHardy I. M., Uttley P., 2010, Monthly Notices of the Royal Astronomical Society, p. 931

Emmering R. T., Blandford R. D., Shlosman I., 1992, The Astrophysical Journal, 385, 460

Evans I. N., Ford H. C., Kinney A. L., Antonucci R. R. J., Armus L., Caganoff S., 1991, The Astrophysical Journal, 369, L27

Falcke H., Sherwood W., Patnaik A. R., 1996, The Astrophysical Journal, 471, 106

Fan X., Strauss M. A., Richards G. T., Newman J. A., Becker R. H., Schneider D. P., et al. 2001, The Astronomical Journal, 121, 31

Fanaroff B. L., Riley J. M., 1974, Monthly Notices of the Royal Astronomical Society, 167, 31P

Farrah D., Lacy M., Priddey R., Borys C., Afonso J., 2007, Astrophysical Journal, 662, L59

Ferland G. J., Korista K. T., Verner D. A., Ferguson J. W., Kingdon J. B., Verner E. M., 1998, Publications of the Astronomical Society of the Pacific, 110, 761

Fernandes R. C., Sodré L., da Silva L. V., 2000, Astrophysical Journal, 544, 123

Fernini I., Burns J. O., Leahy J. P., Basart J. P., 1991, The Astrophysical Journal, 381, 63

Ferrari A., 1998, Annual Review of Astronomy and Astrophysics, 36, 539

Feruglio C., Maiolino R., Piconcelli E., Menci N., Aussel H., Lamastra A., Fiore F., 2010, Astronomy and Astrophysics, 518, L155

Fiorucci M., Ciprini S., Tosti G., 2004, Astronomy and Astrophysics, 419, 25

Forman W., Jones C., Churazov E., Markevitch M., Nulsen P., Vikhlinin A., Begelman M., Böhringer H., Eilek J., Heinz S., Kraft R., Owen F., Pahre M., 2007, The Astrophysical Journal, 665, 1057

Foschini L., Tagliaferri G., Ghisellini G., Ghirlanda G., Tavecchio F., Bonnoli G., 2010, 1004.4518

Franca F. L., Gregorini L., Cristiani S., de Ruiter H., Owen F., 1994, The Astronomical Journal, 108, 1548

Fugmann W., 1988, Astronomy and Astrophysics, 205, 86

Gabuzda D. C., 2003, New Astronomy Review, 47, 599

Gabuzda D. C., Rastorgueva E. A., Smith P. S., O'Sullivan S. P., 2006, Monthly Notices of the Royal Astronomical Society, 369, 1596

Gabuzda D. C., Wardle J. F. C., Roberts D. H., 1989, The Astrophysical Journal, 336, L59

Gabuzda D. C., Éamonn Murray Cronin P., 2004, Monthly Notices of the Royal Astronomical Society, 351, L89

Garofalo D., Evans D. A., Sambruna R. M., 2010, Monthly Notices of the Royal Astronomical Society, 406, 975

Garrington S. T., Conway R. G., 1991, Monthly Notices of the Royal Astronomical Society, 250, 198

Gaskell C. M., 1988, in Proceedings of a conference held at the Georgia State University, Atlanta, Georgia, October 28-30, 1987. Editors, H. Richard Miller, Paul J. Wiita Vol. 307, Double peaked broad line profiles — edge on accretion disks or double quasar nuclei?. Springer, p. 61

Gebhardt K., Bender R., Bower G., Dressler A., Faber S. M., Filippenko A. V., Green R., Grillmair C., Ho L. C., Kormendy J., Lauer T. R., Magorrian J., Pinkney J., Richstone D., Tremaine S., 2000, The Astrophysical Journal, 539, L13

Genzel R., Lutz D., Sturm E., Egami E., Kunze D., Moorwood A. F. M., Rigopoulou D., Spoon H. W. W., Sternberg A., Tacconi-Garman L. E., Tacconi L., Thatte N., 1998, The Astrophysical Journal, 498, 579

Gergely L., Biermann P. L., 2008, Journal of Physics Conference Series, 122, 2040

Ghisellini G., 2009, ArXiv astro-ph 0912.3258

Ghisellini G., Celotti A., 2001, Astronomy and Astrophysics, 379, L1

Ghisellini G., Maraschi L., Tavecchio F., 2009, Monthly Notices of the Royal Astronomical Society, 396, L105

Ghisellini G., Maraschi L., Treves A., 1985, Astronomy and Astrophysics, 146, 204

Giacconi R., Zirm A., Wang J., Rosati P., Nonino M., Tozzi P., Gilli R., Mainieri V., Hasinger G., Kewley L., Bergeron J., Borgani S., Gilmozzi R., Grogin N., Koekemoer A., Schreier E., Zheng W., Norman C., 2002, The Astrophysical Journal Supplement Series, 139, 369

Gopal-Krishna Stalin C. S., Sagar R., Wiita P. J., 2003, Astrophysical Journal, 586, L25

Gopal-Krishna Wiita P. J., 2000, Astronomy and Astrophysics, 363, 507

Gopal-Krishna Wiita P. J., Altieri B., 1993, Astronomy and Astrophysics, 271, 89

Goyal A., Gopal-Krishna S., Anupama G. C., Sahu D. K., 2007, Bulletin of the Astronomical Society of India, 35, 141

Graham A. W., 2007, Monthly Notices of the Royal Astronomical Society, 379, 711

Graham A. W., Erwin P., Caon N., Trujillo I., 2001, The Astrophysical Journal, 563, L11

Granato G. L., Danese L., 1994, Monthly Notices of the Royal Astronomical Society, 268, 235

Granato G. L., Danese L., Franceschini A., 1997, The Astrophysical Journal, 486, 147

Granato G. L., Zotti G. D., Silva L., Bressan A., Danese L., 2004, The Astrophysical Journal, 600, 580

Greenstein J. L., Matthews T., 1963, Nature, 197, 1041

Gupta A. C., Fan J. H., Bai J. M., Wagner S. J., 2008, The Astronomical Journal, 135, 1384

Hamilton T. S., Casertano S., Turnshek D. A., 2002, Astrophysical Journal, 576, 61

Haniff C. A., Wilson A. S., Ward M. J., 1988, The Astrophysical Journal, 334, 104

Hartwick F. D. A., Schade D., 1990, Annual Review of Astronomy and Astrophysics, 28, 437

Hayasaki K., Mineshige S., Sudou H., 2007, Publications of the Astronomical Society of Japan, 59, 427

Heckman T. M., 1980a, Astronomy and Astrophysics, 87, 152

Heckman T. M., 1980b, Astronomy and Astrophysics, 87, 142

Heckman T. M., Krolik J. H., Moran S. M., Schnittman J., Gezari S., 2009, The Astrophysical Journal, 695, 363

Hill G. J., Lilly S. J., 1991, The Astrophysical Journal, 367, 1

Hine R. G., Longair M. S., 1979, Monthly Notices of the Royal Astronomical Society, 188, 111

Hirschmann M., Khochfar S., Burkert A., Naab T., Genel S., Somerville R. S., 2010, Monthly Notices of the Royal Astronomical Society, 407, 1016

Hufnagel B. R., Bregman J. N., 1992, The Astrophysical Journal, 386, 473

Hughes P. A., Aller H. D., Aller M. F., 1985, Astrophysical Journal, 298, 301

Hughes P. A., Aller H. D., Aller M. F., 1989, Astrophysical Journal, 341, 68

Hutchings J. B., Neff S. G., 1991, The Astronomical Journal, 101, 434

Igumenshchev I. V., 2004, Progress of Theoretical Physics Supplement, 155, 87

Igumenshchev I. V., Narayan R., Abramowicz M. A., 2003, Astrophysical Journal, 592, 1042

Impey C. D., Lawrence C. R., Tapia S., 1991, The Astrophysical Journal, 375, 46

Jaffe W., Raban D., Röttgering H., Meisenheimer K., Tristram K., 2007, in proceedings of the conference held 16-21 October, 2006 at Xi'an Jioatong University, Xi'an, China. Edited by Luis C. Ho and Jian-Min Wang Vol. 373, Mid-Infrared interferometric observations of AGNs. p. 439

Jahnke K., Maccio A., 2010, ArXiv astro-ph 1006.0482

Jang M., 2005, Astrophysics and Space Science, 295, 397

Jang M., Miller H. R., 1995, Astrophysical Journal, 452, 582

Jannuzi B. T., Smith P. S., Elston R., 1994, Astrophysical Journal, 428, 130

Jiang L., Fan X., Brandt W. N., Carilli C. L., Egami E., Hines D. C., Kurk J. D., Richards G. T., Shen Y., Strauss M. A., Vestergaard M., Walter F., 2010, Nature, 464, 380

Jones T. W., Rudnick L., Fiedler R. L., Aller H. D., Aller M. F., Hodge P. E., 1985, Astrophysical Journal, 290, 627

Jorstad S. G., Marscher A. P., Mattox J. R., Wehrle A. E., Bloom S. D., Yurchenko A. V., 2001, Astrophysical Journal Supplement Series, 134, 181

Jorstad S. G., Marscher A. P., Stevens J. A., Smith P. S., Forster J. R., Gear W. K., Cawthorne T. V., Lister M. L., Stirling A. M., Gomez J. L., Greaves J. S., Robson E. I., 2007, Astronomical Journal, 134, 799

Kaspi S., Brandt W. N., Maoz D., Netzer H., Schneider D. P., Shemmer O., 2007, Astrophysical Journal, 659, 997

Katz J. I., 1997, Astrophysical Journal, 478, 527

Kellermann K. I., Sramek R., Schmidt M., Shaffer D. B., Green R., 1989, Astronomical Journal, 98, 1195

Kelly B. C., Bechtold J., Siemiginowska A., 2009, The Astrophysical Journal, 698, 895

Kelly B. C., Vestergaard M., Fan X., Hopkins P., Hernquist L., Siemiginowska A., 2010, 1006.3561

Kharb P., Lister M. L., Cooper N. J., 2010, The Astrophysical Journal, 710, 764

Klesman A., Sarajedini V., 2007, Astrophysical Journal, 665, 225

Kollgaard R. I., Wardle J. F. C., Roberts D. H., Gabuzda D. C., 1992, The Astronomical Journal, 104, 1687

Konigl A., Kartje J. F., 1994, The Astrophysical Journal, 434, 446

Koo D. C., Kron R. G., Cudworth K. M., 1986, Publications of the Astronomical Society of the Pacific, 98, 285

Koratkar A., Pian E., Urry C. M., Pesce J. E., 1998, The Astrophysical Journal, 492, 173

Krolik J. H., 1999, Active Galactic Nuclei. Princeton Series in Astrophysics, Princeton University Press

Krolik J. H., 2001, The Astrophysical Journal, 551, 72

Krolik J. H., Begelman M. C., 1988, The Astrophysical Journal, 329, 702

Krolik J. H., Hawley J. F., 2002, The Astrophysical Journal, 573, 754

Kulsrud R. M., 2005, Plasma physics for astrophysics. Princeton University Press

Laing R. A., 1988, Nature, 331, 149

Laing R. A., Bridle A. H., 1987, Monthly Notices of the Royal Astronomical Society, 228, 557

Laing R. A., Jenkins C. R., Wall J. V., Unger S. W., 1994, in The First Stromlo Symposium: The Physics of Active Galaxies. Vol. 54, Spectrophotometry of a complete sample of 3CR radio sources: Implications for unified models. ASPC Conference Series, p. 201

Laor A., 1990, Monthly Notices of the Royal Astronomical Society, 246, 369

Laor A., 2003, The Astrophysical Journal, 590, 86

Laor A., Netzer H., 1989, Monthly Notices of the Royal Astronomical Society, 238, 897

Laor A., Netzer H., Piran T., 1990, Monthly Notices of the Royal Astronomical Society, 242, 560

Lawrence A., 1987, Publications of the Astronomical Society of the Pacific, 99, 309

Lehto H. J., Valtonen M. J., 1996, Astrophysical Journal, 460, 207

Leighly K. M., Halpern J. P., Jenkins E. B., Casebeer D., 2007, The Astrophysical Journal Supplement Series, 173, 1

Leighly K. M., Halpern J. P., Jenkins E. B., Grupe D., Choi J., Prescott K. B., 2007, The Astrophysical Journal, 663, 103

Leismann T., Antón L., Aloy M. A., Müller E., Martí J. M., Miralles J. A., Ibáñez J. M., 2005, Astronomy and Astrophysics, 436, 503

Lister M. L., Cohen M. H., Homan D. C., Kadler M., Kellermann K. I., Kovalev Y. Y., Ros E., Savolainen T., Zensus J. A., 2009, The Astronomical Journal, 138, 1874

Liu F. K., Zhao G., Wu X., 2006, The Astrophysical Journal, 650, 749

Londish D., Heidt J., Boyle B. J., Croom S. M., Kedziora-Chudczer L., 2004, Monthly Notices of the Royal Astronomical Society, 352, 903

Lovelace R. V. E., 1976, Nature, 262, 649

Lyutikov M., Pariev V. I., Gabuzda D. C., 2005, Monthly Notices of the Royal Astronomical Society, 360, 869

Madau P., Pozzetti L., Dickinson M., 1998, The Astrophysical Journal, 498, 106

Mahadevan R., 1998, Nature, 394, 651

Maraschi L., Ghisellini G., Celotti A., 1992, The Astrophysical Journal, 397, L5

Marconi A., Hunt L. K., 2003, Astrophysical Journal, 589, L21

Markarian B. E., 1967, Astrofizika, 3, 55

Marscher A. P., 2009, ArXiv astro-ph 0909.2576

Marscher A. P., Gear W. K., 1985, Astrophysical Journal, 298, 114

Marscher A. P., Jorstad S. G., D'Arcangelo F. D., Smith P. S., Williams G. G., et al. 2008, Nature, 452, 966

Mathis J. S., Rumpl W., Nordsieck K. H., 1977, The Astrophysical Journal, 217, 425

Matteo T. D., Springel V., Hernquist L., 2005, Nature, 433, 604

Matthews T. A., Sandage A. R., 1963, The Astrophysical Journal, 138, 30

McClintock J. E., Shafee R., Narayan R., Remillard R. A., Davis S. W., Li L., 2006, The Astrophysical Journal, 652, 518

McDowell J. C., Canizares C., Elvis M., Lawrence A., Markoff S., Mathur S., Wilkes B. J., 1995, The Astrophysical Journal, 450, 585

McGreer I. D., Hall P. B., Fan X., Bian F., Inada N., Oguri M., Strauss M. A., Schneider D. P., Farnsworth K., 2010, The Astronomical Journal, 140, 370

McLean I. S., Aspin C., Heathcote S. R., McCaughrean M. J., 1983, Nature, 304, 609

Meier D. L., 1999, The Astrophysical Journal, 522, 753

Merritt D., Milosavljević M., 2005, Living Reviews in Relativity, 8, 8

Mihos J. C., 1995, The Astrophysical Journal, 438, L75

Miley G. K., Neugebauer G., Soifer B. T., 1985, The Astrophysical Journal, 293, L11

Miller J. S., Antonucci R. R. J., 1983, The Astrophysical Journal, 271, L7

Miller J. S., Goodrich R. W., 1990, The Astrophysical Journal, 355, 456

Nakamura M., Meier D. L., 2004, The Astrophysical Journal, 617, 123

Nakamura M., Uchida Y., Hirose S., 2001, New Astronomy, 6, 61

Narayan R., Yi I., 1994, The Astrophysical Journal, 428, L13

Neff S. G., Hutchings J. B., 1992, The Astronomical Journal, 103, 1746

Nelson C. H., Whittle M., 1995, Astrophysical Journal Supplement Series, 99, 67

Nelson C. H., Whittle M., 1996, Astrophysical Journal, 465, 96

Nenkova M., Željko Ivezić Elitzur M., 2002, The Astrophysical Journal, 570, L9

Nesvadba N. P. H., Lehnert M. D., Breuck C. D., Gilbert A. M., van Breugel W., 2008, Astronomy and Astrophysics, 491, 407

Netzer H., 1985, The Astrophysical Journal, 289, 451

Nicastro F., Martocchia A., Matt G., 2003, The Astrophysical Journal, 589, L13

Novak G. S., Faber S. M., Dekel A., 2006, Astrophysical Journal, 637, 96

O'Sullivan S. P., Gabuzda D. C., 2009, Monthly Notices of the Royal Astronomical Society, 400, 26

Ouyed R., Pudritz R. E., Stone J. M., 1997, Nature, 385, 409

Owen F. N., Ledlow M. J., 1994, in The First Stromlo Symposium: The Physics of Active Galaxies Vol. 54, The FRI/Il break and the bivariate luminosity function in abell clusters of galaxies. ASPC Conference Series, p. 319

Owen F. N., White R. A., 1991, Monthly Notices of the Royal Astronomical Society, 249, 164

Padovani P., 1993, Monthly Notices of the Royal Astronomical Society, 263, 461

Paggi A., Cavaliere A., Vittorini V., Tavani M., 2009, Astronomy and Astrophysics, 508, L31

Paolillo M., Schreier E. J., Giacconi R., Koekemoer A. M., Grogin N. A., 2004, Astrophysical Journal, 611, 93

Parma P., Fanti C., Fanti R., Morganti R., de Ruiter H. R., 1987, Astronomy and Astrophysics, 181, 244

Peng C. Y., 2007, The Astrophysical Journal, 671, 1098

Peterson B. M., 1988, Publications of the Astronomical Society of the Pacific, 100, 18

Peterson B. M., 1993, Publications of the Astronomical Society of the Pacific, 105, 247

Pier E. A., Krolik J. H., 1992, The Astrophysical Journal, 401, 99

Pier E. A., Krolik J. H., 1993, The Astrophysical Journal, 418, 673

Plotkin R. M., Anderson S. F., Hall P. B., Margon B., Voges W., Schneider D. P., Stinson G., York D. G., 2008, The Astronomical Journal, 135, 2453

Pogge R. W., 1988, The Astrophysical Journal, 328, 519

Porcas R., 1983, Nature, 302, 753

Prestage R. M., Peacock J. A., 1988, Monthly Notices of the Royal Astronomical Society, 230, 131

Ptak A., Heckman T., Levenson N. A., Weaver K., Strickland D., 2003, The Astrophysical Journal, 592, 782

Pushkarev A. B., Kovalev Y. Y., Lister M. L., 2010, The Astrophysical Journal, 722, 7

Qian S., Kudryavtseva N. A., Britzen S., Krichbaum T. P., Gao L., Witzel A., Zensus J. A., Aller M. F., Aller H. D., Zhang X., 2007, Chinese Journal of Astronomy and Astrophysics, 7, 364

Raban D., Jaffe W., Röttgering H., Meisenheimer K., Tristram K. R. W., 2009, Monthly Notices of the Royal Astronomical Society, 394, 1325

Rawlings S., Saunders R., Eales S. A., Mackay C. D., 1989, Monthly Notices of the Royal Astronomical Society, 240, 701

Rector T. A., Stocke J. T., Perlman E. S., Morris S. L., Gioia I. M., 2000, The Astronomical Journal, 120, 1626

Reddy N. A., Steidel C. C., Erb D. K., Shapley A. E., Pettini M., 2006, Astrophysical Journal, 653, 1004

Rees M. J., 1966, Nature, 211, 468

Rieger F. M., 2007, Astrophysics and Space Science, 309, 271

Rieger F. M., Volpe F., 2010, Astronomy and Astrophysics, 520, 23

Rudnick L., Owen F. N., Jones T. W., Puschell J. J., Stein W. A., 1978, The Astrophysical Journal, 225, L5

Rybicki G. B., Lightman A. P., 1986, Radiative Processes in Astrophysics. Wiley-VCH

Sakurai T., 1987, Publications of the Astronomical Society of Japan, 39, 821

Sanders D. B., Phinney E. S., Neugebauer G., Soifer B. T., Matthews K., 1989, The Astrophysical Journal, 347, 29

Sarajedini V. L., Gilliland R. L., Kasm C., 2003, The Astrophysical Journal, 599, 173

Sasada M., Uemura M., Arai A., Fukazawa Y., Kawabata K. S., Ohsugi T., Yamashita T., Isogai M., Sato S., Kino M., 2008, 0812.1416

Schilizzi R. T., de Bruyn A. G., 1983, Nature, 303, 26

Schmidt M., 1963, Nature, 197, 1040

Schmidt M., Green R. F., 1983, The Astrophysical Journal, 269, 352

Schmoll S., Miller J. M., Volonteri M., Cackett E., Reynolds C. S., Fabian A. C., Brenneman L. W., Miniutti G., Gallo L. C., 2009, The Astrophysical Journal, 703, 2171

Schnittman J. D., Krolik J. H., 2008, The Astrophysical Journal, 684, 835

Sedlmayr E., 1997, Astrophysics and Space Science, 251, 103

Shafee R., McClintock J. E., Narayan R., Davis S. W., Li L., Remillard R. A., 2006, The Astrophysical Journal, 636, L113

Shafee R., Narayan R., McClintock J. E., 2008, The Astrophysical Journal, 676, 549

Shakura N. I., Syunyaev R. A., 1973, Astronomy and Astrophysics, 24, 337

Shemmer O., Brandt W. N., Anderson S. F., Diamond-Stanic A. M., Fan X., Richards G. T., Schneider D. P., Strauss M. A., 2009, The Astrophysical Journal, 696, 580

Silk J., Rees M. J., 1998, Astronomy and Astrophysics, 331, L1

Sillanpää A., Haarala S., Valtonen M. J., Sundelius B., Byrd G. G., 1988, Astrophysical Journal, 325, 628

Sillanpää A., Takalo L. O., Pursimo T., Nilsson K., Heinamaki P., Katajainen S., Pietila H., et al. 1996, Astronomy and Astrophysics, 315, L13

Smith M. G., Wright A. E., 1980, Monthly Notices of the Royal Astronomical Society, 191, 871

Somerville R. S., Hopkins P. F., Cox T. J., Robertson B. E., Hernquist L., 2008, Monthly Notices of the Royal Astronomical Society, 391, 481

Sparks W. B., Fraix-Burnet D., Macchetto F., Owen F. N., 1992, Nature, 355, 804

Stalin C. S., Gopal-Krishna Sagar R., Wiita P. J., 2004, Monthly Notices of the Royal Astronomical Society, 350, 175

Stalin C. S., Gupta A. C., Gopal-Krishna Wiita P. J., Sagar R., 2005, Monthly Notices of the Royal Astronomical Society, 356, 607

Stavridis A., Arun K. G., Will C. M., 2009, Physical Review D, 80, 67501

Stawarz L., Siemiginowska A., Ostrowski M., Sikora M., 2005, The Astrophysical Journal, 626, 120

Stiavelli M., Biretta J., Moller P., Zeilinger W. W., 1992, Nature, 355, 802

Stocke J. T., 2001 Vol. 227, Hidden BL lacertae objects near and far. ASPC, p. 184

Stocke J. T., Morris S. L., Weymann R. J., Foltz C. B., 1992, The Astrophysical Journal, 396, 487

Strickland D. K., Heckman T. M., 2007, The Astrophysical Journal, 658, 258

Tadhunter C., Tsvetanov Z., 1989, Nature, 341, 422

Tavecchio F., Ghisellini G., Bonnoli G., Ghirlanda G., 2010, Monthly Notices of the Royal Astronomical Society, 405, L94

Taylor G. B., Perley R. A., Inoue M., Kato T., Tabara H., Aizu K., 1990, The Astrophysical Journal, 360, 41

Tran H. D., 2003, The Astrophysical Journal, 583, 632

Tran H. D., Miller J. S., Kay L. E., 1992, The Astrophysical Journal, 397, 452

Treister E., Urry C. M., Virani S., 2009, The Astrophysical Journal, 696, 110

Trevese D., Kron R. G., Majewski S. R., Bershady M. A., Koo D. C., 1994, The Astrophysical Journal, 433, 494

Tribble P. C., 1992, Monthly Notices of the Royal Astronomical Society, 256, 281

Tristram K. R. W., Meisenheimer K., Jaffe W., Schartmann M., Rix H., Leinert C., Morel S., Wittkowski M., Röttgering H., Perrin G., Lopez B., Raban D., Cotton W. D., Graser U., Paresce F., Henning T., 2007, Astronomy and Astrophysics, 474, 837

Turnshek D. A., 1984, The Astrophysical Journal, 280, 51

Turnshek D. A., 1988, in Probing the universe; Proceedings of the QSO Absorption Line Meeting, Baltimore, MD, May 19-21, 1987 (A89-28976 11-90) BAL QSOs - observations, models and implications for narrow absorption line systems. Cambridge University Press, p. 17

Turnshek D. A., Grillmair C. J., 1986, The Astrophysical Journal, 310, L1

Ulrich M., Maraschi L., Urry C. M., 1997, Annual Review of Astronomy and Astrophysics, 35, 445

Ulvestad J. S., Wilson A. S., Sramek R. A., 1981, The Astrophysical Journal, 247, 419

Urry C. M., Padovani P., 1995, Publications of the Astronomical Society of the Pacific, 107, 803

Uttley P., Mchardy I. M., 2004, Progress of Theoretical Physics Supplement, 155, 170

Valtaoja E., Terasranta H., Urpo S., Nesterov N. S., Lainela M., Valtonen M., 1992, Astronomy and Astrophysics, 254, 80

Valtaoja E., Teräsranta H., Tornikoski M., Sillanpää A., Aller M. F., Aller H. D., Hughes P. A., 2000, Astrophysical Journal, 531, 744

Valtonen M. J., 2007, Astrophysical Journal, 659, 1074

Valtonen M. J., Lehto H. J., Nilsson K., Heidt J., Takalo L. O., Sillanpää A., Villforth C., et al. 2008, Nature, 452, 851

Valtonen M. J., Lehto H. J., Sillanpää A., Nilsson K., Mikkola S., Hudec R., Basta M., Teräsranta H., Haque S., Rampadarath H., 2006, Astrophysical Journal, 646, 36

Valtonen M. J., Nilsson K., Villforth C., Lehto H. J., Takalo L. O., Lindfors E., et al. 2009, Astrophysical Journal, 698, 781

Vaughan S., Edelson R., Warwick R. S., Uttley P., 2003, Monthly Notices of the Royal Astronomical Society, 345, 1271

Veilleux S., Osterbrock D. E., 1987, The Astrophysical Journal Supplement Series, 63, 295

Vermeulen R. C., Ogle P. M., Tran H. D., Browne I. W. A., Cohen M. H., Readhead A. C. S., Taylor G. B., Goodrich R. W., 1995, The Astrophysical Journal, 452, L5

Veron-Cetty M., Veron P., 2006, Astronomy and Astrophysics, 455, 773

Vestergaard M., Fan X., Tremonti C. A., Osmer P. S., Richards G. T., 2008, The Astrophysical Journal, 674, L1

Vestergaard M., Peterson B. M., 2006, Astrophysical Journal, 641, 689

Villata M., Raiteri C. M., Sillanpaa A., Takalo L. O., 1998, Monthly Notices of the Royal Astronomical Society, 293, L13

Villforth C., Heidt J., Nilsson K., 2008, Astronomy and Astrophysics, 488, 133

Volonteri M., Miller J. M., Dotti M., 2009, The Astrophysical Journal, 703, L86

Wagner S. J., Witzel A., 1995, Annual Review of Astronomy and Astrophysics, 33, 163

Wandel A., Peterson B. M., Malkan M. A., 1999, The Astrophysical Journal, 526, 579

Wardle J. F. C., Moore R. L., Angel J. R. P., 1984, The Astrophysical Journal, 279, 93

Warren S. J., Hewett P. C., Osmer P. S., 1991, in Proceedings of the Workshop, Victoria, Canada, June 3-5, 1991 (A93-28776 10-90) Vol. 21, The quasar luminosity function z in the range of 2.2 - 4.5. ASPC, pp 139–148

Warwick R. S., Koyama K., Inoue H., Takano S., Awaki H., Hoshi R., 1989, Publications of the Astronomical Society of Japan, 41, 739

Welsh W. F., Horne K., 1991, The Astrophysical Journal, 379, 586

Wills B. J., Brandt W. N., Laor A., 1999, The Astrophysical Journal, 520, L91

Wills B. J., Netzer H., Brotherton M. S., Han M., Wills D., Baldwin J. A., Ferland G. J., Browne I. W. A., 1993, The Astrophysical Journal, 410, 534

Wills B. J., Netzer H., Wills D., 1985, The Astrophysical Journal, 288, 94

Witzel A., Schalinski C. J., Johnston K. J., Biermann P. L., Krichbaum T. P., Hummel C. A., Eckart A., 1988, Astronomy and Astrophysics, 206, 245

Wold M., Brotherton M. S., Shang Z., 2007, Monthly Notices of the Royal Astronomical Society, 375, 989

Xu Y., Cao X., Wu Q., 2009, The Astrophysical Journal, 694, L107

Young D. S. D., 1993, The Astrophysical Journal, 405, L13

Yuan M. J., Tran H., Wills B., Wills D., 2001, in Blazar Demographics and Physics, ASP Conference Series, Vol. 227. Edited by Paolo Padovani and C. Megan Urry. Vol. 227, The physics of blazar optical emission regions. i. alignment of optical polarization and the VLBI jet. ASPC Conference Series, p. 150

Zhang S. N., Cui W., Chen W., 1997, The Astrophysical Journal, 482, L155

Zirbel E. L., 1997, The Astrophysical Journal, 476, 489

Zirbel E. L., Baum S. A., 1995, The Astrophysical Journal, 448, 521

My contributions to the publications

Intranight polarization variability in radio-loud and radio-quiet AGN
Data Reduction and Analysis. Main writer of publication.

Variability and stability in blazar jets on time scales of years
Optical polarization monitoring of OJ287 in 2005-2009
Data Reduction and Analysis. Main writer of publication.

A new extensive catalog of optically variable AGN in the GOODS Fields
and a new statistical approach to variability selection
Data Reduction and Analysis. Main writer of publication.

A change in the optical polarization associated with a γ-ray flare in the blazar 3C279
Contribution to Data Reduction.