Quasar Host Galaxies at Intermediate and High Redshifts

BY

EVA ÖRNDÅHL
Dissertation at Uppsala University to be publicly examined in Häggsalen, Ångström laboratorium, Friday, May 30, 2003 at 10:15 for the Degree of Doctor of Philosophy. The examination will be conducted in English.

Abstract


Quasars form one of the most energetic phenomena in the universe, and can be traced out to very large redshifts. By studying the galaxies which host the active nuclei, important insights can be gained into the processes that trigger and maintain the quasar powerhouse. The evolution rate of the quasar population is furthermore similar to that of ordinary galaxies, which implies a connection between black hole accretion and star formation in the host galaxies. While the properties of quasar host galaxies at low redshift have become better constrained in recent years, less is known about hosts at earlier cosmic epochs. In addition, though radio-quiet quasars are by far more common than their radio-loud counterparts their host galaxies have not been studied to the same extent, in particular not at higher redshifts.

An imaging campaign of a large sample of quasars at intermediate redshift ($0.4 \leq z \leq 0.8$) was carried out at optical wavelengths using the Nordic Optical Telescope, and is studied in this thesis together with two smaller samples. The joint material forms more than half of the total number of observed sources in this redshift interval and increases the number of resolved radio-quiet hosts at $z > 0.4$ considerably. The morphology and mean magnitudes are found to be similar for radio-loud and radio-quiet host galaxies. Both types of host are shown to have optical colours as blue as those of present-day late-type spirals and starburst galaxies, which is likely the result of ongoing star formation.

With increasing redshift, observations of host galaxies become more difficult. High spatial resolution can be achieved with adaptive optics, but the variation of the point spread function in the near-infrared wavelength band which is most suited for detection is large and rapid. A statistical approach to the problem of characterizing the point spread function has been developed, making use of simulated objects which are matched to the different atmospheric conditions. Bright, compact host galaxies showing signs of merging and interaction were detected in this way for three quasars at $z \sim 2.2$, which were observed with the ESO 3.6 m telescope. The method is not restricted to host galaxy analysis but can be utilized in other applications as well, provided that the underlying extended source can be described by an analytical model.

Keywords: Active galaxies, quasars, host galaxies, imaging, photometry, magnitudes, colours, morphology, statistical methods, high-redshift, infrared.

Eva Örndahl, Uppsala Astronomical Observatory, Department of Astronomy and Space Physics. Uppsala University.
Regementsvägen 1, Box 515, SE-751 20 Uppsala, Sweden

© Eva Örndahl 2003

ISBN 91-554-5642-1
ISSN 1104-232X
List of papers

This thesis is based on the following papers, which are referred to in the text by their Roman numerals:

I. E. Örndahl, J. Rönnback and E. van Groningen:
   ‘An optical imaging study of $0.4 \leq z \leq 0.8$ quasar host galaxies:
   I. Observations and reduction’,

II. E. Örndahl and J. Rönnback:
   ‘An optical imaging study of $0.4 \leq z \leq 0.8$ quasar host galaxies:
   II. Analysis and interpretation’,
   *Astronomy & Astrophysics*, to be submitted (2003).

III. B. Kuhlbrodt, E. Örndahl, L. Wisotzki and K. Jahnke:
    ‘High-redshift quasar host galaxy analysis with adaptive optics.
    A statistical approach’
   *Astronomy & Astrophysics*, to be submitted (2003).
# Contents

1 Introduction ................................. 1

2 Aspects of AGN ................................. 4
   2.1 The engine .................................. 4
   2.2 The Zoo .................................. 6

3 Radio properties of quasars ......................... 9
   3.1 Radio-loud quasars ......................... 10
   3.2 The radio dichotomy ....................... 11

4 Unification .................................. 13

5 The host galaxies of quasars ..................... 16
   5.1 Point spread function subtraction .............. 17
   5.2 Host galaxies at low redshift ................. 19
      5.2.1 Morphology and luminosities ............... 19
      5.2.2 Colours and spectroscopy ................. 20
      5.2.3 The host-nucleus luminosity limit and black hole mass ... 22
   5.3 Host galaxies at higher redshifts ............. 24
   5.4 Adaptive optics imaging ..................... 26

6 Summary of papers ........................... 29
   6.1 Paper I and II ............................ 29
   6.2 Paper III ................................. 32

7 Future work .................................. 36

8 Publications not included in the thesis ........... 38

Acknowledgements ................................ 39

Appendix: Quasar host images and profiles .......... 42
Chapter 1

Introduction

Sometimes, appearances can be deceiving. Consider for instance the case of the “radio stars”. Already in the early days of radio astronomy it was realized that some strong radio emitters have very small angular sizes, leading to the view that these objects were a class of stars in our own Galaxy. As the accuracy and sensitivity of radio astronomy observations developed, optical identification of the “radio stars” became easier. Their counterparts on photographic plates were star-like objects with an excess of ultraviolet emission compared to normal stars. Spectra showed broad emission lines at unfamiliar wavelengths and prompted the new label “quasi-stellar radio source” or quasar. In 1963 Schmidt noticed that four emission lines in the spectrum of 3C 273 had decreasing strength and spacing reminiscent of the Balmer series of hydrogen lines, but with their wavelengths increased by about 16%. The source emitting the lines was thus not a star situated in our Galaxy at all, but a vastly more luminous object at cosmological distance.

Quasars are among the most energetic objects known (only the transient gamma-ray bursts and supernovae are in the same league) with luminosities on the order of $10^{38} - 10^{42}$ W. In comparison, the luminosity of the Sun is $4 \times 10^{26}$ W while that of the Milky Way is $10^{37}$ W. Their high variability has made it possible to constrain the size of the emitting region, since an object cannot vary in brightness faster than light can travel across that object. Despite the large energy output this size is quite small, typically only $\sim 1$ pc. It is clear that an extraordinary power source is needed to drive the quasar, implying physical extremes not found elsewhere in the nearby universe. The current paradigm for this central engine is a hot accretion disk surrounding a supermassive black hole, where gravitational energy is released when gas falls towards the black hole with an efficiency far larger than that of thermonuclear processes in stars. The source of the material fed to the black hole is the faint fuzz of light which can be detected around quasars: the host galaxy.

Thus, quasars are the ultraluminous nuclei of remote galaxies. Less luminous nuclei had been found at the centers of more nearby galaxies two decades earlier but their physical similarity to quasars was not immediately understood.
However, by and large many different subclasses of the phenomenon known as active galactic nuclei (AGN) have been identified. The largest such class apart from the quasars are the Seyfert galaxies which have luminosities ranging between $10^{36} - 10^{38}$ W, but radio galaxies also form an important subset. Many other types of AGN exist, some of which are subdivisions generated by the need to further differentiate observed quantities such as emission line strengths, while other categories have come about as a result of observations at different wavelengths. The taxonomy of this veritable zoo of AGN beasts has grown rather complex over the years. Still, with the gathering of more knowledge it has been realized that some objects with different classifications actually are the same physical object, only altered by some relatively uninteresting parameter such as the orientation to our line of sight. As these effects are understood and the real physics of AGN uncovered, some of the AGN subclasses can be unified.

In the 40 years which have passed since the discovery of the extragalactic nature of quasars, the interest and effort invested in them have only increased. The study of AGN utilizes all wavelength bands and centers on some of the most exciting concepts of modern astrophysics such as black holes, extreme gravity and ultrarelativistic particles, while their enormous distances make them useful in many cosmological aspects. The sources detected at the highest redshifts ($z \sim 5$) probe the universe when it was only $\sim 10\%$ of its current age, giving important insights into the formation of discrete structure from the primordial gas and the appearance of metals. The quasars can also be used as background sources against which we can detect intervening matter along the line of sight, and determine its otherwise unobservable properties.

The quasar population evolves spectacularly with cosmic time and shows a strong peak at redshift $\sim 2 - 3$, which coincides with the main epoch of galaxy formation. Studies of host galaxies can therefore provide us with clues to the links between the growth of supermassive black holes and the formation of galaxies. Observations at different redshifts reflect the changing environmental conditions and can constrain models of quasar evolution, as well as shed light on the connections between the evolution of galaxies and the processes which give rise to and sustain the quasar activity. Since the large-scale surroundings of AGN classes differing only by their relative orientation should be the same, host galaxy studies can also be used to test unification schemes.

The brilliant light from the quasar poses a great challenge for observers of the host galaxy it is situated in. Since this light swamps out the weak emission from the galaxy more or less completely, it must be subtracted before conclusions can be drawn about the host properties. Studies of quasar hosts have predominantly focused on objects at low redshifts ($\leq 0.3$) for which morphological structure and even spectra of the host galaxy stellar populations have recently been obtained. The advent of new powerful telescopes have in the past
few years made host observations at much higher redshifts (∼ 2 and above) possible, again placing us in the position where the mere detection of the hosts requires considerable effort.

The work presented in this thesis explores the properties of quasar host galaxies in the somewhat neglected intermediate redshift range, and also investigates three high redshift hosts by a new method based on the technique of adaptive optics. These subjects are discussed in detail in Chapter 6, but are preceded by a short review of a more general nature where some aspects of the knowledge on AGN, quasars and their host galaxies are presented. For a more thorough introduction to the wonderful world of active galactic nuclei the reader is referred to the excellent books by Peterson (1997) and Kembhavi & Narlikar (1999).
Chapter 2

Aspects of AGN

2.1 The engine

A fundamental question concerning AGN is how the energy that is detected as radiation is generated. The amount of light corresponds to $\sim 10^{12}$ stars and is produced in a volume less than a cubic parsec ($\sim 3 \times 10^{49}$ m$^3$). Early ideas of a supermassive star ($\sim 10^8$ M$_\odot$) functioning as a source of gravitational and thermonuclear energy (Hoyle & Fowler 1963) found a modified expression in the accretion disk paradigm first formulated by Salpeter (1964), Zeldovich (1964) and Lynden-Bell (1969). As matter accretes onto a black hole, its gravitational energy is transformed into radiation due to viscous dissipation in the rotating accretion disk surrounding the hole. Though only circumstantial evidence exists supporting the supermassive black hole model, this is today the commonly accepted explanation.

Consider first material falling in towards a compact object. The gravitational attraction is balanced by the centrifugal force at the point where the angular momentum of the matter is equal to the value required for a stable orbit, and a ring forms around the object. Since the inner parts of the ring have a higher angular velocity than the outer parts, viscosity causes gravitational energy to be dissipated into heat and then radiated away. The gases in the ring spiral inward towards the object to compensate for the energy loss with a decrease in gravitational binding energy. The decrease of angular momentum of the sinking matter is compensated by expansion of the outer parts. Since the loss of energy is much faster than the loss of angular momentum the gas is always in its lowest permitted energy state and the orbits can be assumed to be circular, with the net result that an accretion disk is formed. The compression and heating of the inward-moving material in the disk thus produces the glare of the active nucleus.\(^1\)

However, for a supermassive black hole at the center of a galaxy, the accretion disk scenario may seem conceptually simple but is physically highly

\(^1\)This is the answer to the frequent party question “But if quasars are black holes, how come we can see them?”
complicated. Several important aspects such as the nature of the viscosity and the role of thermal instabilities are poorly understood. A spinning black hole can lead to the formation of a thin disk for which a reasonably well worked out theory exists (see e.g. the review by Blandford 1990), but thick accretion disks are also a viable alternative, especially for the formation of jets (Rees et al. 1982). When the pressure support of a thick disk is provided by hot ions, the magnetic field lines anchored in the disk and twisted by its rotation can collimate the outflow of relativistic charged particles into two beams at right angles to the disk, called jets.

Assuming that the quasar luminosity $L$ is the result of accretion of matter onto a black hole, this luminosity can be expressed as

$$L = \eta \dot{M} c^2$$

where $\eta$ is the efficiency of the conversion process of mass to energy and $\dot{M}$ is the accretion rate. The efficiency is typically $\eta \sim 0.1$, to be compared with that of nuclear fusion for which $\eta \sim 0.007$. There is however a natural limit to the luminosity which can be radiated by accretion onto a compact object, which is called the Eddington limit. Above this luminosity the outward force of radiation pressure (the pressure produced by photons streaming outward from the infalling material) is larger than the inward force of gravity, so that the surrounding gas is pushed outwards, rather than falling inwards, and accretion stops. This causes the luminosity to decrease and the radiation pressure with it, and accretion can start up again. The Eddington luminosity is described by

$$L_{\text{Edd}} = \frac{4\pi G c M m_p}{\sigma_T}$$

where $G$ is the gravitational constant, $m_p$ is the proton mass, $\sigma_T$ is the Thomson cross-section and $M$ is the mass of the black hole. Given the brightness of the quasars the Eddington luminosity must be very large and thus also the black hole mass. For a typical quasar luminosity of $10^{39}$ W the black hole mass required is $\geq 10^8 M_\odot$.

Though the black hole cannot be observed directly, the bulk motions of stars and gas in the nuclei of galaxies can be used to infer its presence dynamically. The high resolution necessary makes this task difficult but such observations have been performed both with the Hubble Space Telescope (HST) and from the ground (see the review by Kormendy & Richstone 1995). Rapid rotation and large velocity dispersions have been detected at the centers of a handful of galaxies, indicative of massive dark objects ($M > 10^7 M_\odot$). The strongest case of all detections is our own Galaxy, based on observations of the velocities of stars in a cluster within 0.02 pc of the radio source Sagittarius A*, which is thought to be the Galactic nucleus (Eckart & Genzel 1997). The mass of
this object is $2.6 \times 10^6 \, M_\odot$ (Ghez et al. 2000). Explanations other than a supermassive black hole are ruled out due to the small radius: brown dwarfs would merge and become luminous and clusters of white dwarfs, neutron stars or stellar-mass black holes would evaporate too quickly (Maoz 1995; Genzel et al. 1997). Other strong cases for a central black hole include the Andromeda galaxy and NGC 4258 (Dressler & Richstone 1988; Statler et al. 1999; Miyoshi et al. 1995).

The one alternative explanation of the AGN phenomenon which has not been definitively discredited is the nuclear starburst scenario of Terlevich et al. (1992). The energy is in this model supplied by young stars and supernovae remnants in starbursts in the nuclear region of the host galaxy. However, it is difficult to explain radio-loudness and rapid X-ray variability in this scenario (Green et al. 1993; Kukula et al. 1998; Blundell & Beasley 1998), and in addition the central star cluster must be very compact since imaging studies with HST have not been able to resolve any AGN. The nearest known AGN is the Seyfert 1 galaxy NGC 4395 at a distance of 2.6 Mpc, for which the size of the nucleus is less than 0.7 pc (Filippenko et al. 1993). NGC 4395 also does not display any stellar absorption line signatures whatsoever, in disfavour of the Terlevich et al. model.

2.2 The Zoo

As mentioned in Chapter 1, a large variety of different types of AGN exist. Identification by two properties – the brightness in radio and the width of the optical emission lines – however goes a long way towards describing many of the subclasses. Table 2.1 (adapted from Padovani 1999) summarizes this simplified classification, and an overview of some of the AGN types is given below.

The first type of AGN to be discovered was the Seyfert galaxy (Seyfert 1943), which appears to be a normal spiral galaxy but with a star superimposed on the center. A spectrum of the nucleus shows strong emission lines of high excitation and contain both permitted and forbidden lines (forbidden in the sense that they are collisionally suppressed in denser environments). The emission lines are produced by the ions of elements such as hydrogen, helium and various metals (among other carbon, nitrogen and oxygen). The width of the lines is caused by Doppler broadening, as the gas clouds which produce the lines move at high velocities in a more or less ordered fashion around the central object. Narrow lines are formed in low-density gas (with an electron density of $\sim 10^3 \sim 10^6 \, \text{cm}^{-3}$) with velocities of some hundred km s$^{-1}$, which is somewhat broader than the lines in normal galaxies. The broad lines are always permitted, which indicates a high density of the gas clouds where these
Table 2.1: AGN taxonomy – A simplified scheme

<table>
<thead>
<tr>
<th>Radio loudness</th>
<th>Optical emission line properties</th>
</tr>
</thead>
<tbody>
<tr>
<td></td>
<td>Type 1 (Broad line)</td>
</tr>
<tr>
<td>Radio-quiet:</td>
<td></td>
</tr>
<tr>
<td>Seyfert 1</td>
<td></td>
</tr>
<tr>
<td>RQQ</td>
<td></td>
</tr>
<tr>
<td>Radio-loud:</td>
<td></td>
</tr>
<tr>
<td>BLRG</td>
<td></td>
</tr>
<tr>
<td>SS RLQ and FS RLQ</td>
<td></td>
</tr>
</tbody>
</table>

lines form \((10^9 \text{ cm}^{-3} \text{ or higher})\). The division between broad and narrow lines is set to 1000 km s\(^{-1}\).

Type 2 Seyfert galaxies only have narrow lines, but Seyfert 1 galaxies in addition also have broad lines. Type 1 makes up \(\sim 70\%\) of the total number of Seyfert galaxies, but subclasses (1.5, 1.8, 1.9) are identified according to the strength of the broad components (Osterbrock 1981). It is not uncommon that a galaxy has a nucleus reminiscent of a type 2 Seyfert, but with lower ionization levels of the constituent lines. These are called LINERs (low ionization nuclear emission-line regions) and can be found in \(\sim 50\%\) of all spiral galaxies (Ho 1996). The relation between LINERs and AGN is however not clear: this type of spectra can also be produced in starburst-driven winds and gas heated by shocks (Heckman 1986; Filippenko & Halpern 1984).

The poor resolution of the first generations of radio telescopes at first only allowed the optical identification of radio sources with large angular extent, leading to the discovery of the subclass of AGN called radio galaxies. The most striking features of these galaxies are the large lobes of radio brightness which are roughly symmetrically placed on opposite sides of the nucleus. The two lobes generally extend over a distance of several hundred kpc and do not differ in luminosity by more than a factor \(\sim 2\). The central source is often connected to one or both of the lobes via a radio jet, which can be interpreted as the pipeline which transports energy from the AGN to the extended regions. Quasars and the brighter radio galaxies only have one-sided jets, though a few exceptions exist (Bridle et al. 1994). In quasars the core is relatively brighter than those found in radio galaxies and the lobes are not as well separated. Lu-
minous radio sources frequently also show hotspots, which are intensity maxima located towards the outer edges of their lobes. A hotspot can be regarded as the place where the jet hits the ambient medium in the lobe. The orderly kinetic energy of the bulk flow which was channelled along the jet is converted into random motion in the hotspot and diffused out into the lobe (Blandford & Rees 1974; Hargrave & Ryle 1974).

There exists a correlation between the radio luminosity of radio galaxies and the radio morphology, first noted by Fanaroff & Riley (1974). Galaxies of the FR I class are weaker sources which are at their brightest in the center and have smooth jets, while the FR II galaxies are more luminous and have bright hotspots and a knotty jet-structure. When observed at visible wavelengths most radio galaxies seem to be quite normal elliptical galaxies. On the basis of their optical spectra they are divided into narrow-line radio galaxies (NLRG) and broad-line radio galaxies (BLRG), which can be thought of as the radio-loud counterparts of the Seyfert 2 and Seyfert 1 type galaxies.

The spectra of quasars contain broad emission lines, thus placing them as Type 1 objects in Table 2.1. Despite the fact that quasars originally were detected due to their radio luminosity, only $\sim 5 - 10\%$ of the population are radio-loud sources. Originally, the term “quasar” or “QSR” referred to the radio-loud objects and the acronym “QSO” (quasi-stellar object) to the radio-quiet sources. These days, most researchers use the term “quasar” interchangeably for both types of sources and instead specify the radio-class, often abbreviated to “RLQ” and “RQQ”. This custom is followed throughout the thesis. The properties of quasars (in particular at radio wavelengths) are further discussed in the next Chapter.

Occasionally, so-called Type 0 objects are appended to Table 2.1, also called blazars. The continuum of AGN in general is variable at all wavelengths, but the blazars can vary by more than 0.1 magnitudes in the visible over a time period as short as a day. The polarization of the blazar light is also high and variable in both position angle and magnitude. The first blazar detected was thought to be a variable star in the constellation of the Lizard, and was subsequently given the stellar type name BL Lac. As further such objects were detected BL Lac came to be used as a label for this subclass of AGN, which are radio sources that display a smooth and featureless continuum without any strong emission or absorption lines (Strittmatter et al. 1972).

Another type of AGN, the optically violently variable quasars (OVV), make up the other subclass of blazars (Penston & Cannon 1970). These objects share many properties with the BL Lac but also show the broad emission lines typical of quasars. The distinction between the two categories is made less clear by the strong variability, since the emission lines may be easily detectable when the underlying continuum is faint but are much less visible when the continuum brightens.
Chapter 3

Radio properties of quasars

The very high luminosity of the quasars make them among the intrinsically brightest objects in the sky, not only in the optical but at every wavelength at which they have been observed, from radio to gamma-rays. Thus, one of the defining characteristics of quasars is the very broad distribution of their energy over the spectrum. In general, the quasar continuum can be described over extended frequency ranges by a power law of the form

$$F_\nu = C\nu^{-\alpha}$$

where $\nu$ is the frequency, $F_\nu$ is the flux density, $C$ is a constant and $\alpha$ is the power law index, which usually falls between zero and unity. The power law form, the compact sizes of the emitting regions and the polarization of the light found at some wavelengths led to the conclusion that the quasar continuum must have its origin in non-thermal processes rather than blackbody emission (Oke & Sargent 1968; Oke et al. 1970). A closer look at the spectral energy distribution of the quasars however reveals various features such as bumps and broad depressions, suggestive of a multi-component continuum with the emission at different frequencies dominated by different physical processes. One of the most important such features is the “big blue bump” or UV excess, which extends roughly between $\sim 10$ nm and $\sim 300$ nm and forms the part of the spectrum where a significant or even dominating fraction of the total quasar energy is emitted (Richstone & Schmidt 1980). It is generally agreed to be of thermal origin, and is produced either in an accretion disk (Shields 1978; Malkan & Sargent 1982) or as thermal bremsstrahlung emission (i.e. the radiation produced by the de-acceleration of a free electron in the field of another charged particle, Barvainis 1993).

While interesting, a detailed presentation of the properties of quasar spectra falls outside the scope of this summary. One fundamental aspect must, however, be further examined: the emission in radio which is several orders of magnitude larger in the small subset of radio-loud quasars than for the bulk of the population.
3.1 Radio-loud quasars

The radio luminosity of the radio-loud quasars typically amounts to $\sim 10^{34} - 10^{39}$ W. In comparison, ordinary galaxies have a radio emission on the order of $10^{30}$ W, as a result of for instance supernovae and energetic particles in the interstellar medium. The process responsible for the radio emission in radio-loud quasars is synchrotron radiation, where relativistic electrons with a power law distribution of energy (achieved by for instance acceleration through shocks, see e.g. Blandford 1990) are accelerated by a magnetic field and emit partially linearly polarized radiation.

For extended regions, the radio spectral index of the synchrotron radiation is relatively steep ($\alpha$ typically $\geq 0.7$), indicating optically thin conditions. More compact sources have flatter spectra, thought to be the result of a superposition of a number of self-absorbed components (for an illustration, see Marscher 1988). The self-absorption occurs at frequencies low enough that the relativistic electrons spiralling in magnetic fields can absorb photons and thus start depleting the synchrotron photons produced. The medium is then optically thick and the power law turns over to yield a spectrum of the form $F_\nu \propto \nu^{5/2}$. Such a slope has so far never been observed, but when different parts of the source become optically thick at different frequencies (either due to source inhomogeneity or the presence of unresolved discrete sources within the compact core), the result is a flat slope. The classification of radio-loud sources is made on the basis of the value of the spectral slope at a few GHz, where the dividing line between steep and flat spectra is usually taken to be $\alpha = 0.5$. Flat spectrum (FS) sources are core-dominated, while steep spectrum (SS) sources are objects where the extended emission (generally associated with the radio lobes) plays the larger role (see Table 2.1).

The flat spectrum and rapid variability of compact sources suggest that they have structure on small scales, which also has been observed using VLBI (very long baseline interferometry) which can reach an angular resolution of milliarcseconds. Parsec-scale jets extend as a series of knots from the core more or less in the direction of the large-scale jet, and when observed repeatedly some knots may show proper motion in the sense that they move away from the core part. The apparent speed with which the knots move away is often larger than the speed of light and the phenomenon is therefore called superluminal motion (see e.g. Cohen et al. 1977). Several different mechanisms can be invoked to explain how the velocity can appear to exceed the light speed (see the review by Blandford et al. 1977), of which the most favoured one is relativistic motion of the blobs in the parsec-scale jet close to our line of sight.

A source consisting of radiating particles which move at relativistic speeds is beamed in the forward direction. The output emission is pressed into a cone with narrow opening angle and is Doppler boosted by a factor depending
on the angle between the observer’s line of sight and the direction of the jet. When this angle is small, the observed flux can exceed the flux which would have been observed if the source was stationary by large amounts. The reverse applies to a receding source, so that intrinsically symmetric features like a two-sided radio jet can appear to be one-sided. Beaming is important in the context of unification, which will be discussed in Chapter 4.

3.2 The radio dichotomy

Radio-quiet quasars are not completely radio silent, only less radio-bright than the radio-loud quasars by $2 - 3$ orders of magnitude. They are however highly luminous in all other wavelength bands. For the large majority of quasars radio emission from the active central region which produces energetic particles must therefore in some manner be inhibited. Studies of radio-quiet quasars in radio show them to be typically unresolved with only a compact core associated with the position of the optical nucleus (Kellermann et al. 1994; Kukula et al. 1998), but linear jet-like structures have been detected in some cases (Miller et al. 1993; Blundell & Beasley 1998). The nuclear emission constitutes a significant and often dominant part of the total radio luminosity of the radio-quiet quasars (Kukula et al. 1998), which in many cases also is substantially larger than that of ordinary galaxies (Wrobel 1991). This indicates that the central engines in the radio-quiet objects resemble the ones in radio-loud quasars, but with radio jets which have bulk kinetic powers $\sim 10^3$ times lower than those of radio-loud quasars with similar luminosity ratios in other wavebands. The circumstances which allow the production and collimation of radio jets only in a small fraction of the quasar population are to date not clear.

The distribution of the parameter $R$ which measures the ratio of optical to radio flux is bimodal, with the radio-loud sources clustered around $R \sim 1000$ and the radio-quiet objects around $R \sim 1$ (Strittmatter et al. 1980; Kellermann et al. 1989). A ratio of $R = 10$ is conventionally taken as the boundary between the radio-quiet and the radio-loud quasars. Another common way of defining the boundary is to regard sources with radio luminosities at 5 GHz in excess of $2.5 \times 10^{24} h_{100}^{-2}$ W Hz$^{-1}$ as radio-loud (Kellermann et al. 1989), where $h_{100}$ is the Hubble constant normalized to 100 km s$^{-1}$ Mpc$^{-1}$.

Objects with radio luminosities falling between the two groups of quasars (so called radio-intermediate quasars) have been detected and may be explained as intrinsically radio-quiet objects where the radio emission has been beamed (Miller et al. 1993; Falcke et al. 1996), or as radio-loud objects of very low luminosity (Kukula et al. 1998). It is also possible that the radio-loud/radio-quiet dichotomy could arise as a result of too small radio-selected samples of quasars acquired by instruments not sensitive enough to probe the division line (Hooper et al. 1995). White et al. (2000) investigated the distribution
of the $R$ parameter for the quasars discovered in the FIRST survey (Becker et al. 1995) and found no bimodality, but this could be a spurious result. As pointed out by Ivezić et al. (2002), White et al. failed to account for selection effects, making their sample biased by objects near the flux limit. The analysis by Ivezić et al. using FIRST and the large and unbiased SDSS catalogue of optical identifications (York et al. 2000) instead again suggests bimodality.
Chapter 4

Unification

As has been hinted at in earlier Chapters, it is possible that the appearance of a given type of AGN is dependent on the viewing angle towards the observer, perhaps even so strongly as to wholly determine the classification of the source. Different types of objects occasionally share many properties, suggesting unified models as a means to separate apparent properties from intrinsic ones and to simplify the process of understanding the underlying physics of the objects.

The main idea centers on the observational evidence for anisotropic emission in the innermost parts of the AGN (see the reviews of Antonucci 1993 and Urry & Padovani 1995, and references therein). An aid for visualization is presented in Fig. 4.1. The central engine is surrounded by a luminous accretion disk (as discussed in Sect. 2.1). The fast-moving gas clouds (dark spots) producing the broad emission lines orbit above the disk in the so-called broad line region (BLR). The lines are almost certainly produced by photoionization by the continuum radiation from the central source, since the fluxes of the emission lines vary in response to changes in the continuum flux. The narrow emission lines form in the narrow line region (NLR) which is situated much further from the central source (these clouds are indicated by grey spots). At these distances, the bulk motions of the clouds are not wholly determined by the central source, leading to the possibility of using their dynamics as a probe of AGN fuelling mechanisms. The NLR clouds are also of lower density, allowing the formation of forbidden lines (see Sect. 2.2).

The NLR is even in the closest AGN the smallest linear scale on which details can be resolved, and reveals in general an axisymmetric rather than a spherically symmetric morphology. Absorbing material which surrounds the central parts (usually pictured to be in the form of a dusty torus) obscures the inner accretion disk and BLR from direct view for observers located at a large enough angle to the torus axis, so that only the narrow lines are seen directly. Some continuum and broad line emission can however be scattered into the line of sight by hot electrons which are found throughout the region (shown as black points in Fig. 4.1). In those AGN which are radio sources, the direction of the relativistic jet is roughly aligned with the symmetry axis,
Figure 4.1: A schematic view of the central engine and its close environment in the unified scheme (not to scale). The black hole is surrounded by a luminous accretion disk and a larger, dusty torus. Broad emission lines are produced in gas clouds marked as dark irregular spots, whereas the narrow emission lines are formed in the gas clouds represented by light grey spots. The small black points mark hot electrons. The relativistic jets of a radio-loud AGN are also shown. This figure originally appeared in the Publications of the Astronomical Society of the Pacific (Urry and Padovani, 1995, PASP, 107, 803). Copyright 1995, Astronomical Society of the Pacific; reproduced with kind permission of Prof. Padovani and the Editors.
but no preferential orientation relative to the rotation axis of the host galaxy is seen.

Thus, depending on the orientation of the obscuring torus relative the observer, different types of objects are seen. In type 1 sources both the BLR and the NLR are seen directly, whereas type 2 objects only show narrow emission lines since the BLR is hidden from view (see Table 2.1). Observations of Seyfert 2 galaxies in polarized light have shown the presence of weak reflected broad lines from a concealed central region, pointing towards a unification of the two types of Seyfert galaxy (Antonucci & Miller 1985; Tran et al. 1992). In a similar manner, the flat spectrum radio-loud quasars are believed to be FR II radio galaxies oriented at small angles ($\leq 15^\circ$) to the line of sight, whereas the parent population of the steep spectrum radio-loud quasars are FR II galaxies beamed at angles between $15^\circ - 45^\circ$ (Barthel 1989; Padovani & Urry 1992). The BL Lac sources have from quantitative estimates of number densities and luminosities been unified with FR I radio galaxies (Schwartz & Ku 1983; Ulrich 1989; Browne 1989). Blazars are believed to have their jets oriented very close to the line of sight, which explains their high variability and rarity.

However, unification models are complicated by the tendency of real objects to sometimes deviate from the simple picture painted here. One of the more significant questions concerns the existence of type 2 quasars. If the unified scheme is correct, we would expect to see quasars without broad emission lines. Where are these objects? It may be that they are so well obscured that they fall out of quasar surveys which are based on UV excess, or surveys using spectroscopy which select for the strong emission lines characteristic of quasars. Applying orientation-independent selection criteria is a route to finding type 2 quasars. In particular, X-ray radiation is less sensitive to absorption and most quasars are bright in X-rays. No large-scale sky survey in X-ray has yet been performed, but from investigations at these wavelengths some few candidate objects have been detected (Almaini et al. 1995; Georgantopoulos et al. 1999), the clearest example of which is the $z = 3.7$ object observed by Norman et al. (2001). Ultraluminous infrared galaxies may also contain buried quasars, which can be found by X-rays or spectroscopic observations of polarized light (Franceschini et al. 2000).

Though unification of radio-loud and radio-quiet quasars has been proposed (Scheuer & Readhead 1979), such schemes have not been successful in matching source properties and statistics. It is therefore possible that radio loudness is a fundamental parameter which is related to the physics of the AGN engine, with the most likely candidate being the spin of the black hole (Wilson & Colbert 1995). As already mentioned the issue is, however, far from being clearly understood.
Chapter 5

The host galaxies of quasars

Ten years after the discovery of the extragalactic nature of the quasars Kristian (1973) suggested that they form the active nuclei of galaxies, in analogy with Seyfert galaxies. Spectroscopic confirmation that the extended nebulosities seen around the quasars indeed were of stellar origin was successfully performed a few years later (Green et al. 1978; Boroson et al. 1982). The introduction of CCD detectors resulted in an upsurge of host galaxy observations. The photographic techniques used earlier gave non-conclusive results since the plates are limited in terms of linearity and dynamic range and are not well suited for the finer points of host galaxy investigation.

Early CCD studies reported varying results, with the hosts of radio-loud quasars found to be brighter than those of radio-quiet quasars by $\sim 0.7$ to $2$ magnitudes (Gehren et al. 1984; Smith et al. 1986) and smaller by a factor of $1.3$ (Hutchings et al. 1989) or $3 - 4$ (Gehren et al. 1984). The morphological division between the radio-quiet Seyfert galaxies and the radio-loud radio galaxies into spiral and elliptical types respectively led to the belief that a similar scheme held for the two different types of quasar host galaxies (which later has been shown to be an oversimplification, see Sect. 5.2.1). Many of these results were however influenced by poorly selected samples where for instance radio-loud and radio-quiet quasars at different redshifts were compared, or a significant portion of Seyferts included (as noted by Véron-Cetty & Woltjer 1990).

The field of host galaxy studies has evolved further during the last decade by the advent of space-based imaging, detectors capable of high sensitivity in the near-infrared and improved point spread function subtraction methods. Initially, results from host galaxy observations with the Hubble Space Telescope (HST) caused some confusion. The study by Bahcall et al. (1995) of low-redshift quasar hosts resulted in several non-detections, so called “naked” quasars, and indicated much lower luminosity hosts than previously found. Subsequent reanalysis of the data set (McLeod & Rieke 1995; Bahcall et al. 1997) and new imaging (McLure et al. 1999) however showed that the original results were caused by difficulties in interpreting the HST images, which
suffered from scattered light and a complicated point spread function.

In this Chapter the general properties of host galaxies at various cosmic epochs are discussed, but are preceded by an introduction to the complex problem of host galaxy retrieval. The Chapter concludes with a short introduction to the technique of adaptive optics imaging.

5.1 Point spread function subtraction

In general, host galaxy observations are made challenging due to the presence of the quasar nucleus. In an image of a quasar, the faint underlying host is dominated by the bright light of the point source which must be subtracted before the host galaxy can be studied (for an illustration of images before and after subtraction, see the Appendix). Since the nucleus of a quasar always is unresolved, it can be characterized by the point spread function (PSF). This function describes how the surface brightness of a point source is recorded by the detector in two dimensions, according to the properties of the instrument and the atmospheric seeing (if any). The PSF varies with time and can also vary over the field of view of the detector, and is not known beforehand. By analyzing other point sources in the field of view (foreground stars), the PSF can be determined.

One-dimensional subtraction methods make use of the luminosity profile of the quasar, which is represented by azimuthally averaging the two-dimensional PSF over all radii (see Fig. 5.1). The simplest form of host galaxy analysis is then to compare the profile of the quasar to that of a field star or a PSF model and evaluate whether the host galaxy is resolved or not. However, in order to remove the nuclear light contribution and extract the host luminosity profile, the PSF must be subtracted. Since the intrinsic brightness of the nucleus itself is unknown, the main problem of this approach is to find the factor with which to scale the PSF. To this end, it is first noted that both nucleus and host must have positive flux in the central point. Scaling the PSF so that the resulting host luminosity profile is zero in the central pixels removes all quasar light to a certainty, but also an unknown amount of host galaxy light. A more realistic representation of a galaxy has a profile which increases monotonically towards the center. Such a profile is still likely to result in an oversubtraction for elliptical galaxies and spirals with a bulge since these have a peaked profile, so that only upper limits for the host magnitudes can be determined in this way.

One-dimensional PSF subtraction has the advantage of being simple and model-independent and has been shown to be fairly robust (Rönnback et al. 1996; McLeod & McLeod 2001), with host magnitudes underestimated by a few tenths of a magnitude as a result of the systematic oversubtraction of the PSF. However, not all spatial information in the image is used. In order to do that two-dimensional analysis methods must be constructed, which take full
Figure 5.1: In the left panel the circular isophotes of an object are shown as they fall on the plane of the detector (where the spacing between the tickmarks on the axes is one arcsecond). The spacing of the isophotes is one magnitude. In the right panel the distribution of surface brightness (in magnitudes) is shown as a function of radius (in arcseconds), where the position of the isophotes in the left panel have been marked by black dots. The radial luminosity profile is created by computing an average value for the surface brightness in the ring between two isophotes.
advantage of the depth and resolution of the image. The most successful of these employ simultaneous fitting of nucleus and host, where the free parameters are the point source luminosity and host galaxy properties such as central brightness, scale length, position angle and axial ratio (Taylor et al. 1996; McLure et al. 1999; Kuhlbrodt et al. 2003b). It is also possible to perform numerical deconvolution of the quasar image, but such methods run the risk of creating artifacts (like ringing) which can complicate the analysis of host galaxy morphology and close companions.

5.2 Host galaxies at low redshift

5.2.1 Morphology and luminosities

Much work on host galaxies has been aimed at determining their luminosities and morphologies. In order to do the latter, the luminosity profiles of the host galaxies are compared to those of normal galaxies. For ordinary galaxies the relationship between surface brightness and radius is well described by two empirical relations. Elliptical galaxies (and the central bulges of spiral galaxies) obey a de Vaucouleurs $r^{1/4}$ law

$$I(r) = I_e \exp \left[ -7.67 \left( \frac{r}{r_e} \right)^{1/4} - 1 \right]$$

where $I$ is the surface brightness and $r_e$ is the scale length (de Vaucouleurs 1948). Spiral galaxies follow an exponential law of the form

$$I(r) = I_d \exp \left[ -\frac{r}{r_d} \right]$$

(Freeman 1970). For elliptical galaxies the scale length equals the radius which encircles half the total flux of the galaxy ($r_{1/2}$), while for disk galaxies the relation is of the form $r_{1/2} = 1.68 \ r_d$.

Host galaxies are luminous objects, generally at the bright end of the normal galaxy luminosity function\(^1\) (Dunlop et al. 1993; Hamilton et al. 2002). While quasars can be found in a diversity of host types, studies made in the near-infrared suggest that the brighter a quasar is the more likely it is to be hosted by a massive elliptical galaxy, whereas lower luminosity quasars in addition sometimes are found in disk galaxies (McLeod & Rieke 1994; Dunlop et al. 2001). However, Percival et al. (2001) have found examples of bright radio-quiet hosts with disk-like structure. Some very few radio-loud quasars have also been shown to reside in spiral type hosts, though these often display tidal...
arm structures which may be responsible for the better fit of the exponential galaxy profile (Rönnback et al. 1996; Hamilton et al. 2002).

The scale lengths of the host galaxies are usually $5 - 15 \text{kpc}$ (McLure et al. 1999; Dunlop et al. 2001) which makes them larger than the normal galaxy population, where scale length sizes above $\sim 3 \text{kpc}$ only are found in giant elliptical galaxies (Capaccioli et al. 1992). The radio-quiet hosts seem to be slightly smaller than their radio-loud counterparts (Dunlop et al. 1993). Furthermore, the relation between the half light radius and the surface brightness follows the same slope as that determined for inactive elliptical galaxies by Kormendy (1977). A simpler way of investigating the host galaxy morphological type is to study the ratio of minor to major axis ($b/a$) which, in agreement with profile fitting, results in values of $b/a \geq 0.8$, just as for the normal elliptical galaxy population (Sandage et al. 1970; Lambas et al. 1992; Boyce et al. 1998; Dunlop et al. 2001).

Comparisons of the mean absolute magnitudes of radio-loud and radio-quiet host galaxies indicate that the radio-quiet hosts are fainter than those of radio-loud quasars, though a large variation in the size of the difference has been reported. In optical studies the difference is seen to be $\sim 0.7 - 1$ magnitudes (Smith et al. 1986; Véron-Cetty & Woltjer 1990; Kirhakos et al. 1999), while no difference was seen in the near-infrared study of Taylor et al. (1996). In the well-defined sample of Dunlop et al. (2001) a difference in the $R$ band of $\sim 0.5$ magnitudes was found, and was also derived for the studies of Hooper et al. (1997) and Hamilton et al. (2002). The luminosities of radio-loud and radio-quiet hosts both range between $1 - 4L^*$ (Boyce et al. 1998; McLeod & Rieke 1994; Jahnke & Wisotzki 2000). Thus, the hosts of both radio-loud and radio-quiet quasars at low redshift seem to be predominantly bright and massive elliptical galaxies.

### 5.2.2 Colours and spectroscopy

Many of the recent investigations of host galaxies at low redshift have been performed in the near-infrared, due to the fact that the galaxy starlight peaks at these wavelengths while most quasars simultaneously have a local minimum in their energy distributions (see e.g. McLeod & Rieke 1994). Since the focus mainly has been on constraining the possible differences between radio-loud and radio-quiet hosts in terms of mean magnitude and typical morphology, few studies of host galaxy colours have been made. Apart from one early study which only used a very simple host galaxy retrieval method (Hutchings 1987), no large undertakings have been made until the investigations by Dunlop et al. (2001) and Jahnke (2002). While Dunlop et al. find $R - K$ host colours which are very similar to those of massive, well-evolved ellipticals, the analysis by Jahnke of 19 objects in seven wavelength bands resulted in colours bluer than
those of normal inactive galaxies both for short and long wavelength baselines.

Spectroscopy performed on host galaxies is a difficult task and even more scarce than colour investigations. By placing the slit in an off-nuclear position, spectra can be obtained which are of high enough signal-to-noise for stellar population analysis to be carried out, but which at the same time are not overly contaminated by the nuclear emission. The major spectroscopical study of Boroson et al. (1985) found evidence for two characteristic groups of host galaxies, one having blue continua and strong gas lines, the other lacking gas emission. This study was followed by few others, which mainly concentrated on the properties of extended gas and tidal features (Hickson & Hutchings 1987; Hutchings & Crampton 1990), until Hughes et al. (2000) and Nolan et al. (2001) performed off-nuclear spectroscopy on parts of the Dunlop et al. (2001) sample, suggesting that the host stellar populations were dominated by evolved stars with ages of $6 - 14$ Gyr.

By using spectroscopy, the connection between ultraluminous infrared galaxies and quasar hosts was recently explored for several “transition objects” (Canalizo & Stockton 2000a,b, 2001). These are sources which while being classified as quasars have far-infrared colours closer to those of ultraluminous infrared galaxies, in accordance with the evolutionary sequence proposed by Sanders et al. (1988). In this scenario the merger of two molecular gas-rich spirals in its first stages is interpreted as an ultraluminous infrared galaxy which after blowing away the surrounding dust cocoon becomes a classical quasar. All of the objects in the “transition” sample of Canalizo & Stockton are undergoing tidal interactions and show signs of strong recent star formation, indicating that there is a connection between interactions and activity for these sources. Since it is common for host galaxies to have close companions and display tidal tails, asymmetries and extended emission, it has long been suspected that interactions and merging form the means by which material can be transported to the center of the host galaxy where it can trigger and fuel the active nucleus (see e.g. Smith et al. 1986; Stockton 1990; Hutchings & Neff 1992; Hutchings & Morris 1995; Boyce et al. 1996; Bahcall et al. 1997). It must however be noted that only circumstantial evidence exists for the importance of interactions and merging in this context.

In the last year, on-nuclear spectral analysis methods have been developed by Jahnke (2002) and Courbin et al. (2002b). While Courbin et al. spatially deconvolve the spectra, Jahnke models the host and nucleus spectra simultaneously in two dimensions, making use of the spatial information in the 2-D longslit together with knowledge of the PSF shape and the host galaxy parameters. The two methods have been applied to a common object, with results in good agreement (Courbin et al. 2002a; Jahnke 2002). For spectra obtained at the ESO Very Large Telescope (VLT) Jahnke finds generally young host ages ($\leq 2$ Gyr), consistent with the results from his broad-band colour investiga-
tion. Taken together with the results from Boroson et al. (1985) and Nolan et al. (2001) this could possibly indicate the existence of two populations of host galaxies, where one is blue and gas rich, and the other larger and redder (Jahnke 2002). The recent result of Scoville et al. (2003), who detect $H_2$ molecular gas masses in a majority of luminous quasar host galaxies at low redshifts ($\leq 0.1$) which suggests that they are more gas rich than normal ellipticals, is consistent with this picture.

5.2.3 The host-nucleus luminosity limit and black hole mass

Even though active quasars are a relatively rare phenomenon in the local universe, many present-day inactive elliptical galaxies seem to contain a massive black hole. A linear correlation was shown to exist between the black hole mass and the bulge luminosity (Kormendy & Richstone 1995; Magorrian et al. 1998; Merritt & Ferrarese 2001), and an even tighter correlation has been found between the velocity dispersions of the bulge stars and the black hole mass (Ferrarese & Merritt 2000). This is suggestive of a close link between the formation of galaxy bulges and of the black holes hosted by them.

Indeed, there seems to exist a minimum host galaxy luminosity which increases with nuclear luminosity, indicating that a more massive host is required to sustain a brighter quasar (e.g. Véron-Cetty & Woltjer 1990; McLeod & Rieke 1995). It is therefore not surprising that the correlation between black hole mass and bulge luminosity has been observed to hold also for quasar hosts (Laor 1998; Ferrarese et al. 2001; McLure & Dunlop 2002; Wandel 2002). This is consistent with Eddington-limited accretion onto supermassive black holes, making the host-nucleus luminosity limit the upper bound to the constant fraction of the Eddington rate at which the quasar radiates. Figure 5.2 (taken from McLeod & McLeod 2001), demonstrates that quasars at low redshifts have Eddington rates of no more than $\leq 20\%$.

In the hierarchical galaxy formation scenarios of Kauffmann & Haehnelt (2000), supermassive black hole growth has been incorporated into the models. At later cosmological epochs, less merging of galaxies take place, which in combination with a decrease of the available gas supply and more slowly accreting holes can explain the decreasing space density of bright quasars from $z = 2$ to $z = 0$. Thus, the models state that the more massive hosts of present-day bright quasars formed relatively recently, but predict that as the redshift increases the luminous quasars will be found in progressively less bright hosts which accrete at higher rates, making the upper limit in Fig. 5.2 change accordingly (see also Sect. 5.3). The life-times of quasars depend on the fuel availability, and are from the models of Kauffmann & Haehnelt determined to be on the order of a few times $10^7$ years. After this time the black hole is starved and the quasar activity then switches off. The seemingly parallel evolu-
**Figure 5.2:** Quasar nuclear absolute $B$ band magnitudes versus host galaxy $H$ band magnitude. The dashed vertical line shows the boundary between quasar and Seyfert galaxies (set to $M_B > -23$, Schmidt & Green 1983), and the dashed horizontal line the position of an $L^*$ galaxy (which has the characteristic luminosity of present-day galaxies). The diagonal lines mark the loci of 10% and 100% of the Eddington luminosity. Figure reproduced from McLeod & McLeod (2001).
tion of luminous quasars to that of the stellar populations in massive spheroidal
galaxies (e.g. Franceschini et al. 1999) taken together with the black hole de-
tections in inactive galaxies suggests the possibility that a significant subset of
the present-day galaxy population are harbouring dead quasars at their centers.

A difference between the black hole masses of radio-loud and radio-quiet
quasars has been traced (Laor 2000; McLure & Dunlop 2001), indicating that
a black hole mass in excess of $10^9 \, M_\odot$ is a necessary (but perhaps not suf-
cient) condition for the production of a powerful radio source. Similarly, a
black hole mass larger than $5 \times 10^8 \, M_\odot$ seems required for sustaining the ac-
tivity of a radio-quiet quasar. Translating the mass thresholds into spheroid
absolute magnitudes results in radio-loud hosts which are brighter than those
of radio-quiet quasars by $\sim 0.7$ magnitudes. The sharp drop at the bright end
of the elliptical galaxy luminosity function then naturally leads to a factor of
ten difference in number density between radio-loud and radio-quiet quasars
(Dunlop et al. 2001). However, the relation between black hole mass and radio
luminosity is not unambiguously determined (Ho 2002; Oshlack et al. 2002).
The latter authors argue that radio-loud quasars with low black hole masses
have not been measured in previous studies due to selection effects that tend
to disfavour the less optically luminous radio-loud sources. The methods used
for estimating the black hole masses are also associated with rather large un-
certainties but are currently undergoing a phase of intense development, which
hopefully will lead to a firmer understanding of these issues.

5.3 Host galaxies at higher redshifts

When turning to higher redshifts, the host galaxies become increasingly diffi-
cult to resolve and also suffer from rapid cosmological surface brightness dim-
ming of the host in contrast to the nucleus. The advances in telescope technol-
yogy during recent years have stimulated a large interest in hosts at $z \geq 1 - 2$,
mainly inspired by the similarity between the strong evolution of the quasar
population with redshift and the rate of galaxy formation (e.g. Heckman et al.
1991; Arexaga et al. 1998b; Lehnert et al. 1999). In contrast, host galaxies
in the intermediate redshift range ($0.4 < z < 1$) have not been as extensively
investigated. The earliest studies were performed in the optical (Romanishin
& Hintzen 1989; Hutchings et al. 1989) but later authors have concentrated on
near-infrared imaging (Carballo et al. 1998; Márquez et al. 1999, 2001; Kotil-
lainen et al. 1998; Kotilainen & Falomo 2000), with the exception of the HST
$R$ band study by Hooper et al. (1997) and the optical multicolour investigation
by Rönneback et al. (1996).

The results from these studies show that the hosts are a few factors brighter
than an $L^*$ galaxy and obey the correlation between host and quasar luminosity.
Morphological determination is more difficult. The de Vaucouleurs luminosity
Figure 5.3: Mean absolute $V$ band magnitude obtained for samples of radio-loud host galaxies (open circles) and radio-quiet host galaxies (filled circles) at three epochs, plotted versus mean sample redshift. The dotted lines show the luminosity evolution of present-day $L^*$, $2L^*$ and $4L^*$ elliptical galaxies, presented for two different cosmologies with parameters as indicated in the panels. Figure reproduced from Kukula et al. (2001).

profile differs most from the disk galaxy profile at small radii and in the tail of the wings, making high-quality data in the outer parts of the host galaxy profile a requirement for successful type determination. Rönnback et al. (1996) replaced the outer parts of the PSF with a model, thus reaching lower levels of host galaxy flux which made profile fitting possible (see also Sect. 6.1). As at lower redshifts, an elliptical host type is the preferred fit. The studies in the intermediate redshift interval have targeted radio-loud quasars almost exclusively, with the exception of Rönnback et al. These authors find a difference between the mean magnitudes of radio-loud and radio-quiet hosts of 0.3 magnitudes, which is smaller than that found at lower redshift. Colour studies at intermediate redshift are rare and seldom comprise more than a few objects, but indicate host galaxies as blue as late-type spirals or irregular galaxies (Véron-Cetty & Woltjer 1990; Kirhakos et al. 1999; Rönnback et al. 1996).

At $z > 1$ results from investigations utilizing ordinary PSF subtraction as well as two-dimensional modelling show objects brighter than low-redshift hosts by $2 - 3$ magnitudes (Heckman et al. 1991; Lehnert et al. 1992, 1999; Aretxaga et al. 1995, 1998b). Kukula et al. (2001) have investigated the evolution of host luminosities by obtaining data for host galaxies at $z \sim 0.2$, $z \sim 1$ and $z \sim 2$ (see Fig. 5.3). For radio-loud hosts they find an increase in luminosity with redshift which is consistent with that expected from simple passive evolution of massive spheroids (see also Falomo et al. 2001). While the radio-loud hosts have become about a factor of three brighter at redshift $z \sim 2$, the
radio-quiet hosts only reach $\sim L^*$ (Hutchings 1995; Kukula et al. 2001; Ridgway et al. 2001) and thus seem little changed in luminosity over the redshift range. However, exceptions can be found, as shown by the detection of a high-redshift radio-quiet host as bright as those of the most luminous radio-loud quasars by Aretxaga et al. (1998a) with adaptive optics. This finding was supported by a similar result from HST data for two radio-quiet quasars by Hutchings et al. (2002). On the other hand, Lowenthal et al. (1995) failed to resolve the radio-quiet hosts in their $z \sim 2.5$ sample. The high-redshift objects detected to date are more compact than their low and intermediate redshift counterparts, having scale lengths of approximately only $3 - 5$ kpc (Falomo et al. 2001; Ridgway et al. 2001; Aretxaga et al. 1998b). Close companions or foreground objects are a relatively common feature, occurring for $\sim 40\%$ of the sample in the investigations of Lehnert et al. (1999), Ridgway et al. (2001) and Hutchings (1995).

Figure 5.3 evokes the possibility of a different evolutionary scheme for radio-loud and radio-quiet quasar host galaxies, where the radio-loud hosts are already fully assembled at $z = 2$ and only evolve passively to present-day. With the majority of the radio-quiet hosts fainter at $z = 2$ than expected from passive evolution, there is the suggestion of mass acquisition taking place even at lower redshifts for these objects so that they are significantly different than their radio-loud counterparts. If the black hole mass threshold is higher for radio-loud objects, it is however possible that the criterion of radio-loudness ensures that hosts with massive black holes and thus high spheroid mass are selected irrespective of cosmic epoch. As suggested by Kukula et al. (2001), radio-quiet hosts may therefore be more representative of the trends in host galaxy evolution. These authors also note that the assumption of passive evolution influences the interpretation of Fig. 5.3. If the hosts are undergoing more active star formation, even the radio-loud hosts may be experiencing mass acquisition at lower redshifts.

5.4 Adaptive optics imaging

For a perfect telescope operating in vacuum, the resolution is directly proportional to the inverse of the telescope diameter. The plane wavefront arriving at the telescope from a distant point source would then result in an image with an angular resolution limited only by the light diffraction. However, telescopes are not perfect, and when observing with Earth-bound instruments the rapid and random turbulence in various layers of the atmosphere also distorts the wavefront.

An adaptive optics (AO) system is capable of adjusting itself to compensate both for imperfections in the telescope system and for the effects of turbulent
air above the telescope. To this end the AO system uses a reference point source (like an unresolved star) close to the observed source. The wavefront from the reference star passes through the same atmospheric patch as that from the object of interest and is used to evaluate the phase deviations from an ideal wavefront at several points across the aperture. The alterations needed to correct these phase departures are calculated and signals sent to the flexible mirror. All these calculations and the physical deformation of the mirror itself have to take place within less than a millisecond, before the wavefront changes yet again.

In general, it is difficult to find reference stars of sufficient brightness close enough to an arbitrary source on the sky. Work is in progress on artificial reference stars (also called laser guide stars), which are patches of light created by the back-scattering of pulsed laser light from particles in high atmospheric layers. These can be created arbitrarily close to the desired target and will overcome the selection limitations imposed by the natural reference stars. By moving to the near-infrared, the situation for the latter is improved, however, since atmospheric turbulence has less of an influence at these wavelengths and thus permits the use of fainter guide stars. Further details on the intricacies of AO systems can be found e.g. at the web pages of the European Southern Observatory.

Adaptive optics has been used with increasing success for imaging of galactic objects like protoplanetary disks and binary star systems. It has more seldom been used in quasar host galaxy studies, even though this is a discipline which benefits from high spatial resolution in combination with the great light-gathering power of ground-based telescopes. One reason for such studies being scarce is certainly that the method’s fundamental advantage of producing diffraction-limited images with large telescopes comes at the price of new challenges in correctly differentiating between the compact nucleus and the extended host galaxy, considering the constantly changing PSF.

Previous investigations of host galaxies with AO have focused on low to intermediate redshifts, where the host galaxies are resolved and the determination of the PSF is not crucial to the detection of the objects (Stockton et al. 1998; Márquez et al. 2001), or has probed higher redshifts (Hutchings et al. 1998, 1999, 2001; Aretxaga et al. 1998a). In general, no outright removal of the nuclear contribution was made, instead concentrating the efforts on investigating substructures in the host galaxies. For studies of low-redshift quasar hosts AO shows an improvement over traditional imaging in the resolution of clumps and companions, but apart from that the results obtained are rather similar to studies made using standard observational techniques. The true power of AO appears in the analysis of high-redshift quasars, where the most important factor for a successful study is a PSF as narrow as possible due to the compact appearance of the objects. The image quality of AO systems potentially en-
ables a much better separation of nucleus and extended host than uncorrected, seeing-limited imaging.

Finally, note that while the technique of adaptive optics was developed as a means to improve astronomical observations, it has also been used to investigate the retina of the human eye (Roorda & Williams 1999). Individual, living cells were imaged and the first pictures of the arrangement of the colour vision receptor cones were recorded using this technique.
Chapter 6

Summary of papers

6.1 Paper I and II

We have conducted an optical imaging study aimed at resolving the host galaxies of radio-loud and radio-quiet quasars with redshifts in the interval $0.4 \leq z \leq 0.8$, in order to extend the knowledge of host galaxies in the intermediate redshift regime. The few studies already performed at intermediate redshift have almost exclusively targeted radio-loud quasars and have furthermore usually only been carried out in a single wavelength band, with the result that neither the differences between the two types of hosts nor the host galaxy colours are well known at these redshifts.

Paper I describes the details of observation and reduction for that part of the sample which was obtained at the Nordic Optical Telescope (NOT). This data set was imaged mainly in the $R$ band but also in the $V$ and $I$ band, and consists of 79 radio-loud and radio-quiet quasars with matched distributions of redshift and apparent $V$ band magnitude. The analysis in Paper II also incorporates 23 quasars, observed at the ESO 3.5 m New Technology Telescope (NTT) and described in Rönnback et al. 1996, into the sample. Taken together, the two parts comprise $\sim 55\%$ of the collected total number of investigated sources at intermediate redshifts, and also increase the number of observed radio-quiet quasars in this range significantly. In addition to the sources observed by us we have also been given access to data for the intermediate redshift quasars observed at NOT by Wold et al. (2000, 2001), for which further eight host galaxy detections were made.

We performed PSF subtraction, using one-dimensional luminosity profiles, on the quasar images and as a test also on a star in each observed field. For the NTT sample a combined PSF constructed from empirical data in the core and model data in the wings was used in order to extend the residual left after PSF subtraction to fainter flux levels, but it was found that this approach was less satisfactory for the NOT data due to higher ellipticity of the PSF. For these objects we preferred to subtract a purely empirical PSF, which simply consists of a suitable field star. The PSF was scaled to result in a residual with a flat-top luminosity profile and positive flux at all radii. Subtracted images and
luminosity profiles are shown for each quasar field and wavelength band in the Appendix.

Host galaxies were detected in a total of 66 sources or 72% of the total sample. Of these, 29 are radio-quiet objects (detection rate 66%) and 37 are radio-loud objects (detection rate 79%). Profile fitting could not be carried out for the NOT sources, limiting the morphological analysis of that part of the sample to axial ratio investigation. For the radio-loud hosts we find a mean axial ratio of \( b/a = 0.84 \pm 0.02 \), while for the radio-quiet hosts the mean value is \( b/a = 0.85 \pm 0.02 \). Thus the axial ratios of the hosts peak at \( b/a \geq 0.8 \), as do those of the normal elliptical galaxy population.

To obtain absolute magnitudes, \( K \)-corrections for elliptical galaxies have been applied to the total sample (excepting those NTT objects for which the profile fitting indicated a disk morphology). The mean absolute magnitude of the radio-quiet hosts is \( M_R = -23.5 \pm 0.2 \), which is indistinguishable from that of the radio-loud hosts. A similar result is found in \( V \) band, but a slightly larger difference can be seen in \( I \) band where the mean of the radio-quiet hosts is \( M_I = -23.4 \pm 0.2 \) and that of the radio-loud hosts \( M_I = -23.8 \pm 0.2 \). This deviates from the results at lower redshifts where a mean difference of \( \sim 0.5 \) magnitudes is found between radio-loud and radio-quiet hosts. The magnitudes of the radio-loud hosts brighten with increasing \( z \) over the redshift range investigated, connecting to low redshift hosts from the literature and extending towards the bright radio-loud sources found in studies at higher redshift. The radio-quiet hosts seem to remain of more similar brightness over the range, with only a weak dependence on redshift.

We find host galaxy colours which are as blue as those of present-day late-type disks and starburst objects, with no difference between the mean \( V - R \) colour of radio-quiet and radio-loud hosts (see Fig. 6.1). To investigate the impact of scattered nuclear light as a contributor to the host colours, we have also measured the colours in annular apertures. The difference between full and annular aperture values is in general \(< 0.1 \) magnitudes, implying a negligible contribution of scattered light. The effect of galaxy evolution over the redshift range only influences the colours by \( \leq 0.2 \) magnitudes and is thus also not a major contributor to the blue host colours. The mean difference in \( V - R \) between the hosts and normal elliptical galaxies at the same redshifts is \( \sim 0.7 \) magnitudes, while the mean difference in \( R - I \) is \( \sim 0.6 \) magnitudes. There is no morphological indication that the hosts are of late Hubble type, and close companions in projection are not uncommon (with a few sources even exhibiting tidal tail-like features and other signs of interaction). Thus, ongoing star formation is a reasonable explanation of the blue host colours.

The composition and selection of the NOT sample was made by Ernst van Groningen, together with whom I performed the observations. The data reduction and photometric calibration was primarily carried out by me, with the
Figure 6.1: Host colours (measured in an annular aperture) as a function of redshift. Filled and empty squares, triangles and diamonds represent radio-loud sources. Crosses, asterisks and stars represent radio-quiet sources. The encircled symbols mark the objects which have an annular aperture magnitude differing from that of the full aperture by $> 0.1$ magnitudes. The lines represent the colours of present-day galaxies of different Hubble types. Figure taken from Paper II, where the full legend can be found.
aid of Ernst and Jari Rönnback. The PSF subtraction and all further work on Paper I (inclusive the writing) was made by me. The calibration and PSF subtraction of the Wold sample hosts was performed by Jari, as well as the profile fitting and magnitude determination of the NTT objects incorporated into the sample from Rönnback et al. (1996). All further work on Paper II (inclusive the writing) has been carried out by me, though I of course have benefited from input from Jari.

6.2 Paper III

Observations of host galaxies at redshifts of $\sim 2$ represent an opportunity to gain insight both into the phenomenon of quasar evolution as well as galaxy formation in the early universe. At these redshifts the near-infrared wavelengths sample the rest-frame optical regime and $K$-corrections are not important for comparisons with low redshift data. By applying the technique of adaptive optics with its high spatial resolution a clearer view of the high redshift hosts can potentially be achieved as compared to seeing-limited imaging.

To this end we selected five high-redshift quasars from the Hamburg/ESO Survey for bright QSOs (HES, Wisotzki et al. 2000) which have nearby bright stars, thus making them suitable for AO observations. The high background emission in the $K$ band required short exposure times, for which reason we expect to find a PSF which varies both with time and position. This introduces large errors in the characterization of the PSF, making existing methods used for disentangling host from quasar nucleus (PSF subtraction, modelling and deconvolution) poorly matched to the type of data acquired by AO.

We have therefore constructed a new tool to evaluate possible host galaxy detections. Instead of concentrating on PSF removal, we investigate and map the fluctuations of the PSF as described by the variation of the two radii encircling 20% and 80% respectively of the total flux. Since an extended object will have more diffuse light at large radii than a point-like source observed under the same conditions while the difference at small radii is less pronounced, comparison of these two parameters enables a differentiation between resolved and point-like objects. A set of quasar observations will hence be statistically wider than a set of stellar observations. We investigate different combinations of host galaxy geometries and luminosity ratios and construct simulated objects which are matched to the different atmospheric conditions prevailing during the observations. In this way we are able to give estimates of host galaxy scale lengths and luminosities.

In Fig. 6.2 comparisons of true and model data are shown for the three observed quasars. To the left the best-estimate model sets are shown while the right panels show the case where the models contain no host galaxy flux contribution. Thus, a single host galaxy model can adequately represent the
distribution of individual object images, while the non-detection case simultaneously is rejected for all objects. Note that the rejection of non-detections is independent of assumptions of the host galaxy and is derived using only the observational data with their given S/N, since this procedure only compares the PSF stars to the quasars.

High S/N images were computed by coadding the better half of the set of quasar and PSF stellar images respectively, scaling the PSF to quasar nuclear flux and subtracting it. Luminosity profiles and coadded images are shown in Fig. 6.3. The detected host galaxies are bright and compact, with a mean absolute magnitude in the R band of $-27.2$ and scale lengths which typically are $4 - 7$ kpc. In the direct images only one object appears undisturbed, while the others show non-concentric isophotes or even a severely disturbed geometry, possibly indicating ongoing merging.

It should be noted that the method designed in this paper is not restricted to host galaxy analysis but can be utilized for the detection of any kind of faint structures onto which a point source is superimposed, as long as the underlying objects can be described by an analytical model.

Paper III is very much a collaborative effort made by Björn Kuhlbrodt and me. I performed the observations together with Lutz Wisotzki, and data reduction was primarily carried out by Knud Jahnke. Björn contributed most of the software and constructed the graphs in the paper. The method development and the paper composition was done by me and Björn, with valuable input from Lutz and Knud.
Figure 6.2: Comparison of true and model data. Quasar images are marked by circles, simulated data with dots. The left panel side shows for the three observed quasars the result for models having a best-estimate host galaxy flux and half-light radii, whereas the panels to the right show models having zero host galaxy flux. Figure taken from Paper III.
Figure 6.3: Coadded images. To the left are the luminosity profiles of the data (points), the scaled coadded PSF (dotted line) and the remaining flux after subtraction of the PSF (solid line). To the right are contour plots of the residual at 1 mag spacing. The lowest isophote is 20 mag arcsec$^{-2}$ and the radii are in arcsec. Figure taken from Paper III.
Chapter 7

Future work

The field of quasar host galaxy studies has grown and developed tremendously during its 30 years of existence. A sign of the increasing importance of the subject is that the European Southern Observatory recently created a new program subcategory expressly devoted to these studies (B9, AGN host galaxies), to handle all the related incoming applications for observing time.

Continued research offers – quite literally – a host of possibilities. At low redshifts the study of quasar host galaxies is now turning from the determination of fundamental parameters such as magnitudes and morphology to the more complex questions of host stellar populations and ages. Broad-band colours obtained from a larger range of filters promise the possibility to evaluate the stellar populations of host galaxies even at higher redshifts. Such studies can help distinguish the processes responsible for the blue host colours found at low and intermediate redshift, and by comparison to the normal galaxy population provide clues to the triggering and fuelling of nuclear activity.

The possible indication of two different kinds of host galaxy population, separable by their broad-band colours (see Sect. 5.2.2), represents an intriguing new piece of the puzzle to peruse. The on-nuclear spectroscopic methods developed by Jahnke (2002) will be of great use for this problem. As a first step, I have together with Knud Jahnke and Björn Kuhlbrodt imaged a low redshift multicoline sample of bright quasars drawn from the Palomar-Green survey (Schmidt & Green 1983) and the HES (Wisotzki et al. 2000). Data for 44 objects were obtained at the Nordic Optical Telescope in the B, V, R and H band, with a subsample taken also in the I and K band, for which we aim to separate young and old stellar populations and set strong constraints on the contribution of possible recent starbursts to the total luminosity.

In order to properly address the connection between lower redshift hosts and those found at intermediate redshifts further observations are needed. With higher S/N in the wings of the quasar images, the proper morphological types of the hosts can be determined. This will permit the application of appropriate K-corrections and also enable estimation of the scale lengths. By using broad-band colours over large wavelength baselines the circumstances giving rise to
the blue host colours can be better defined. It is also of interest to target hosts at redshifts \( \sim 0.7 - 1 \) in order to better constrain host galaxy evolution, where investigations of the neglected radio-quiet population are of particular interest.

The statistical host galaxy detection tool developed in Paper III has proved to be a robust method capable of overcoming the difficulties posed by adaptive optics observations in the near-infrared. Further development, e.g. by allowing the modelling of other host galaxy morphologies, is a planned project. Obtaining spectral information is essential for investigation of the importance of star-forming regions in the objects discussed in Paper III, while also making it possible to determine whether the disturbed appearance of one of the objects is due to foreground sources or if an actual merger is taking place. It will be exciting to apply the method to other high redshift host galaxies and also to other types of sources where the same detection problems apply (e.g. circumstellar disks).

Astronomy as a subject will in the future be booming with the influx of new high-quality data from the recently constructed \( 8 - 10 \) m class telescopes and from interferometry performed with the VLT, from soon-to-be completed large surveys covering many wavelength regions and from new facilities (both space-born and ground-based) exploring less well investigated frequency ranges to greater depth. Many new insights will spring from sources such as the upcoming millimeter facility ALMA, the near-infrared survey of 2MASS and the X-ray investigations of XMM-Newton. The impact of these instruments and surveys will be further increased by the possibility of data mining and cross-correlation of large databases using virtual telescopes. Further technical developments are also to be expected, like reliable laser guide stars for adaptive optics observation and the OWL project of the European Southern Observatory, which is a 100 m diameter optical telescope projected to become fully operational in 2015. The future is looking bright indeed for the upcoming 30 years of quasar host galaxy studies.
Chapter 8

Publications not included in the thesis


Acknowledgements

These words are some of the last written during my work on the thesis (but probably among the first looked at by the reader). It is a pleasure for me to be able to thank the numerous persons who in one way or another have contributed towards the completion of this thesis.

I am grateful to my former supervisor Ernst van Groningen for giving me space to grow and develop independently and not the least for initiating the German collaboration. He is wished best of luck in his new position as administrator at the University of Kalmar. Jari Rönnback is sincerely thanked for taking partial leave from his teacher’s responsibilities to spend some time at the Observatory with me and the intermediate redshift host galaxy project, and for being on-line with advice and support afterwards.

It has truly been a privilege to have such good colleagues and friends as Knud Jahnke, Björn Kuhlbrodt and Lutz Wisotzki. Travelling down to work in the wonderful Freie und Hansestadt Hamburg has been greatly rewarding in many ways! Thanks for the warm welcome you always have given me (Sandra K included), and for the good times we have had meeting up at conferences and on our observing trips. Through our collaboration I have experienced some aspects of science I would otherwise have gone without, such as Serious Cooking™ and adventures on foreign continents. Who can forget “The Hamburg Hundred-Plus Sushi Session” or getting trapped by a tropical rainstorm on top of a Maya pyramid in the Yucatan peninsula...

The galaxy group at the Astronomical Observatory has provided a friendly and relaxed atmosphere, and I thank its present as well as former members for pleasant interactions on both professional and personal levels. Nils Bergvall is thanked for his sincerity, support and in particular for the scientific discussions during the last critical stages of writing, and Erik Zackrisson and Kjell Olofsson for close and careful readings of my papers. Erik is furthermore thanked for sharing some of his secrets and Kjell for being completely crazy in general. Ignaz Wanders and Leif Festin are remembered fondly (Leif also for good company on the hellish 1999 Romanian solar eclipse trip), as is Göran Östlin.
for his artful jokes and generous heart. With Ana Hidalgo-Gámez and Arnaud Pharasyn I shared not only professor Malmquist’s old office but also quite a number of memorable moments (most of which involved lots of laughing).

I have greatly enjoyed the easy camaraderie of my dear friends and fellow musketeers Patrik Thorén and Marcus Gunnarsson throughout my time as a PhD student here at the Observatory. In spite of specializing in subjects covering rather different length and time scales, we have many things in common. Thank you for all the tea breaks, discussions, fun and games we have had together!

So many others at the Observatory – too many to mention you all – have helped in creating the very special environment of this workplace. I wish to thank extragalaxians-turned-stellar Michelle Mizuno-Wiedner and Torgny Karlsson for their kind enthusiasm and thoughtful optimism. Togge is especially thanked for letting me foist off the library duties on his back. The planetary boys Björn Davidsson and Johan Warell are thanked for making ordinary lunches into such high-spirited occasions, and Björn in particular for exchanges on topics from therapsides to Gilgamesh. Christer Sandin is a computer wiz and a hero in my book. Thanks also to Emma Olsson, Ana Garcia-Pérez and Karin Jonsell for interesting group discussions.

I am grateful to The Swedish Institute, The Royal Swedish Academy of Sciences and The Swedish Research Council for financial travel support which has enabled me to participate in conferences and perform observations in various locations over the world.

Thank you all my friends for being there for me, always ready to give me patient support and a healthy dose of escapism. Whether here in Uppsala, in ancient times or on the shores of foreign worlds: thank you Anders Westermark, Jon Thorvaldson, Leif “Laffé” Eriksson, Anna Lundqvist, Henrix Gudmundsson, Fredrik Innings, Jonas Schiött, Patrik Lundquist, the ANOWA crew and all others. Leif Rob Eriksson, Carin Westerlund and Mia Köhler are especially thanked for hammering some manners (albeit superficial) into Alan Daly. Jens Sundström and Martin Frändén are in particular thanked for their warm-hearted jamtlander stubbornness, their brilliant teamwork and for never failing to believe in another missive from the Vicomte de Bouvard.

Thank you Boman for your steadfast encouragement and innumerable kindnesses, and for tenaciously cooking me so many dinners and enlightening my life with all your pooka pranks. Freunde für’s Leben!

I cannot thank my family enough for all the love and support given me. My interest in the natural sciences was sparked by my father and the chemistry
set, but it was my mother who showed me the constellations and the poetry of nature. Thank you for letting me follow my own path. Camilla will always be the best little sister ever. Thank you for the journeys and for ye darke pigchilde Mollan!

The brightest source of joy in my sky is Mattias Huss, sharp-eyed kindred spirit. You found my hand when we were blind in the darkness and then never let go, for which I am eternally amazed and thankful. The multiverse awaits our explorations...

Uppsala, Good Friday 2003

Eva Örndahl
Appendix: Quasar host images and profiles

In this Appendix the full set of luminosity profiles and images of the intermediate redshift host galaxy sample obtained at the NOT (see Paper I) is presented, since the large part of these figures only are available in the electronic version of Paper I. These figures can also be obtained from the author.

The figures are presented in order of right ascension, and for each object field and filter five plots are shown. In the leftmost graph the luminosity profile is plotted (in mag arcsec$^{-2}$) versus radius in arcseconds. The points mark the quasar profile, the full-drawn line is the PSF, and the dotted line the residual after PSF subtraction. In the fourfold greyscale plot the image sizes are always 12$^\prime$5 $\times$ 12$^\prime$5 (except for the case of EX 0240+0044, where it is 20$^\prime\prime$ $\times$ 20$^\prime\prime$), with the objects always centred in the plots. Top left shows the host galaxy residual, top right is the unsubtracted quasar frame and in the bottom right graph we show the residual which is left from the scaling of the PSF to a field star. The bottom left graph is a contour plot of the host galaxy residual, where the number inside the plot denotes the value of the lowest contour in mag arcsec$^{-2}$ and the spacing between contours is 1 mag arcsec$^{-2}$. The contours have been smoothed by a 3 $\times$ 3 box for better clarity of low-intensity features. North is up and east is to the left.

Fields observed in the $R$ band are labelled only with the quasar name, while fields observed in the $V$ or $I$ band are marked also with the filter name. Non-calibrated objects have been indicated by a #-symbol, and plots where I present a quasar residual subtracted to zero in the center in order to highlight the non-detection of a host galaxy have been marked with “zero”.

Bibliography


—. 2000b, AJ, 120, 1750 5.2.2


Courbin, F., Letawe, G., Magain, P., et al. 2002a, The Messenger, 107, 28 5.2.2
—. 2002b, A&A, 394, 863 5.2.2

de Vaucouleurs, G. 1948, Ann. Astrophys., 11, 247 5.2.1


Hutchings, J. B., Crampton, D., Morris, S. L., & Steinbring, E. 1998, PASP, 110, 374  5.4


Lynden-Bell, D. 1969, Nature, 223, 690 2.1


Padovani, P. 1999, in Frontier Objects in Astrophysics and Particle Physics, ed. Giovannelli & Mannocchi, Vol. 65 (SIF), p. 159 2.2
Peterson, B. M. 1997, An Introduction to Active Galactic Nuclei (Cambridge University Press) 1

62
Roorda, A. & Williams, D. R. 1999, Nature, 397, 520 5.4
Schmidt, M. 1963, Nature, 197, 1040 1
Stockton, A. 1990, in Dynamics and Interactions of Galaxies, ed. R. Wielen (Springer), p. 440 5.2.2

63