Nearby radio galaxies
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Introduction

ACTIVE GALACTIC NUCLEI undoubtedly belong to the most exotic phenomena in our Universe. Active Galactic Nuclei, or AGN, are identified with a class of galaxies - so called active galaxies - where a significant fraction of the energy is not emitted by stars, dust and gas (as is the case for normal galaxies), but comes from a very small emitting region in the very centre of the galaxy. In the most extreme cases, the energy output of an AGN exceeds the amount of radiative energy from all the stars in the galaxy by several orders of magnitude.

The work on active galaxies started slowly in the early 1900s, with the discovery of ‘planetary-nebulae like’ emission lines in the nearly stellar nucleus of nearby spiral galaxies (e.g. Fath 1903; Seyfert 1943).* After the pioneering work of Jansky (1932) and Reber (1944), a boost in the field of active galaxies came with the rise of radio astronomy right after World War II. Using radar-technology inherited from the war, Hey et al. (1946) accidentally discovered a small and fluctuating radio source in the constellation of Cygnus. Some of the first bright radio sources on the sky were catalogued by Bolton (1948), followed by the discovery of thousands of radio sources in the following years.† Slowly, the idea rose that these radio sources were bimodal ejections of relativistic particles. The relativistic particles would be collimated in two beams, and radiate at radio frequencies through synchrotron and inverse-Compton processes (e.g. Blandford & Rees 1974). The discovery of radio sources inevitably led to the optical identification of these systems as extra-galactic objects, with redshifts ‘reflecting the Hubble expansion’ (e.g. Minkowski 1960; Hazard et al. 1963; Schmidt 1963; Oke 1963; Greenstein & Matthews 1963). On optical photographic plates these objects had a star-like, or ‘quasi-stellar’, appearance (e.g. Matthews & Sandage 1963), and the study of ‘quasars’ was launched.

With the research on quasars, the awareness rose amongst astronomers that AGN represent phenomena with unprecedented amounts of energy in the nuclei of distant galaxies,

*For an elaborate historic review of AGN, see the review by Shields (1999).
†In 1951, another revolutionary milestone in radio astronomy occurred with the discovery of the 21cm spectral line for neutral hydrogen by Ewen & Purcell (1951) and Muller & Oort (1951), earlier predicted by van de Hulst (1945).
often outshining the starlight of the entire galaxy. The search for the nature of AGN in the last century has culminated in the generally accepted paradigm that most of the energy output in AGN is generated by matter that is accreting onto a super-massive black hole in the centre of the galaxy. This century, astronomers have started to assess the role of AGN as an important and integral part of galaxy evolution.

\subsection{1.1 Active Galactic Nuclei}

A black hole is an object formed by a single point in space (a so called singularity), in which so much mass has accumulated that, out to a certain distance (the event horizon), no information can be released, because the escape velocity exceeds the velocity of light. The typical mass of a super-massive black hole in the nucleus of a galaxy is between $10^6$ and $10^{9.5} \text{M}_\odot$ (see Kormendy & Gebhardt 2001). The gravitational forces that the black hole exerts may cause matter in the central region of the galaxy to fall inward. In the proximity of the black hole, conservation of angular momentum causes the matter to flatten into a rapidly spinning accretion disk, before it eventually disappears into the black hole. Further out (but still in the tens of pc scale region), a dusty torus can form (e.g. Klöckner et al. 2003). Such a torus may block our view of the accretion disk, depending on the opening angle and our line-of-sight. Figure 1.1 (right) shows a sketch of an active galactic nucleus.

The material in the accretion disk gains a high speed and temperature due to the large gravitational potential of the black hole. Frictional heating causes the infalling material to turn into a plasma and radiate strongly in the optical, ultra-violet and X-ray bands. If the nuclear engine is not obscured by the dusty torus (or other dust in the central region), the AGN is often directly visible as a bright point source.\footnote{For very powerful AGN at high-redshift, the optical light of the AGN (when seen directly) often dominates over that of the host galaxy. The object therefore has a quasi-stellar appearance and is classified as a Quasi Stellar Object (QSO - radio quiet) or Quasi Stellar Radio Source (quasar - radio loud).} If the dusty torus obscures the central engine, the AGN can still be identified indirectly. The AGN might be visible in polarised light, which is scattered by electrons or dust, from broad radiation cones of the obscured AGN (e.g. Fabian 1989; Tadhunter et al. 1992; Miller et al. 1991). Also, gas in the nuclear region can be photo-ionised by radiation from the AGN, which results in the occurrence of strong permitted and forbidden emission lines, in particular those of high ionisation. In
general, line-ratios between the stronger emission-lines can be used to identify the excitation mechanism of the gas (Baldwin et al. 1981; Veilleux & Osterbrock 1987). In this way, photoionisation due to AGN radiation can be distinguished from shock-heating or ionisation due to young O and B stars. Indirect evidence for an obscured AGN can also come from the thermal infra-red (IR) emission. A possible source of IR emission in active galaxies is the reprocessing of soft X-ray and UV emission from the AGN by the dust in the circum-nuclear torus (e.g. Pier & Krolik 1992; van Bemmel & Dullemond 2003, and references therein). However, IR studies of AGN are being complicated by the fact that a substantial part of the IR emission might come from dusty star formation (e.g. Barthel 2001).

In roughly 15–20% of all AGN (Kellermann et al. 1989), the central engine also produces large amounts of radiation at the longer radio-wavelengths in the form of two relativistic jets of radio plasma that are expelled on either side of the black hole’s accretion disk. Although the exact formation mechanism of these relativistic jets yet remains uncertain, the magneto-hydrodynamic (MHD) model (see e.g. Meier et al. 2001) suggests that differential rotation of the black hole + accretion disk creates a magnetic field helix in the direction of the rotation axis. A plasma of high energy electrons – stripped off the accretion disk material – is directed along the magnetic field-lines at high speeds.§ Synchrotron radiation coming from these plasma-outflows results in the typical radio-source morphology that is observed in these galaxies (see Fig. 1.1 - left). Radio sources may range in size from parsec up to mega-parsec scales, forming some of the largest single-structures in the Universe. Powerful radio sources can serve as beacons for massive structures in the most distant reaches of the Early Universe (e.g. Venemans 2006).

1.2 Radio Galaxies

Regarding radio galaxies, there are two tantalising aspects related to the morphology of the radio source:

**Fanaroff & Riley classification:** The first aspect is related to the total radio power of the source. There is a striking difference in radio source morphology regarding the Fanaroff & Riley classification (Fanaroff & Riley 1974). Generally, the weaker radio sources are of Fanaroff-Riley type-I (FR-I); these have turbulent, subsonic radio jets, which decrease in radio brightness from the centre outward. The more powerful radio sources are of Fanaroff-Riley type-II (FR-II); these have collimated, supersonic jets that end in a bright hot-spot. Figure 1.2 gives a clear example of both types of radio-source structures. The dividing power between both FR-types lies around $P_{1.4\text{GHz}} \sim 10^{25}$ W Hz$^{-1}$, although this also depends on the luminosity of the host galaxy (Ledlow et al. 2002; Owen & White 1991; Owen & Laing 1989). The main question regarding these two types of radio sources is whether they are different because of the intrinsic properties of the central engine (“nature”) or because of the properties of the host galaxy in which they reside (“nurture”). Understanding the difference between both types of radio sources could be vital for understanding their relation to the host galaxy.

**Size of the radio source:** The second aspect is related to the size of the radio source. While for some radio galaxies the radio source is contained within the optical host galaxy, for others

§The high-energy electrons in these plasma-flows may be accelerated to near-light speeds, in which case relativistic effects become important.
the radio-plasma stretches out to far beyond the optical host galaxy (reaching Mpc-scale distances in the most extreme cases). Many studies have been devoted to the relation between compact and extended sources. An excellent review on this topic is given by O’Dea (1998) and for the remainder of this paragraph we refer to the references given therein. Two scenarios that have been proposed to explain the properties of compact radio sources are the youth scenario and the frustration scenario. In the youth scenario, compact sources are the young counterparts of what will become extended radio sources. In the frustration scenario, compact radio sources are confined by an ambient, dense ISM. Although the debate has not yet been settled, currently most of the evidence favours the youth scenario. This is in particular the case for the powerful Gigahertz Peaked Spectrum (GPS) and Compact Steep Spectrum (CSS) radio sources, which are believed to be the progenitors of extended, powerful radio sources. This conclusion is mostly based on the similarity in morphology between GPS/CSS and extended radio sources, on the fact that GPS/CSS sources do not show evidence for old, diffuse halos of radio emission and on the fact that there is no compelling evidence for large enough amounts of ISM to frustrate these radio sources. This also agrees with the typical short lifetimes of GPS and CSS sources (≲ 10⁵ yr), as derived from spectral ageing arguments and jet advance speeds. However, in particular for the less luminous compact radio sources (e.g. Low Power Compact, or LPC, sources), the case is much less clear. It is possible that many of these sources remain compact, either because they cannot bore through the local ISM, or because their fuelling stops before they manage to grow to galaxy-size scales (see e.g. Giroletti et al. 2005a). As a final note, we would like to add that there is a group of radio sources that appears small, not because they are intrinsically compact, but because

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**Figure 1.2:** The two Fanaroff & Riley types of radio sources. **Left:** FR-I radio source 3C 31 (see Bridle et al. 1994). **Right:** FR-II radio source 3C 175 (see Laing & Bridle 2004). (Credit: A.H. Bringle & R.A. Laing.)

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¶The GPS and CSS classification (see O’Dea 1998) is commonly used to describe sources with $P_{1.4\,\text{GHz}} \gtrsim 10^{25} \, \text{W Hz}^{-1}$, convex radio spectrum and small size (≲ 1 kpc for GPS sources and between 1 and 20 for CSS sources). We note, though, that this classification is somewhat arbitrary and often other nomenclature is used to describe fairly similar classes of objects, such as Steep Spectrum Core (SSC), Compact and Medium Symmetric (CSO and MSO) and Compact Double (CD) objects.
they are oriented along our line-of-sight. For these radio sources the core radio emission is enhanced by relativistic beaming and these sources generally have a flat spectrum. They are called blazars (high radio power) or BL Lac objects (low radio power). Blazars and BL Lac objects are beyond the scope of this thesis.

While reading this thesis, it is important to keep in mind the difference in radio-source properties. Our project will extend our knowledge about the host galaxy properties for different types of radio sources.

1.3 Triggering the radio source

Recent studies suggest that at least a large fraction of all galaxies contains a central supermassive black hole (see reviews by Kormendy & Richstone 1995; Kormendy & Gebhardt 2001). However, only a small fraction of the galaxies in the universe has an active galactic nucleus. Of these, only about 15 — 20% contain a radio source (Kellermann et al. 1989). To power a radio source, a mass accretion rate as little as $10^{-3} - 10^{-5} M_\odot\,\text{yr}^{-1}$ may be sufficient (e.g. van Gorkom et al. 1989). This means that, in principle, a modest galaxy has potentially enough material to fuel the central black hole for a Hubble time. So why does not every galaxy have an active nucleus with powerful radio jets?

The answer is partially related to the fact that the material that is present in a galaxy must lose enough angular momentum to be accreted onto the sub-pc scale accretion disk and eventually disappear in the black hole. Therefore, certain physical processes are necessary to remove this angular momentum. One possibility is that perturbations in the galactic potential stir the gas in a galaxy and enhance cloud-cloud collisions. The resulting loss of angular momentum transports the gas deeper in the potential well of the galaxy, until it eventually fuels the AGN. These gravitational perturbations may be ascribed to tidal interactions by galaxy encounters (e.g. Lin et al. 1988) or to central bars (Schlosman et al. 1989). Tidal interactions may enhance accretion on a time scale comparable to the dynamical time scale of the perturbed gas in the nuclear region. This might explain why AGN activity is a short (possibly recurrent) phase, rather than a continuous process, in galaxies evolution. However, since only a fraction of all AGN also harbour a radio source, an additional physical mechanism may be necessary to explain the ejection of radio jets. According to Wilson & Colbert (1995), this mechanism may be related to the black hole spin. They argue that major mergers, and the subsequent coalescence of roughly equal-sized black holes of the parent galaxies, can produce a very massive, rapidly spinning black hole, which can be the genesis of powerful radio sources. From optical observations, Heckman et al. (1986) and Baum et al. (1992) conclude that signs of major mergers are indeed more frequently observed around powerful FR-II radio galaxies than around radio-quiet early-type galaxies. However, they also argue that the less powerful FR-I radio sources could be triggered through other processes, related to, for example, the stored rotational energy of the black hole, or the accretion of gas from the galaxy’s atmosphere or inter-cluster medium. As we will see below, many of these triggering events will leave their mark also on the host galaxy.

1.3.1 Major mergers

Mergers are often invoked to trigger starburst as well as AGN activity in galaxies. In the hierarchical model of galaxy formation, early-type galaxies such as E (elliptical) and S0 galaxies form the end products of merging systems. The overwhelming majority of bright,
low-z radio sources are hosted by these early-type galaxies, which often still show optical signatures of the merger event (like optical tails, bridges, shells; Smith & Heckman 1989). Also for low redshift QSOs, Smith et al. (1986) find a trend that the host galaxies of radio-loud objects tend to be better fitted by elliptical galaxy models, while the radio-quiet hosts are better fitted by disk galaxies. Moreover, they find some indication that radio-loud hosts are more likely to have optical peculiarities than radio-quiet hosts. In addition, a growing number of radio galaxies is found to contain a young or intermediate age stellar population, indicating that they are post-starburst systems (e.g. Aretxaga et al. 2001; Wills et al. 2002, 2004; Tadhunter et al. 2002, 2005; Raimann et al. 2005; González Delgado et al. 2006). The same holds for optically selected AGN from the Sloan Digital Sky Survey (SDSS), of which a significant fraction experienced bursts of star formation in the recent past (Kauffmann et al. 2003).

Since the work of Toomre & Toomre (1972), numerous simulations have helped to clarify the fate of gas in galaxy mergers. In a major merger event between two gas-rich disk galaxies (with mass ratio between 1:1 and 1:3), part of the gas is transported to the central region, while another part is expelled in large structures of low surface brightness (tidal-tails, bridges, shells, etc.). Due to tidal forces, the gas that is transported to the central region will be subject to bar formation (Barnes & Hernquist 1996). As such bars form, the gas in the inner half of the galaxies’ disks will be subjected to strong gravitational torques and lose most of its angular momentum. This gas may be identified by large amounts of CO that have been detected in the central region of radio galaxies (e.g. Evans et al. 2005). The strong strong gravitational torques acting on the central agglomeration of gas will also trigger a massive burst of star formation on kpc-scales (e.g. Mihos & Hernquist 1994, 1996; Springel et al. 2005a). Such a starburst event has been modelled by Mihos & Hernquist (1994) to have a typical lifetime

\[ \text{See footnote in Sect. 1.1 for a definition of QSO.} \]
of $\sim 50$ Myr and it could give the galaxy the appearance of an Ultra-Luminous Infra-Red Galaxy for a short period. Much of the gas in the optical host galaxy is either consumed by the massive starburst, or expelled from the system by strong starburst driven superwinds (Heckman et al. 1990; Rupke et al. 2002). If some of the gas in the nuclear region continues to lose angular momentum, it might eventually be deposited in the sub-pc scale region around the black hole. There it may be able to feed the central black hole, resulting in the triggering of an AGN. Recent numerical simulations of gas-rich galaxy mergers by Di Matteo et al. (2005), Springel et al. (2005a) and Hopkins et al. (2005) include black hole growth and feedback. In these simulations, AGN activity is the outcome from gas that is deposited onto the central black hole, until feedback effects terminate the gas supply. While major mergers certainly are a viable explanation for the occurrence of AGN activity, the exact timing of triggering the AGN could be related to secondary effects, such as the merging of individual black holes of the progenitor galaxies (e.g. Wilson & Colbert 1995; Milosavljevic & Merrit 2001; Escala et al. 2004) or of a black hole with an individual cloud (e.g. Bekki 2000).

The gas in the outer disks of the progenitor galaxies is expelled from the merger system and may form large-scale tidal features, such as tails, plumes, bridges, etc. A good example of this are the Antennae Galaxies (Hibbard et al. 2001), shown in Fig. 1.3. Part of the expelled gas may remain gravitationally bound to the system (provided that the environment is not too hostile) and will slowly fall back onto the host galaxy. In the meanwhile, the stars in the progenitor galaxies also rearranged under the strong gravitational forces induced by the collision. This gives the merger product the appearance of a typical early-type galaxy (see also numerical simulations by Naab et al. 1999). Hibbard & van Gorkom (1996) studied both the stellar and the gaseous appearance of a sequence of galaxies involved in different stages of a major merger. An important fact to consider is that the timescales for the stars to settle after the merger are much shorter than those required for the large-scale cool gas. This means that, while in the optical the merger product already gained the primary optical characteristics of an early-type galaxy (with an $r^{1/4}$ radial light profile and obeying the Faber-Jackson relation between luminosity and velocity dispersion), the signatures of the merger event could still be visible in observations of neutral hydrogen (H I) gas at tens to hundreds of kpc distance from the galaxy. Models by Barnes (2002) show that within a few galactic orbits ($> 1$ Gyr), this gas is likely to fall back onto the host galaxy and settle into a disk- or ring-like structure. The formation of an early-type galaxy with a large-scale H I disk or ring is therefore a natural outcome of a major merger between gas-rich galaxies. NGC 5266 (Morganti et al. 1997, see Fig. 1.4) is a good example of an early-type galaxy that contains such a large-scale H I disk, which has a diameter of about 200 kpc (which is $8 \times$ the optical half-light diameter) and an H I mass of $2.4 \times 10^{10} M_\odot$. The overall surface density of this H I gas is too low for violent star formation to occur. Such tidal H I structures can therefore remain as long-lived remnants of the merger event. Similar large-scale structures of neutral gas are found in a growing number of early-type galaxies (Schiminovich et al. 1994, 1995; Veron-Cetty et al. 1995; van Gorkom & Schiminovich 1997; Sadler et al. 2000; Oosterloo et al. 2001, 2002; Serra et al. 2006; Morganti et al. 2006a; Oosterloo et al. 2006).

### 1.3.2 Dry mergers

Mergers between two gas-poor early-type galaxies are called dry mergers (e.g. Naab et al. 2006, and references therein). Dry mergers are frequent in the nearby universe (on average every early-type galaxy has gone through 0.5 - 2 dry mergers since $z = 0.7$), and the merger
time scales (150 Myr) are much shorter than those of major mergers between gas-rich systems (Bell et al. 2006). In many of these dry mergers there will most likely not be enough gas to trigger massive bursts of star formation or produce large-scale gaseous tidal features. However, very low amounts of gas might still be sufficient to fuel a radio source (see Sect. 1.3). It has been proposed by Colina & de Juan (1995) that FR-I sources may be triggered in a merger between two elliptical galaxies with median mass ratio (factor 3 or less).

### 1.3.3 Cooling flows and cold accretion

An alternative mechanism for feeding an AGN consists of cooling flows (see the review by Fabian 1994, and references therein). Cooling flows are generally believed to originate from the hot, inter-galactic medium (IGM). Around a massive galaxy, where this IGM is naturally densest, the hot gas loses energy through radiation (mostly X-rays). Here the gas starts to cool and slowly falls towards the central region of the galaxy. When penetrating all the way into the nuclear region of the galaxy, these cooling flows may provide the fuel for an AGN and, when the physical conditions are right, possibly also trigger radio jets. This scenario is particularly appealing for the FR-I sources that are often found in bright ellipticals in the centre of clusters. Cooling flows have recently been mapped in CO in a number of clusters (Edge & Frayer 2003; Salomé & Combes 2004).

Simulations by Kereš et al. (2005) show that galaxies can accrete gas from the IGM along large filaments, without it being shock-heated. This cold mode of gas accretion is most effective in low density environments and at high redshifts, and may result in the accumulation of large amounts of gas with $T < 10^5$ K around the host galaxy over a period of many Gyr (see also the discussion by Serra et al. 2006). If part of this gas can cool even further, it may be able to reach the cold temperatures of neutral and molecular gas. Simulations by Kaufmann et al. (2006) and Macciò et al. (2006) suggest that cooling of hot halo gas can result in the formation of cold gas disks or polar rings.
At present there is still a debate about what is the dominant mechanism for feeding AGN and triggering radio jets. As discussed above, it is possible that different mechanisms are at work for different types of radio galaxies. In this thesis we investigate this issue in more detail.

### 1.4 Feedback

Not only are the host galaxy conditions important for triggering the AGN, but there is growing evidence that the AGN activity in the very nuclear region is important for the evolution of the host galaxy. Maybe the most convincing evidence that super-massive black holes are related to the properties of the host galaxy comes from an empirical relation between the mass of the black hole and the velocity-dispersion of the bulge in which it resides (e.g. Merritt & Ferrarese 2001, and references therein). This relation suggests that there is some sort of feedback mechanism that connects the black hole mass with the bulge properties. Silk & Rees (1998) explore one possible source of feedback in the earliest objects, assumed to be super-massive black holes that formed before the first epoch of star formation. When such a black hole accretes gas, it starts to radiate as an AGN and this radiation drives out a wind that acts back on the accretion flow.

Recent simulations by Di Matteo et al. (2005), Springel et al. (2005a) and Hopkins et al. (2005) include black hole growth and feedback in merger processes. Di Matteo et al. (2005) show that gas flowing into the nuclear region yields strong accretion for a timescale of roughly $10^8$ yr, after which feedback from the AGN heats the gas and drives it out of the nuclear region. This self-regulating nature of the black hole growth explains the observed correlation between black hole mass and host galaxy properties (Di Matteo et al. 2005), as well as the colour distribution of ellipticals (Springel et al. 2005b). Galaxy merger simulations of Narayanan et al. (2006) show that embedded AGN can drive significant outflows of molecular gas.

Observationally, outflows of warm/hot gas (e.g. Heckman et al. 1981; Veilleux et al. 2002; Kriss 2004, and references therein), emission-line gas (e.g. Tadhunter 1991; Villar-Martín et al. 1999; Tadhunter et al. 2001; Holt et al. 2003; Taylor et al. 2003) and recently also neutral gas (Morganti et al. 2005; Emonts et al. 2005) are frequently seen in active galaxies in the nearby universe. Although the exact driving mechanism of these outflows is not always clear, they could be driven by AGN induced winds (Krolik & Begelman 1986; Balsara & Krolik 1993; Dopita et al. 2002) or by the interaction of the radio plasma with the ambient ISM (Oosterloo et al. 2000; Morganti et al. 2004a). An additional driving mechanism could consists of starburst-induced winds (Heckman et al. 1990) from young stellar populations that are known to be present in some radio galaxies (see Sect. 1.3.1).

Some authors propose that star formation can even be induced when the radio jets interact with the ambient ISM. A good candidate for jet-induced star formation in the nearby universe is Minkowski’s object (van Breugel et al. 1985b; Croft et al. 2006). At high-z, the galaxy-scale alignment of UV/optical emission with the radio plasma (e.g. McCarthy et al. 1987; Chambers et al. 1987) might also be related to jet-induced star formation, which would indicate the importance of the propagating radio plasma for the properties of the host galaxy.

AGN and radio jet activity are therefore important phases in the evolution of galaxies throughout the universe.
1.5 This thesis

This thesis studies the interplay of gas, star formation and active nucleus in nearby radio galaxies. We use different observational techniques to study the link between the host galaxy and the radio source. The thesis project is focused around the following main topics:

- Are mergers the main mechanism for triggering the radio-AGN activity in radio galaxies, or do other processes need to be considered?
- In case of a merger, what are the timescales involved regarding the triggering of starburst and radio-AGN activity?
- Are particular triggering-processes related to the morphological appearance of the radio source (e.g. FR-I vs. FR-II sources)?
- Does the (re-)distribution of the ISM influence the radio source properties (e.g. compact vs. extended sources)?
- What are the feedback effects of the radio source on the host galaxy?

Investigating these physical processes in nearby radio galaxies – which we can study in great detail – is also important for high-redshift studies, where mergers are much more frequent and where radio sources are generally much stronger. A detailed knowledge about the interplay between radio source and host galaxy (v.v.) is therefore invaluable for understanding galaxy evolution throughout the universe.

1.5.1 From small to large scales

Many observational studies have been done on the properties of gas and stars in the vicinity of AGN. With the aid of high-resolution instruments, such as the Hubble Space Telescope (HST), and with the use of Very Long Baseline Interferometry (VLBI), the gas, dust and radio source properties in the direct vicinity of AGN can be traced on sub-kpc scales (e.g. Ferrarese et al. 1996; Verdoes Kleijn et al. 1999; O'Dea et al. 2002; Peck & Taylor 2002). These high-resolution studies are very effective at investigating a direct link between the central engine and the nuclear and circum-nuclear properties of the dust and gas, which is useful for studying the details of feeding and feedback processes of the AGN. We will further explore certain feedback processes in Chapter 6 of this thesis. However, the dynamical timescales of the dust and gas in the nuclear region are relatively short compared with the timescales of the physical processes that might be important for triggering the radio source (such as mergers or cooling flows). This implies that in the nuclear region relic features of such an event may have already been washed out, while at galactic scales they can still be traced (for example in the form of tidal debris, accreted cold gas or post-starburst stellar populations).

This thesis therefore aims to investigate the large-scale properties of the host galaxy in relation to the small-scale physical processes of the central engine. To address the main topics of this thesis (Sect. 1.5) we use the following observational techniques:

- HI imaging $\rightarrow$ long-lived tidal debris from merger events
  
  In case of a merger event, H I gas can leave long-lived signatures of this event (Sect. 1.3.1). If the conditions are good, these H I signatures can remain visible in emission up to many Gyr after the merger. The spatial and kinematic information about the distribution of the H I gas makes a rough dating of the merger event possible.
• **Optical spectroscopy → starburst events**
  A merger event generally triggers a burst of star-formation (Sect. 1.3.1). Modelling the spectral energy distribution in optical long-slit spectra of galaxies is a useful technique to trace and date stellar populations that formed during a starburst event. A study of the stellar populations is therefore another way to find indications of a past merger event.

• **Line studies of neutral and ionised gas → interplay between radio source and ISM**
  HI absorption (detected against the radio continuum) and optical emission lines provide excellent tools to study the kinematics and physical state of the ambient ISM that surrounds the radio source in the centre of the galaxy. This can be used to compare the large-scale properties of the ISM with the gas-properties in the central region of the radio galaxy. It is also an excellent way to study feedback effects that the propagating radio jets exert on the ISM in the host galaxy.

We compare these studies of the gas and stars with the known properties of the radio source (age, morphology, total luminosity, etc.) in order to investigate possible links between the large-scale host properties and the central engine.

A few **important points** to our approach are:

1). A study of tidal HI debris and of the stellar populations in nearby radio galaxies allows for a reasonable accurate dating of a merger event up to many Gyr after the merger. This is long after the optical signatures of a merger from the distribution of stars (which gives the galaxy its characteristic optical morphology) have mostly vanished (Hibbard & van Gorkom 1996). We are therefore sensitive to much older merger events compared to many optical (broad-band) studies. But also, if mergers are not the explanation for the triggering of the radio source, perhaps we will be able to test this with these observations (if, for example, minor interactions or cooling flows are important for the triggering of the activity, we might see evidence for this in the cool gas, but not necessarily in the star formation history). In that case, the distribution of the ISM and the stellar populations still provide deeper insight in the formation history of the radio galaxy.

2). While HI emission studies can be used to trace HI at large scales, HI absorption against the central radio continuum allows us to trace HI down to the very nuclear region. We combine the information about the neutral ISM at large and small scales to get a complete picture of the cool gas in the early-type host galaxies of the radio sources.

3). For the first time, a **complete sample** of nearby radio galaxies is observed to look for HI on large scales. This will give us reliable statistics on the HI properties. We can compare this with recent studies on HI in radio-quiet early-type galaxies, which allows us to investigate the occurrence of radio-AGN activity in early-type galaxies. **This project will therefore also add to our knowledge about early-type galaxies in general.**

### 1.6 Thesis outline

**Chapter 2** gives the story of radio galaxy B2 0648+27. In B2 0648+27 we detect a large-scale structure of neutral hydrogen gas and a post-starburst stellar population, both indicative of a past merger event. There appears to be a significant time-delay between the various phases of activity (merger event, starburst episode and onset of radio-AGN activity) in this system. B2 0648+27 is an important link between Ultra-Luminous Infra-Red Galaxies (ULIRGs)
and genuine early-type galaxies. The techniques used to study the formation history of B2 0648+27 are illustrative of our approach to systematically study a whole sample of nearby radio galaxies in the following chapters.

Chapter 3 shows the results of an H I study (both in emission and in absorption) of a complete sample of nearby radio galaxies and their environment. The sample consists of compact sources and extended FR-I sources. Similar to B2 0648+27, we detect several more radio galaxies with large-scale H I. These H I structures are likely formed either though a past merger event or through cold accretion of circum-galactic gas. Most of the H I structures are apparently old compared to the current phase of radio-AGN activity. We find evidence for a trend that radio galaxies with massive ($M_{\text{HI}} \gtrsim 10^9 M_\odot$), large-scale H I structures all have a compact radio source, while extended FR-I sources lack similar amounts of H I. This suggests that there is a link between the central radio-AGN and the large-scale properties of the ISM in radio galaxies.

Chapter 4 describes the results of a stellar population analysis of the H I-rich radio galaxies from Chapter 3. The main goal is to trace past starburst events by modelling optical spectra of these galaxies. This can be used to verify and date a possible merger origin of these systems. Although some of the H I-rich radio galaxies experienced a starburst event in the past several Gyr, others contain only an old stellar population. This means that there is no clear one-to-one correspondence between the H I content and the stellar populations in our sample, which suggests that, while some of the H I-rich radio galaxies have gone through a major merger, this is not necessarily the case for all of them. We do find a link between the presence of a young stellar population and the IR luminosity of our radio galaxies.

Chapter 5 gives the H I analysis of the southern radio galaxy NGC 612, which contains an extended, powerful radio source of hybrid FR-I/FR-II morphology. NGC 612 contains large amounts of neutral hydrogen and intermediate age stellar populations, which are consistent with the scenario that a major merger formed this system about 1 Gyr ago (although other scenarios can not be ruled out). In addition, several tails of H I are seen towards three small, nearby companions and very faint H I debris is detected in the direction of the gas-rich peculiar galaxy NGC 619.

Chapter 6 investigates how the central radio-AGN influences the properties of the host galaxy through feedback-effects. We describe two powerful, nearby radio galaxies that display an outflow of neutral and ionised gas from the central few kpc of the host galaxy. The outflow is driven by a jet-ISM interaction and reaches velocities up to $\sim 1000$ km s$^{-1}$. The most important new result is that the neutral gas in the outflows dominates over the outflow of ionised gas by a factor of about 100, indicating that the role of the neutral gas in feedback effects is much larger than generally assumed in observational and theoretical studies. The detection of these jet-driven neutral outflows implies that AGN feedback can be as important in galaxy evolution as for example the starburst-driven feedback in infra-red bright merger systems.

Chapter 7 gives a general overview of the results obtained from this thesis project. The implication of these results for understanding radio galaxy evolution, as well as for future research on this topic, are also described.